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SENSORY QUALITY OF BOILED POTATO CLONES AND SPUNTA USING QUANTITATIVE DESCRIPTIVE ANALYSIS (QDA) AND INSTRUMENTAL COLOUR MEASUREMENT

Y Cadersa[1*], B Aumjaud[2], J Govinden Soulange[3], S Saumtally[4] and Y Parmessur[5]

ABSTRACT: The selection of advanced potato clones for their culinary characteristics as table potato is a major research activity in the breeding and selection programme at the Food and Agricultural and Extension Institute. The objective of this study was to assess the sensory quality of six advanced potato clones and Spunta variety using boiling as a cooking method. Quantitative Descriptive Analysis (QDA) was applied to develop sensory profiles. A trained sensory panel of 7 assessors identified 16 descriptors comprising of 3 appearance, 5 texture, 4 aroma, 3 flavour and 1 taste characteristics. Sensory data showed that all potato clones obtained significantly higher mean ratings for white colour but significantly lower values for yellow colour compared to Spunta ($P \leq 0.05$). These results were consistent with the instrumental CIE b* measurements for yellowness. Mean sensory ratings for most texture descriptors (compressibility, stickiness and dryness) were not significantly different between clone 29/5/16 and Spunta ($P \geq 0.05$). On the other hand, Spunta obtained a significantly higher mean boiled potato aroma rating than all clones ($P \leq 0.05$) while the mean sensory ratings for potato–like flavour of 29/5/14, 29/5/16 and 142/16 1/5 were not significantly different from the corresponding values for Spunta ($P \geq 0.05$). Texture and flavour profiles indicated suitability of potato clone 29/5/16 and Spunta for the development of boiled potato products.

KEYWORDS: potato clones, Spunta, boiled potato, sensory quality, Quantitative Descriptive Analysis (QDA), instrumental colour

INTRODUCTION

Potato (*Solanum tuberosum* L.) is the fourth most important food crop in the world after maize, wheat and rice (FAOSTAT, 2021; OECD/FAO, 2022). In Mauritius, it is the most cultivated and most consumed among all food crops with a per capita consumption of 19.64 kg/year (Statistics Mauritius, 2022).

Boiled potatoes contribute to a sustainable diet with a good source of several B vitamins, vitamin C, dietary fibre, potassium, folate and iron (Camire *et al.,* 2009). They are rich in carbohydrates and energy and have little fat (Camire *et al.,* 2009). In addition, they contain a lot of antioxidants and have a very high rating of satiety (Gustavsen, 2021). A survey among households in urban, semi-urban and rural areas in Mauritius indicated that potato is used for six main purposes: curry (25.4%), crisps (17.3%), French fries (15.5%), stew (fricassée or daube) (15.5%), mash (11%)

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and salad (10.9%) (Govinden *et al.,* 1997). Furthermore, Gunputh (2009) found that among housewives of different age groups and with diverse cultural backgrounds, the percentage respondents expressing that they "very often" utilised potato for dish preparation was highest for curry (42.5%), crisps (44.2%) and French fries (42.5%). These findings highlight the importance of boiled potato in curry and mash recipes although culinary choices in a typical Mauritian diet are limited. The selection of potato clones for their culinary use is a major thrust in the Research and Development programme at the Food and Agricultural Research and Extension Institute (FAREI).

Recently, eighteen advanced potato clones were selected for the fresh and processed market segments based on their tuber characteristics and dry matter content (Cadersa *et al.,* 2019). During the advanced stages of selection, six promising clones were identified as high-yielding and late blight resistant compared to Spunta which is the most popular table potato variety. It is important to determine whether these promising local clones are suitable for boiled table potatoes to replace the Spunta variety. Quantitative Descriptive Analysis (QDA) is being used to assess the organoleptic properties including appearance, texture, aroma, flavour, taste and after taste of foods and beverages (Meilgaard *et al.,* 2007; Cruz *et al.,* 2010) by using human assessors as measuring instruments (Kemp *et al.,* 2018). The objectives of this study were to (i) identify the sensory descriptors of boiled potato clones and Spunta using QDA (ii) develop the sensory lexicon and measurement scales for each sensory descriptor (iii) rate the perceived intensity of the different sensory descriptors (iv) determine the CIELAB colour variables of the boiled potato genotypes using instrumental measurement and (v) select clones suitable for boiled table potato according to their sensory profiles.

MATERIALS AND METHODS

Potato genotypes

Seven potato clones were used in this study: six advanced clones (142/161/4, 142/161/5, 161/142/16, 29/5/10, 29/5/14 and 29/5/16) and the widely grown commercial variety Spunta. The tuber characteristics of the clones are presented (Table 1, Fig. 1). All clones were grown in the first potato season in May 2020 at the Réduit Crop Research Station and harvested in July 2020. 30 kg tubers of each accession of marketable size (150- 200g) and free from external defects and pathogens were allowed to cure at ambient temperature for 24 hours and then stored at 11-13°C at 80-90% relative humidity for one week before samples were used for sensory training and evaluation sessions. This brief storage period

Table 1. Tuber characteristics of potato clones including the control variety Spunta

Potato genotype	Tuber shape	Eye depth	Skin colour	Flesh colour	Dry matter content (%)
142/161/4	Oval long	Shallow	White cream	White	19.2
142/161/5	Oval round	Shallow	White cream	White	21.3
161/142/16	Oval long	Deep	White cream	Cream	17.4
29/5/10	Oval long	Shallow	White cream	White	22.8
29/5/14	Oval	Shallow	White cream	White	22.9
29/5/16	Oval long	Shallow	White cream	White	19.4
Spunta	Long	Shallow	Yellow	Yellow	22.4

Source: Cadersa *et al*. (2019)

Fig. 1. Tuber characteristics of 6 promising clones and Spunta evaluated for the suitability for boiled potatoes.

ensures wound healing of tubers and stabilises biochemical composition.

Selection of assessors

The sensory panel was made up of the following: (i) selected assessors who were undergraduate students of food science and technology of the University of Mauritius (ii) the panel leader and(iii) the panel supervisor. Details for establishing the sensory profile of boiled potato was in accordance with ISO 8586 (2012) and 1SO13299 (2003(E)). Seven trained assessors (5 females/2 males, aged between 21–24 years) were selected to participate in the development of the sensory profiles and final evaluation of the boiled potato clones. They were chosen from an initial population of 32 candidates based on their sensory acuity, descriptive and discriminating ability in scoring above 80% in the different screening tests namely triangle test, odour recognition test, taste recognition test, jelly- flavour test and colour sensitivity (ISO 8586, 2021), motivation and willingness to participate in the project and availability for the whole duration of the study. Since the panel size was small, rigorous training and monitoring was done to ensure consistency and reliability of data among the panelists.

Training of Assessors

Identification of sensory descriptors and lexicon development

Selected assessors were required to individually identify sensory descriptors of 4 potato samples, namely 3 clones and Spunta variety. Sensory descriptors which were identified by most assessors were retained for quantitative analysis. The list of descriptors was further refined and consolidated using additional documented literature on boiled potato sensory characteristics (Van Marle *et al.*, 1997; Thybo and Martens, 1999; Seefelt *et al.*, 2011) and ISO (International Organisation for Standardisation) reference materials (ISO 5492, 2008). The assessors were introduced to the different terminologies from the following perspectives (i) general terminology (ii) the senses (iii) organoleptic attributes and (iv) sensory methods (ISO 5492, 2008). In addition, they were also introduced to sensory terms used to describe appearance, aroma, flavour, taste and solid oral texture (Meilgaard *et al.*, 2007). Collective discussion of the meaning of each selected sensory descriptor was facilitated by the panel leader to ensure consistent interpretation and reach consensus among the assessors.

Training in the use of quantitative response scales

15 cm unipolar and bipolar line scales with anchors at 2.5 cm were used for quantitative evaluation (ISO 4121, 2003).

Assessors collectively agreed on ratings for the reference materials. The assessors also practiced quantitative assessment of reference materials to ensure that they give close responses to the same sensory stimuli and minimise variation in individual ratings. Boiled potato variety Spunta and boiled sweet potato were the key reference samples for defined points of measurement scales of many sensory descriptors. Boiled sweet potato was chosen because it is a starchy vegetable with similar cooking methods like potato. Fig. 2 shows the agreed ratings of reference materials for texture, aroma and taste descriptors.

Training and monitoring

Selected assessors undertook two- hour training sessions every week from 05 March 2020 to 13 March 2020 and from 06 August to 17 September totalling 20 hrs. Training sessions started with appearance and texture descriptors followed by aroma, flavour and taste attributes. A standard procedure for order and method of sensory evaluation was developed to control sources of variations. For appearance descriptors, assessors were provided with longitudinal sections of boiled potato tubers (7cm × 3.5 cm) in open containers and presented on a white background. They were requested to rate the perceived intensity of each colour descriptor by carefully examining the sample under a source of light and assessing the proportion of white, cream or yellow colour which can be observed on the sample surface. For describing oral texture descriptors, assessors were required to place a piece of the boiled potato sample of controlled size between incisor teeth, bite half of the sample with incisors and chew down with molar teeth.

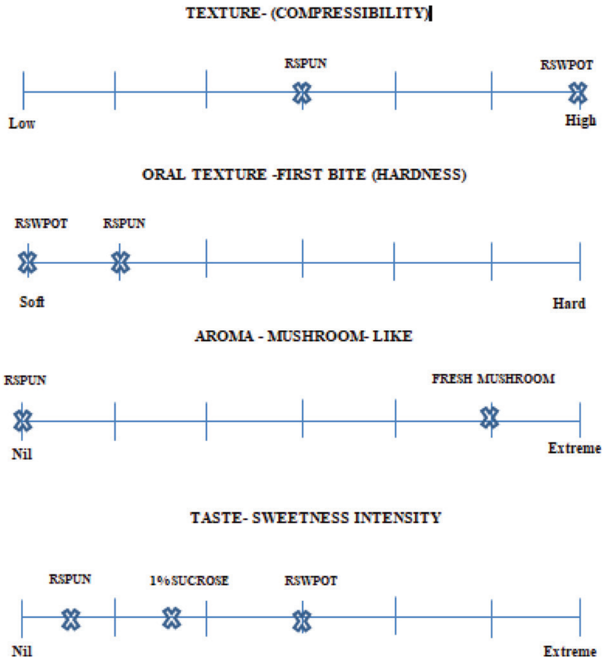

Fig. 2. Unipolar and bipolar line scales showing the agreed ratings for reference materials. Examples are given for texture, aroma and taste descriptors. Lines are not drawn to scale. The respective crosses on the line represent the corresponding ratings for the different reference materials (RSPUN- reference Spunta; RSWPOT- reference sweet potato).

For aroma, flavour and taste descriptors, boiled potato samples were provided in closed containers. To ensure effective detection, recognition and quantification of aroma descriptors, assessors were instructed to bring the sample container close to their nose, take a few short sniffs and concentrate on the perceived intensity of the odour. They were required to close the container immediately after smelling the samples to prevent volatile odour compounds of one sample from interfering with odour assessment of other samples. This was also important to allow the volatiles to concentrate in the headspace of the sample container.

Monitoring tests involving blind coded samples/reference materials were implemented to evaluate the effectiveness of the training sessions in terms of bias and between-assessor variation. Assessor's bias was estimated from the difference between the individual monitoring rating for the sensory descriptor of a sample/reference material and the collectively agreed rating during training sessions for the specific descriptor and same sample/reference as follows: Assessor bias (d) = x - μ where d is the deviation or bias, x is the observed assessor rating, and μ is the corresponding agreed rating (Meilgaard *et al.*, 2007).

Retraining was conducted for specific descriptors namely white and cream colour, rancid-like and mushroom- like aroma and flavour to ensure that assessors achieve consistent results by using the same part of the scale when evaluating the same sample.

Sensory profiling

Preparation of boiled potato samples

The potato samples were washed in running water to remove any soil or dirt present on the surface of the tubers. Two uniform sized tubers (200 – 250g each per accession) were placed into 2-L stainless steel saucepans, covered with 1.25–1.50 L water and boiled with their skins for approximately 45 minutes with a lid on the saucepan to prevent excessive moisture loss. The water was replenished as and when required to ensure that it covered the potato tubers. The potato samples were cooked until soft by inserting a fork in the centre of the tubers and removing it without resistance. The cooked potatoes were removed from the saucepan and allowed to cool slightly before peeling. It was observed that the cooking time varied slightly between the different cultivars.

Serving procedure

For the evaluation of appearance and texture attributes, the boiled potato samples were cut into 2 halves and a representative sample (7 cm long × 3.5 cm wide) of each accession was served to the assessors in open containers against a white background. For aroma, flavour and taste descriptors, the boiled potato samples were cut into cubes of 2cm × 2cm × 2cm. Two potato cubes approximating 30g were half-filled in 60g plastic vials leaving enough space to allow the odour volatiles to concentrate in the headspace. The potato cubes were allowed to cool to room temperature before being placed in the plastic vials to prevent production of off-odours and flavours that might arise from contact of the hot potato with the plastic containers. Care was also taken to replace used plastic vials by new ones for the next evaluation session. All samples were blind-labelled with random three- digit codes. The order of presentation format was randomised to control positional error which may influence sensory verdicts. Panel members were provided with the score sheet together with the instruction sheet and the agreed ratings for the reference materials. They were advised to drink water between sample evaluations which served as palate cleansers. All samples were evaluated at the Food Science Laboratory, Faculty of Agriculture, University of Mauritius. Since the laboratory did not provide standard sensory facilities, measures were taken to control sources of errors associated with the laboratory environment such as ensuring that assessors are effectively separated, adequate lighting, comfortable seats and no interfering odours. Samples were evaluated in two replicate sessions on two consecutive days on 24 and 25 September 2020 respectively.

Instrumental colour measurement

The flesh colour of boiled potato samples was measured instrumentally with a digital chromameter (Minolta Chroma meter CR-200, Minolta Ltd., Osaka, Japan). The potato samples were cut in half from the bud end to the stem end. Colour measurements were taken at the peripheral and central locations on each potato. Six measurements were taken for each sample. Results were expressed as tristimulus values, L* (lightness, 0 for black, 100 for white), a* (-a* = greenness,

+a* = redness) and b* (-b = blueness, +b = yellowness). The instrument (45°/0° geometry, D25 optical sensor) was calibrated against a standard white reference tile (L* = 92.75, a* = -0.76, b* = -0.07).

Statistical analysis

The IBM SPSS (version 20.0) statistical software was used for sensory quantitative descriptive data analysis. Mean ratings for all sensory descriptors (appearance, texture, aroma, flavour and taste) of the different potato samples and were determined using two- way analysis of variance (ANOVA) which tested the main effect of the replicates, samples, assessors, replicate by assessor and assessor by sample interactions at the 5%, 1% and 0.1% ($P \leq 0.05$, 0.01 and 0.001) level of significance. Instrumental colour measurements were analysed to determine the differences in CIELAB to put punctuation after genotypes mean separation between potato samples (clones) was calculated using the Duncan Multiple Range Test (DMRT). Radar diagrams were generated to visualise and compare the sensory profiles of the different potato samples.

RESULTS AND DISCUSSION

Sensory lexicon

Sensory descriptors, their definitions as well as agreed ratings for reference materials are presented in Table 2. The assessors identified 16 attributes for describing the sensory characteristics of the boiled potato clones. The sensory lexicon comprised of 3 appearance, 5 texture, 4 aroma, 3 flavour, and 1 taste characteristics. Similar results were reported by Ulrich *et al.* (2000) and Bough (2017) when profiling the aroma and flavour of boiled potato. The majority of the descriptors were also present in the sensory lexicon of Sharma *et al.* (2020) comprising of 64 attributes from 55 cultivars of potatoes that were prepared mashed and air- fried. The appearance descriptors of the potato clones were white, cream and yellow. According to Nourian *et al.* (2003a), one of the determining sensory attributes of boiled potato resides in its internal flesh colour which should be creamy white with no anomalous colouration. In line with the above literature, both Spunta and clones therefore possessed the desired flesh colour of table potato varieties.

Sensory profiles of potato clones and Spunta variety

The mean ratings of the 16 sensory descriptors for the six advanced clones compared to the control variety Spunta are presented in Table 3. In terms of appearance, Spunta scored significantly higher for yellow colour (11.07) while all 6 clones obtained significantly higher scores for white ($p \leq 0.05$). The appearance scores indicated that Spunta is a yellow- fleshed variety while the clones are predominantly white- fleshed.

The scores for the texture attributes namely compressibility and stickiness did not differ significantly among clones ($P \leq 0.05$). When compressed with a fork, all potato samples remained compact and homogeneous without disintegrating into pieces. Spunta obtained significantly lower mean sensory ratings for texture characteristics (hardness and coarseness) compared to the remaining clones. All clones obtained low scores for sweet aroma attributes while rancid-like aroma (8.21) was significantly higher in Spunta. However, the non- significant difference in mean sensory ratings for rancid-like flavour between Spunta and the remaining clones could be due to the high between-assessor variations as evidenced by the standard deviation values. Significantly higher ratings for boiled potato aroma (9.12) and boiled potato flavour (8.77) were recorded in Spunta. Although all

Table 2. Definitions and reference materials for sensory descriptors.

Item number	Sensory descriptors	Definitions	Reference materials and agreed ratings*
		Appearance	
1	White	White colour characteristic of white fleshed potato varieties (RHS colour chart, 2001)	Shades of white Boiled potato variety Spunta = 0.0
2	Cream	Cream colour characteristic of white fleshed potato varieties (RHS colour chart, 2001)	Shades of cream Boiled potato variety Spunta = 2.5
3	Yellow	Yellow colour characteristic of yellow fleshed potato varieties (RHS Colour chart, 2001)	Shades of yellow Boiled potato variety Spunta = 10.0
		Texture	
4	Compressibility	Force required to compress the boiled potato using a fork and the degree to which the sample disintegrates (falls into pieces) or remains compact and homogeneous	Boiled potato variety Spunta = 7.5 Boiled sweet potato = 12.5
		Texture (First bite)	
5	Hardness	Force required to bite through one full spoon of the boiled potato sample with incisor teeth and to bring the teeth together (ISO, 2008)	Boiled potato variety Spunta = 2.5 Boiled sweet potato = 0.0
		Texture (Chew down)	
6	Coarseness	Degree of coarse particles in the mouth when one full spoon of the boiled potato is chewed with molar teeth	Boiled potato variety Spunta = 2.5 Boiled sweet potato = 0.0
7	Stickiness	Force required to remove potato sticking to teeth and palate after chewing one full spoon of the boiled potato with molar teeth	Boiled potato variety Spunta = 0.0 Boiled sweet potato = 0.0
8	Dryness	Ease with which the sample is swallowed, amount of moisture released while chewing and the perceived amount of dry particles in the throat after chewing one full spoon of the boiled potato with molar teeth (ISO, 2008)	Boiled potato variety Spunta = 0.0 Boiled sweet potato = 0.0
		Aroma	
9	Sweet	Aroma associated with the perception of sweet substances	Boiled potato variety Spunta = 0.0 Boiled sweet potato = 10.0
10	Boiled Potato	Aroma associated with the flesh of a boiled potato	Boiled potato variety Spunta = 10.0 Boiled sweet potato = 1.5
11	Rancid-like (oxidised/ hydrolysed lipid)	Aroma associated with heated butter	Boiled potato variety Spunta = 10.0 Heated butter = 15.0
12	Mushroom-like	Aroma associated with dried edible mushroom	Boiled potato variety Spunta = 0.0 Fresh mushroom = 12. 5
		Flavour	
13	Potato	The starchy, cooked vegetable- like character associated with the flesh of boiled potato	Boiled potato variety Spunta = 10.0
14	Rancid-like (oxidised/ hydrolysed lipid)	The typical flavour associated with oxidative rancidity of lipid	Boiled potato variety Spunta = 2.5 Boiled sweet potato = 0.0
15	Mushroom-like	The typical flavour associated with dried edible mushroom	Boiled potato variety Spunta = 0.0
		Taste	
16	Sweet	Clean sweet taste of which sucrose is typical	Boiled potato variety Spunta = 2.5 Boiled sweet potato = 3.75

*Perceived intensities were generated on a 0- to 15-cm line scale with 0 = nil and 15 = extreme

Table 3. Mean sensory ratings of 6 advanced potato clones compared to the control variety Spunta (n = 7 assessors)

Sensory Attribute	SED	P-value	Potato genotypes						
			142/161/4	142/161/5	161/142/16	29/5/10	29/5/16	29/5/14	Spunta
						Appearance			
White	0.55	0.000	$7.03^{a}\pm2.81$	$5.14^{b}\pm3.43$	$6.64^{ab}\pm3.06$	$7.05^{a}\pm3.14$	$4.91^{b}\pm2.91$	$6.69^{ab}\pm2.96$	$0.45^{b}\pm0.79$
Cream	0.76	0.037	$4.00^{ab}\pm3.75$	$5.98^{a}\pm3.74$	$5.03^{a}\pm3.23$	$3.93^{ab}\pm3.56$	$4.98^{a}\pm3.07$	$3.96^{ab}\pm2.75$	$2.23^{b}\pm1.56$
Yellow	0.34	0.000	$0.62^{b}\pm1.45$	$1.60^{b}\pm2.56$	$0.79^{b}\pm1.51$	$0.61^{b}\pm1.36$	$0.62^{b}\pm1.36$	$0.27^{bc}\pm0.53$	$11.07^{a}\pm2.07$
						Texture			
Compressibility	0.57	0.779	6.57±2.28	7.50±3.43	6.44±2.67	5.82±2.64	6.66±3.02	5.38±3.82	6.87±2.53
Hardness	0.54	0.006	$5.48^{a}\pm2.77$	$5.49^{a}\pm2.30$	$4.62^{a}\pm2.12$	$5.17^{a}\pm1.50$	$5.10^{a}\pm3.46$	$6.17^{a}\pm2.55$	$2.92^{b}\pm1.52$
Coarseness	0.43	0.029	$4.14^{a}\pm2.78$	$3.84^{a}\pm2.52$	$3.75^{a}\pm1.62$	$4.28^{a}\pm2.12$	$3.57^{a}\pm1.75$	$4.14^{a}\pm2.25$	$2.32^{b}\pm0.72$
Stickiness	0.13	0.550	0.08±0.33	0.00±0.00	0.08±0.33	0.00±0.05	0.00±0.05	0.00±0.05	0.00±0.05
Dryness	0.68	0.020	$5.71^{ab}\pm3.74$	$5.48^{b}\pm2.82$	$6.21^{ab}\pm2.25$	$6.16^{ab}\pm2.69$	$7.80^{a}\pm3.09$	$4.83^{b}\pm2.74$	$7.80^{a}\pm1.60$
						Aroma			
Sweet	0.43	0.000	$1.43^{ab}\pm1.37$	$0.89^{b}\pm1.14$	$2.59^{a}\pm2.96$	$0.53^{b}\pm0.94$	$1.73^{ab}\pm1.62$	$2.89^{a}\pm2.84$	$0.44^{b}\pm0.62$
Boiled Potato	0.67	0.001	$4.82^{b}\pm3.53$	$5.92^{b}\pm3.15$	$6.37^{b}\pm3.25$	$5.28^{b}\pm2.45$	$6.57^{b}\pm2.70$	$6.10^{b}\pm2.40$	$9.12^{a}\pm1.24$
Mushroom-like	0.71	0.145	$2.14^{ab}\pm1.26$	$1.16^{b}\pm0.88$	$2.05^{ab}\pm0.63$	$3.25^{a}\pm0.55$	$1.33^{b}\pm0.37$	$2.17^{ab}\pm0.55$	$0.69^{b}\pm0.46$
Rancid-like	0.98	0.001	$2.35^{b}\pm3.06$	$4.55^{b}\pm3.45$	$4.71^{b}\pm4.48$	$3.37^{b}\pm3.94$	$4.37^{b}\pm3.59$	$2.32^{b}\pm3.59$	$8.75^{a}\pm2.03$
						Flavour			
Potato-like	1.61	0.002	$5.35^{c}\pm0.505$	$7.76^{a}\pm0.12$	$6.07^{bc}\pm0.00$	$4.94^{c}\pm0.76$	$7.12^{ab}\pm1.29$	$7.14^{ab}\pm1.06$	$8.77^{a}\pm0.32$
Mushroom-like	0.73	0.751	1.87±2.58	1.78±3.12	1.51±2.90	1.87±2.80	1.25±2.59	1.07±2.67	0.36±0.34
Rancid-like	1.03	0.804	4.5±3.64	3.12±3.05	4.23±4.36	2.85±2.47	2.92±3.27	1.78±2.48	3.66±2.79
						Taste			
Sweet	0.39	0.603	1.52±1.78	1.27±1.28	1.62±1.92	0.89±1.33	0.98±1.48	1.25±1.77	0.65±0.83

Mean values in a column with different letters differ significantly ($P \leq 0.05$) by DMRT. Sensory scores were rated on a 15 cm line scale where 0 = nil and 15= extreme

clones obtained significantly lower ratings for boiled potato aroma, clones 29/5/14, 29/5/16 and 142/161/5 were similar to Spunta in terms of their perceived intensity for potato-like flavour. There was no significant difference in mean scores between Spunta and the clones for both rancid-like and mushroom-like flavour. Similarly, low sweetness ratings were obtained for all clones and Spunta.

The radar diagrams showed visual differences among the potato clones in terms of appearance and aroma (Fig.3). The scores for yellow colour, boiled potato aroma, rancid- like aroma radiated to the outside of the spider diagrams for Spunta which differentiated it from the advanced potato clones. Nevertheless, the visual sensory profiles revealed that the clones were close to Spunta in terms of texture and flavour.

The non- significant and low scores for sweet aroma and sweet taste among all potato clones corroborate with the findings of Seedfelt *et al.* (2011) and Booysen *et al.* (2013) who found that the aroma descriptors for boiled potato were associated with cooked potato, earthy and buttery notes but not with sweet aroma. In another study by Sharma *et al. (*2020), among 55 potato cultivars evaluated for their sensory characteristics as mashed potato, only nine varieties were found to have sweet aroma. The mild sweetness of the potato

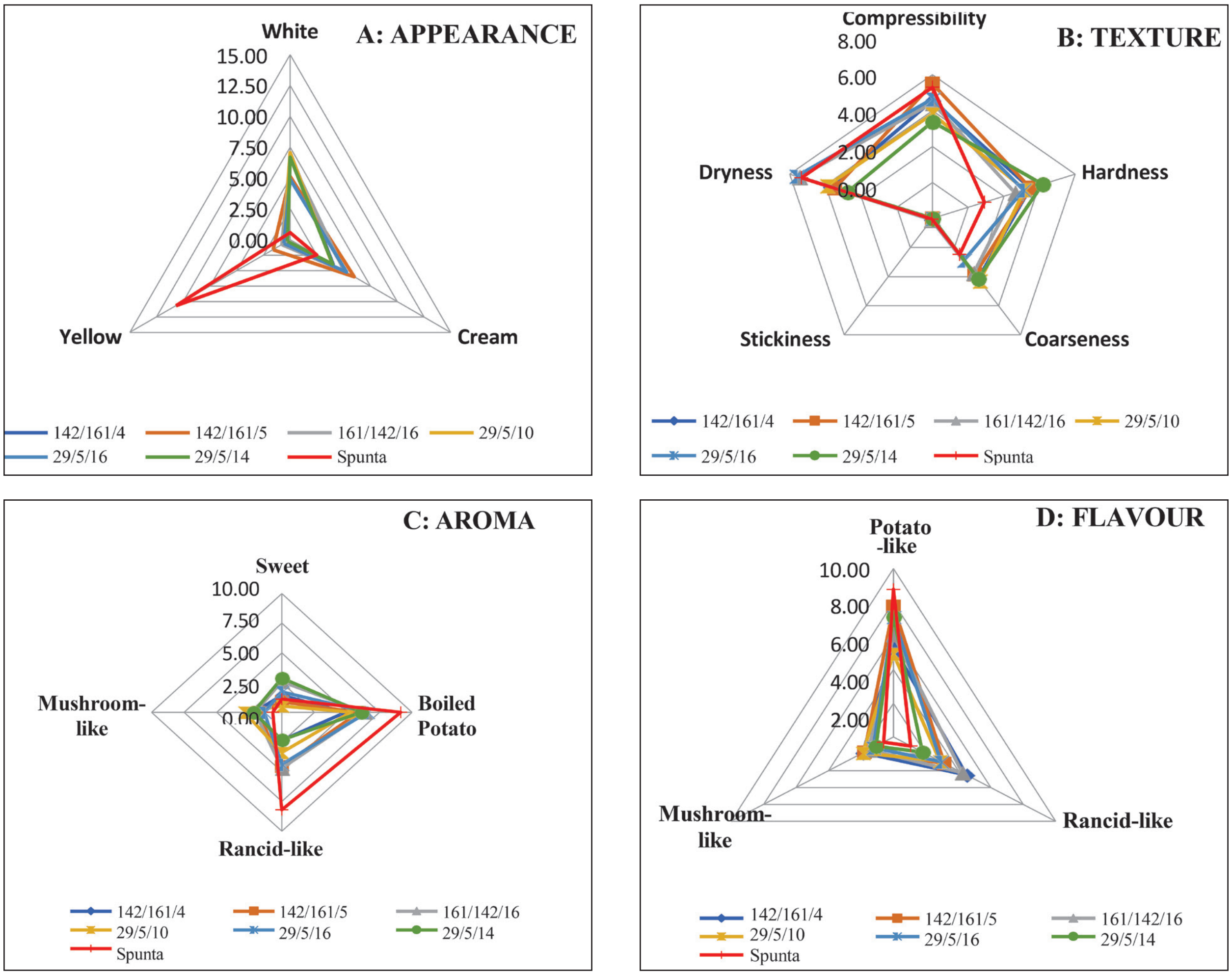

Fig. 3. Radar diagrams of boiled potato genotypes: A: Appearance, B: Texture, C: Aroma, D: Flavour

clones matched the findings of Jansky (2008) who showed that the intensity of sweetness of potato flavour in baked potatoes from a range of market class cultivars (Russets, reds, whites and speciality types) did not exceed 40%.

The low scores obtained for texture attributes (hardness, dryness and stickiness) as well as the moderate perceived intensity ratings for compressibility among potato clones could be attributed to their low tuber dry matter content (Silveria *et al.*, 2020). After compression with a fork, the potato tubers were found to retain their shape without disintegrating apart while imparting a smooth texture during biting and chew down. These observations are in line with the findings of Thybo and Martens (1998), Smith *et al.* (2009), Seefeldt *et al.* (2011) and Pádua *et al.* (2012b) who reported that boiled potato should retain their shape, be moist, creamy and have low mealiness and starch content as their main attributes. Boiled potato aroma and potato-like flavour detected in Spunta as well as the perceived intensity of potato- like flavour in the clones 142/161/5, 29/5/14 and 29/5/16 contribute to desirable sensory characteristics (Whitfield, 1992; Maarse, 1991). Volatiles in boiled potato predominantly include aldehydes, alcohols, ketones, acids, esters, hydrocarbons, amines, furans and sulphur compounds (Dresow and Bohm, 2009). Among them, methional, diacetyl and alkyl pyrazines are the desirable key odorants reported to exhibit "a cooked/boiled potato aroma" (Ulrich *et al.*, 1998; Lindsay, 1996). Sentence should read: Based on the above arguments, those clones which obtained high mean scores for boiled potato aroma and potato- like flavour should be selected for further sensory profiling studies to improve the market value of potato. Currently, at the FAREI, the local breeding programme is focused on yield, tuber characteristics and disease resistance as key traits while organoleptic characteristics including aroma and flavour are not included as selection criteria because generally most breeding programmes only require the absence of off- flavours (Jansky, 2008). The quantitative descriptive analysis data on aroma and flavour attributes indicated that clones 142/161/5, 29/5/14, 29/5/16 and Spunta have potential for crossing to develop varieties with enhanced flavour characteristics.

Instrumental colour of boiled potato samples

Significant differences in CIELAB colour space values L*, a* and b* ($P \leq 0.05$) were observed among the flesh colour of the boiled potato genotypes after storage at 4- 8 °C overnight (Table 4). All potato clones obtained significantly higher L* values than Spunta except 29/5/10 and 29/5/14. Significantly higher b* values were recorded in Spunta (30.3) and the lowest in 29/5/10 (14.4) and 29/5/14 (14.3). Significantly higher b* values in Spunta corresponded to more yellowness as observed by Pieniazek and Messina (2017) who found that the b* values in cooked Spunta (28.52) is significantly higher than in the cooked freeze- dried form (24.05).

Table 4. Instrumental colour measurements of boiled potato clones compared to the reference Spunta after storage at 4-8°C overnight.

Potato samples	Colour		
	L*	a*	b*
142/161/4	77.7^{a} ± 0.43	-7.7^{b} ± 0.66	20.6^{b} ± 3.59
142/161/5	78.4^{a} ± 1.17	-7.9^{ab} ± 0.24	19.8^{b} ± 0.81
161/142/16	79.9^{a} ± 1.19	-7.8^{ab} ± 0.04	21.9^{b} ± 0.42
29/5/10	75.5^{b} ± 0.57	-7.2^{c} ± 0.19	14.4^{c} ± 0.30
29/5/16	78.0^{ab} ± 0.14	-7.6^{bc} ± 0.69	19.6^{b} ± 0.13
29/5/14	72.0^{b} ± 2.32	-7.1^{c} ± 0.38	14.3^{c} ± 1.61
Spunta	75.2^{b} ± 0.59	-8.4^{a} ± 0.10	30.3^{a} ± 1.72
SE±	0.93	0.25	1.36

Colour measurement: L* (lightness, 0 for black, 100 for white), a* (-a* = greenness, +a* = redness) and b* (-b = blueness, +b = yellowness). Mean values in a column with different letters differ significantly ($P < 0.05$) by DMRT.

Assessor performance

The results of ANOVA of the mixed model for the 16 attributes are summarized in Table 5. Sources of variation were assessor, sample (genotype), replication and double interactions. The assessors were a significant ($P \leq 0.05$; $P \leq 0.01$; $P \leq 0.001$) source of variation for the majority of the sensory descriptors except for yellow colour, degree of compressibility, rancid-like aroma and rancid –like flavour. However, the replication factor, replication by assessor interaction and replication by sample interaction were not significant except for mushroom- like and rancid like aroma and flavour characteristics. Assessor × sample interaction was not significant for the majority of the sensory descriptors except for coarseness. Significant assessors' effect indicated that variations among assessors may have contributed to observed differences in sensory ratings. Differences amongst assessors' ratings are typical for sensory data (Kreutzmann *et al.*, 2007; Thybo and Martens, 1999). Interestingly, the effect of replication was not significant for most descriptors which implied a low within-assessor variation in repeated sensory profiling sessions. The non- significant assessor × sample interaction gave confidence that overall, the assessors rated the samples

Table 5. ANOVA of the mixed model for sensory attributes of boiled potato clones indicating main effects and interaction effects. Assessor, replicate/session, and their interactions were considered as random, while the sample was studied as fixed factor/variable.

Sensory Attribute	P- values					
	Assessor	Sample	Replication	Replication × Assessor	Assessor × Sample	Replicate × Sample
			Colour			
White	0.000***	0.000***	0.672	0.264	0.159	0.366
Cream	0.003**	0.037*	0.631	0.703	0.382	0.108
Yellow	0.348	0.000***	0.738	0.893	0.524	0.678
			Texture			
Compressibility	0.019	0.579	0.463	0.121	0.696	0.254
Hardness	0.004**	0.006**	0.666	0.534	0.145	0.961
Coarseness	0.001**	0.027*	0.363	0.640	0.032*	0.776
Stickiness	0.034*	0.550	0.125	0.034*	0.714	0.548
Dryness	0.000***	0.020*	0.084	0.023*	0.641	0.528
			Aroma			
Sweet	0.006**	0.000***	0.182	0.827	0.268	0.043*
Boiled Potato	0.000***	0.001**	0.634	0.824	0.555	0.577
Mushroom-like	0.000***	0.145	0.427	0.001**	0.964	0.000**
Rancid-like	0.414	0.001**	0.009*	0.779	0.804	0.844
			Flavour			
Potato-like	0.000***	0.002**	0.151	0.211	0.120	0.890
Mushroom-like	0.000***	0.751	0.115	0.000***	0.999	0.550
Rancid-like	0.868	0.572	0.000***	0.104	0.999	0.060
			Taste			
Sweet	0.004**	0.603	0.057	0.492	0.737	0.176

*P ≤ 0.05; **P ≤ 0.01; ***P ≤ 0.001.

in the same direction and with close relative perceived intensities of sensory descriptors. However, the ANOVA data revealed that assessors had difficulty in differentiating between white and cream colour which could be ascribed to low discriminatory/ separating ability (Sipos *et al.,* 2021). In fact, non-conform discrimination is possible because of sensory fatigue or inadequate sensory concentration as the assessors performed the roles of both panelists and students. Thus, in future sensory studies, it is recommended to regularly monitor the performance of selected assessors in order to ensure that they use the scale correctly, score the same product consistently in different replicates as well as attribute intensity evaluation in concertation with other assessors.

CONCLUSION

This study has applied QDA in identifying potato clones for the table potato market. Assessors were effectively trained as measuring instruments to quantify 16 sensory descriptors and develop the sensory profiles of potato clones. Based on texture and flavour attributes, clone 29/5/16 and Spunta were found to be suitable for their culinary use as boiled potato. Furthermore, the assessors further differentiated the variety Spunta from the remaining clones by the intensity of yellow flesh colour as well as strong boiled potato aroma. Both Spunta and clone 29/5/16 are potential varieties to be used in developing mashed potato product formulations.

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AUTHOR STATEMENT

All authors read, reviewed, agreed and approved the final manuscript

CONFLICT OF INTEREST

None declared

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KUFRI RATAN: A NEW RED SKIN POTATO VARIETY

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ABSTRACT: Kufri Ratan is a medium-maturing, high-yielding table potato variety recommended for cultivation in the North Indian plains and plateau regions during the main growing season. It is a clonal selection derived from a cross between CP3391 and Kufri Sutlej. The plants are medium-tall and vigorous, exhibiting field resistance to late blight. This variety produces aesthetically appealing red coloured, ovoid tubers with shallow to medium eyes, yellow flesh, and a mealy texture. It contains approximately 18% tuber dry matter content and demonstrates excellent storage quality. Kufri Ratan is responsive to crop nutrition and is capable of yielding 36–38 t/ha in the North Indian plains and 20–22 t/ha in plateau regions.

KEYWORDS: Kufri Ratan, potato, red skin, high yield, late blight resistance, keeping quality, North Indian plains, plateau regions.

INTRODUCTION

In India, consumers, particularly in the eastern regions of the country, including eastern Uttar Pradesh, Bihar, Jharkhand, West Bengal, and Orissa, as well as in Jammu & Kashmir, exhibit a preference for red-skinned potatoes. In Bihar, red-skinned potatoes are favored over white-skinned varieties due to culinary practices that utilize potato varieties suitable for “bhujia” (fried sabzi) preparation (Yadav *et al.,* 2024). The preference for red-skinned potatoes is expanding to other regions, driven by increased awareness and the influence of the migrant population from eastern states who favor red-skinned tubers. Market supply chain dynamics are also prompting potato growers in various regions to cultivate red-skinned varieties. Farmers in Kannauj (UP) are cultivating red-skinned potatoes to meet the demand of local markets and neighboring countries such as Nepal. Similarly, in the district of Bareilly (UP), the local cultivar Bareilly Red is highly favored among consumers in this area due to its dark red tubers with variegated flesh colour and waxy texture (Luthra *et al.,* 2023). Some local potato varieties with purple-black or purple skin, although possessing low yield potential, are cultivated and consumed in several pockets of the North-Western hills and the North-Eastern region. These locally adapted varieties remain popular due to their slow rate of degeneration and unique taste appreciated by the local population (Luthra *et al.,* 2015). As consumers become increasingly health-conscious and aware of the superior nutritional value of food, coloured potatoes are likely to be preferred due to their higher antioxidant potential (Luthra *et al.,* 2018). ICAR- Central Potato Research Institute (CPRI) has developed ten indigenous varieties with red skin and white or white-cream flesh colour, as well as two purple-skinned varieties: Kufri Neelkanth with yellow flesh

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colour (Luthra *et al.*, 2020b) and Kufri Jamunia with purple skin tubers and purple flesh (Luthra *et al.*, 2025). Breeders are persistently working to create enhanced genotypes in this area to satisfy the increasing needs of potato farmers and consumers. This work has led to the development of a new high-yielding, late blight-resistant potato variety named Kufri Ratan, which produces red ovoid tubers with shallow-medium eyes and yellow flesh. This variety possesses excellent keeping quality and taste with a mealy texture, providing farmers with new opportunities for higher profits and offering consumers a wider array of choices in their food basket.

BACKGROUND

Advanced clone MS/14-1381 released as a table purpose potato variety, Kufri Ratan was bred and selected at Modipuram (Uttar Pradesh), a regional station of ICAR-Central Potato Research Institute, Shimla (Himachal Pradesh), following breeding protocols (Luthra *et al.*, 2020a). The clone was derived from a cross between CP3391 × Kufri Sutlej made in the year 2012 at Kufri (Himachal Pradesh). Female parent CP3391 is an exotic variety Cardinal produces pink ovoid tubers with shallow eyes and cream flesh colour. Male parent Kufri Sutlej is a medium maturing indigenous variety released in 1996 for the North Indian plains. The male parent produces white-cream ovoid tubers with shallow eyes and cream flesh and is moderately resistant to late blight. The pedigree of Kufri Ratan is described in Fig.1. The clone was in the seedling stage (2013-14), five-hill plots (2014-15), 30 hill plots (2015-16) and multiple row trials (2016-17). It was evaluated in one preliminary (2017-18) and two confirmatory yield trials (2018-19 and 2019-20) at Modipuram. Advanced clone MS/14-1381 was introduced in the All India Coordinated Research Project on Potato (AICRP on Potato) in 2019 for multi-location evaluation across the country.

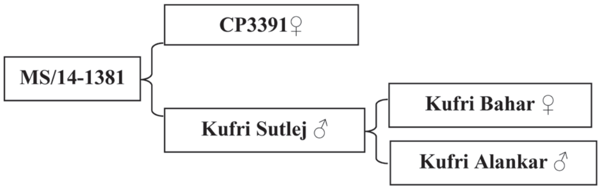

Fig. 1. Pedigree of Kufri Ratan

The advanced clone MS/14-1381 was evaluated in multi-location replicated trials under AICRP on Potato during 2021-22, 2022-23 and 2023-24 in North Indian plains (17 locations) comprising northern, central and eastern plains and in plateau regions (3 locations). It showed wider adaptability and higher yield than the controls. The data was analyzed following standard statistical procedures using the online statistical software OPSTAT, CCS HAU, Hisar, Haryana (Sheoran *et al.*, 1998). Based on its performance, the clone was recommended for release as table purpose potato variety by the 42nd AICRP (Potato) Group Meeting, 22-24 September 2024, ANDUAT, Kumarganj, Ayodhya for the North Indian plains and Plateau regions. Advanced clone MS/14-1381 has been released and notified as variety in the name of Kufri Ratan in the 32nd meeting held on 04.04.2025 by the Central Sub-Committee on Crop Standards Notification and Release of Varieties for Horticultural Crops, Ministry of Agriculture, Department of Agriculture and Co-operation, Government of India, New Delhi vide F.No. No. 3-77/2025-SD-lV dated 15th April, 2025..

VARIETAL DESCRIPTION

Plants: Morphological characteristics of the variety Kufri Ratan (leaf, flower, tuber and sprouts) have been depicted in Figure 2.

Plant: Medium, plant canopy compact, stem medium thick, predominantly green, secondary stem colour red brown throughout lightly scattered, wings poorly developed and straight.

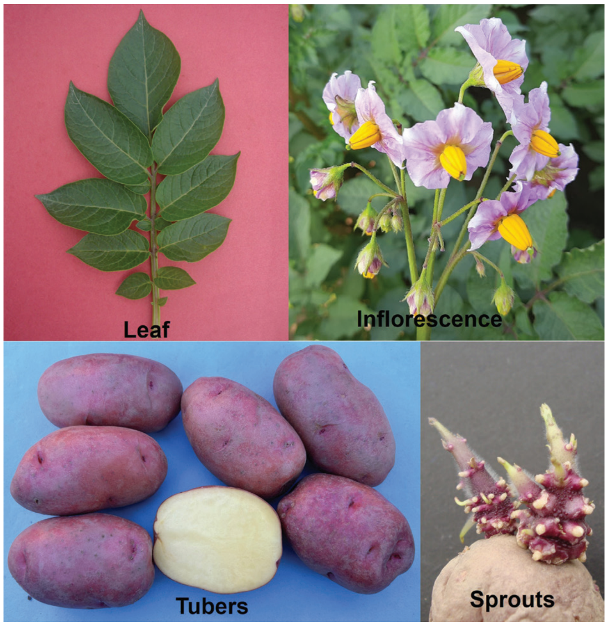

Fig. 2. Morphological characteristics of Kufri Ratan: Leaf, flower, tuber and sprouts

Foliage: Grey green, leaves intermediate, leaf width medium, leaflets lanceolate, leaflet coalescence absent, rachis coloured, midrib green.

Inflorescence

Flowering: Flowering profuse, inflorescence medium, floral stalk weakly coloured, floral stalk-pedicle articulation clearly visible and located above the middle, calyx light red brown, corolla blue violet, corolla shape semi-stellate, anther orange, anther cone normally developed, stylar length longer than stamen column and stigma round and uni-lobed.

Tubers

Size: Medium to large, 8-10 tubers per plant; ***Shape:*** Ovoid; ***Skin:*** Smooth and red; ***Eyes:*** shallow-medium, predominantly apical; ***Eyebrows:*** Normal; ***Flesh:*** yellow with mealy texture.

Sprout

Red purple, conical, pubescence at sprout base is weak, sprout tip closed, length of apical sprout is medium (2-5 cm).

YIELD PERFORMANCE

Station trials

In station trials at Modipuram during 2017-18, 2018-19 and 2019-2020, advanced clone MS/14-1381 (36.94 t/ha) yielded 20 and 23 % higher total tuber yield over the control varieties Kufri Lalima (30.81 t/ha) and Kufri Lalit (29.93 t/ha) at 75 days (Table

Table 1. Yield Performance of advanced clone MS/14-1381at Modipuram during 2017-2020

Genotypes	Total tuber yield (t/ha)								Yield increase (%) over controls	
	2017-18		2018-19		2019-20		Mean			
	75 days*	90 days	75 days	90 days	75 days	90 days	75 days	90 days	75 days	90 days
MS/14-1381	40.20	49.69	35.73	46.31	34.87	41.53	36.94	45.84		
Kufri Lalima	35.00	37.83	28.57	37.71	28.89	34.25	30.81	36.60	19.88	25.27
Kufri Lalit	35.10	40.85	26.23	39.39	28.51	37.95	29.93	39.40	23.42	16.36
CD (0.05)	1.38	2.17	1.61	1.67	2.26	1.96				
	Marketable tuber yield (t/ha)									
MS/14-1381	37.60	46.46	32.95	43.23	31.56	39.96	34.04	43.22		
Kufri Lalima	32.21	35.67	26.02	35.52	25.63	32.15	27.95	34.45	21.76	25.46
Kufri Lalit	33.00	38.91	24.36	37.25	25.32	36.03	27.56	37.40	23.50	15.56
CD (0.05)	1.76	2.54	1.75	2.06	3.01	1.9				

*Days after planting

1). The MS/14-1381 produced nearly 92% marketable tuber yield, which was at par with Kufri Lalima and Kufri Lalit. The advanced Clone MS/14-1381 (45.84 t/ha) yielded 25 and 16 % higher total tuber yield over Kufri Lalima (36.60 t/ha) and Kufri Lalit (39.40 t/ha) at 90 days. The MS/14-1381 produced nearly 94% marketable tuber yield, which was at par with both Kufri Lalima and Kufri Lalit.

Multi-location evaluation under AICRP (Potato)

The replicated yield trials with controls were conducted at 75 & 90 days during 2021-22, 2022-23 and 2023-24 in North Indian plains (17 locations, Table 2) comprising northern, central and eastern plains during *rabi* season and three locations in plateau regions (Table 3, 4, 5, 6, 7) during *rabi*/ *kharif* season.

Table 2. Yield performance of advanced clone MS/14-1381 in AICRP (Potato) replicated yield trials (pooled over 2021-22, 2022-23 & 2023-24) at 75 and 90 days (t/ha)

Regions	Locations	75 days					90 days				
		MS/14-1381	Kufri Manik	Kufri Lohit	Kufri Lalit	Kufri Lalima	MS/14-1381	Kufri Manik	Kufri Lohit	Kufri Lalit	Kufri Lalima
Northern plains	Hisar	28.99	30.26	30.15	29.64	29.03	32.64	34.34	34.69	35.06	32.86
	Jalandhar	36.48	34.75	39.39	36.05	32.59	47.55	42.74	50.74	46.73	40.06
	Modipuram	31.22	28.77	32.64	29.51	28.77	41.43	33.82	40.51	35.17	34.34
	Pantnagar	47.05	36.64	41.14	37.23	36.92	50.90	41.18	44.15	42.09	40.45
	Mean	35.93	32.60	35.83	33.11	31.83	43.13	38.02	42.52	39.76	36.93
	% Yield ±		10.21	0.29	8.53	12.90		13.45	1.43	8.47	16.79
Central plains	Chhindwara	31.49	25.72	30.57	34.45	33.24	35.08	28.97	34.81	37.90	37.92
	Deesa	42.00	35.60	41.30	37.10	35.17	56.14	42.19	51.43	47.11	41.17
	Gwalior	44.06	40.82	38.18	40.23	35.47	52.02	45.89	43.16	43.16	40.08
	Kanpur	33.76	20.95	34.99	30.01	27.90	46.07	27.73	39.31	36.08	32.93
	Kota	35.16	27.00	26.67	28.70	30.72	43.41	31.89	32.39	36.17	40.60
	Raipur	34.10	28.17	38.70	26.19	33.05	40.00	31.11	41.39	30.74	37.19
	Mean	36.76	29.71	35.07	32.78	32.59	45.45	34.63	40.41	38.53	38.32
	% Yield ±		23.73	4.83	12.14	12.79		31.25	12.47	17.97	18.62
Eastern plains	Ayodhya	34.08	30.60	33.13	34.84	25.51	37.36	32.61	35.68	37.75	31.05
	Bhubaneshwar	20.30	14.42	21.56	22.71	20.02	23.77	16.48	25.28	23.04	22.57
	Dholi	27.44	17.00	26.36	17.46	18.26	36.38	18.87	29.34	19.95	21.71
	Jorhat	19.20	16.42	16.89	16.49	19.25	18.79	18.73	19.01	16.94	18.01
	Kalyani	31.37	24.00	28.22	27.53	26.87	34.56	27.03	32.41	30.31	30.32
	Patna	28.41	26.18	31.42	31.70	26.27	37.74	29.63	38.83	35.06	31.57
	Pasighat	17.71	13.81	17.89	15.50	17.09	22.58	16.83	25.76	18.75	21.67
	Mean	25.50	20.35	25.07	23.75	21.90	30.17	22.88	29.47	25.97	25.27
	% Yield ±		25.34	1.73	7.38	16.46		31.84	2.36	16.17	19.38
Overall	Mean	31.93	26.54	31.13	29.14	28.01	38.61	30.59	36.40	33.65	32.62
	% Yield ±		20.33	2.57	9.58	14.00		26.23	6.07	14.75	18.38
CD (0.05)	Genotype: 0.48; Location × Genotype:1.94						Genotype:0.52; Location × Genotype:2.09				

Performance in North Indian Plains

75 days: Advanced clone MS/14-1381 (35.93 t/ha) yielded 10, 9 and 13% higher total tuber yield over Kufri Manik (32.60 t/ha), Kufri Lalit (33.11 t/ha) and Kufri Lalima (31.83 t/ha) in northern plains (4 locations: Hisar, Jalandhar, Modipuram and Pantnagar). The performance of MS/14-1381 (36.76 t/ha) was 24, 5, 12 and 13% superior to Kufri Manik (29.71 t/ha), Kufri Lohit (35.07 t/ha), Kufri Lalit (32.78 t/ha) and Kufri Lalima (32.59 t/ha) in central plains (5 locations, Chhindwara, Deesa, Gwalior, Kanpur, Kota and Raipur). However, in eastern plains (7 locations: Ayodhya, Bhubaneshwar, Dholi, Jorhat, Kalyani, Patna and Pasighat), MS/14-1381 (25.50 t/ha) out yielded the control Kufri Manik (20.35 t/ha), Kufri Lohit (25.07 t/ha), Kufri Lalit (23.75 t/ha) and Kufri Lalima (21.90 t/ha) by margin of 25, 2, 7 and 16% respectively (Table 2).

***90 days*:** Advanced clone MS/14-1381 (43.13 t/ha) yielded 13, 1, 8, and 17% higher total tuber yield over Kufri Manik (38.02 t/ha), Kufri Lohit (42.52 t/ha), Kufri Lalit (39.76 t/ha) and Kufri Lalima (36.93 t/ha) in northern plains (4 locations: Hisar, Jalandhar, Modipuram and Pantnagar). The performance of MS/14-1381 (45.45 t/ha) was 31, 12, 18 and 19% superior to Kufri Manik (34.63 t/ha), Kufri Lohit (40.41 t/ha), Kufri Lalit (38.53 t/ha) and Kufri Lalima (38.32 t/ha) in central plains (5 locations: Chhindwara, Deesa, Gwalior, Kanpur, Kota and Raipur). However, in eastern plains (7 locations: Ayodhya, Bhubaneshwar, Dholi, Jorhat, Kalyani, Patna and Pasighat), MS/14-1381 (30.17 t/ha) out yielded the control Kufri Manik (22.88 t/ha), Kufri Lohit (29.47 t/ha), Kufri Lalit (25.97 t/ha) and Kufri Lalima (25.27 t/ha) by margin of 32, 2, 16 and 19% respectively (Table 2).

Overall performance in North Indian Plains: At 75 days, MS/14-1381 (31.93 t/ha) produced 20, 3, 10, and 14% higher total tuber yield over Kufri Manik (26.54 t/ha), Kufri Lohit (31.13), Kufri Lalit (29.14 t/ha) and Kufri Lalima (28.01 t/ha). The advanced clone produced nearly 91% marketable tuber yield, which was at par with Kufri Manik, Kufri Lalima (90%), Kufri Lohti (91%), and Kufri Lalit (92%). However, at 90 days, MS/14-1381 (38.61 t/ha) produced 26, 6, 15, and 18% higher total tuber yield over Kufri Manik (30.59 t/ha), Kufri Lohit (36.40), Kufri Lalit (33.65 t/ha) and Kufri Lalima (32.62 t/ha). The advanced clone produced nearly 93% marketable tuber yield, which was at par with Kufri Manik, Kufri Lohit (93%), and Kufri Lalit and Kufri Lalima (92%).

Performance in Plateau regions

The MS/14-1381 was evaluated at Pune (*Rabi*/*Kharif* season) and Dharwad and Hassan (*Kharif* season**).**

Pune (Rabi season): At 75 days, MS/14-1381 (20.29 t/ha) showed 16 and 22% total tuber yield increase over Kufri Lohit (17.13 t/ha) and Kufri Lalit (16.67 t/ha), respectively. However, at 90 days, MS/14-1381 (22.69 t/ha) exhibited a 19% higher total tuber yield over Kufri Lohit (19.05 t/ha) and Kufri Lalit (19.07 t/ha). The tuber dry matter content in MS/14-1381 was 19% at 75 days and 20% at 90 days (Table 3).

Pune (Kharif season): At 75 days, MS/14-1381 (19.38 t/ha) exhibited 12 and 13% superiority in total tuber yield over the control Kufri Lohit (17.26 t/ha) and Kufri Lalit (17.10 t/ha). However, at 90 days, MS/14-1381 (21.61 t/ha) showed 14 and 10% total tuber yield superiority over the control Kufri Lohit (19.02 t/ha) and Kufri Lalit (19.61 t/ha), respectively. The tuber dry matter content in MS/14-1381 was 19% at 75 days and 20% at 90 days (Table 4).

Dharwad (Kharif Season): At 75 days, MS/14-1381 (15.19 t/ha) exhibited 26, 13, and 8% total tuber yield superiority over Kufri Lohit (12.05 t/ha), Kufri Lalit (13.47 t/ha) and Kufri Lalima (14.13 t/ha), respectively. However, at 90 days, MS/14-1381 (17.21 t/ha) exhibited 21, 10 and 8% total tuber yield superiority over Kufri Lohit (14.26 t/ha), Kufri Lalit (15.60 t/ha) and Kufri Lalima (15.92 t/ha), respectively. The tuber dry matter content in MS/14-1381 was 19% at 75 days and 90 days (Table 5).

Hassan (Kharif Season): At 75 days, MS/14-1381 (19.12 t/ha) exhibited 16, 24 and 12% higher total tuber yield compared to Kufri Lohit (16.52 t/ha), Kufri Lalit (14.44 t/ha) and Kufri Lalima (17.01 t/ha), respectively. However, at 90 days, MS/14-1381 (24.10 t/ha) exhibited 11, 28 and 14% total tuber yield superiority over Kufri Lohit (21.63 t/ha), Kufri Lalit (18.81 t/ha) and Kufri Lalima (21.10 t/ha), respectively. The tuber dry matter content in MS/14-1381 was 18% at 75 days and 19% at 90 days (Table 6).

Overall performance of MS/14-1381 in plateau regions over *Rabi*/*Kharif* seasons: At 75 days, MS/14-1381 (18.50 t/ha) recorded 18 and 20% higher total tuber yield than Kufri Lohit (15.74 t/ha) and Kufri Lalit (15.42 t/ha), respectively. However, at 90 days, MS/14-1381 (21.40 t/ha) exhibited 16 and 17% total tuber yield superiority over Kufri Lohit (18.49 t/ha) and Kufri Lalit (18.27 t/ha), respectively. The tuber

Table 3. Performance of MS/14-1381 in AICRP replicated yield trials at Pune (*Rabi* Season, Mean of 2021-22, 2022-23 and 2023-24)

Genotypes	75 days			90 days		
	Tuber yield (t/ha)		Dry matter (%)	Tuber yield (t/ha)		Dry matter (%)
	Total	Marketable		Total	Marketable	
MS/14-1381	20.29	19.52	18.66	22.69	21.58	19.93
Kufri Lohit	17.13	16.00	18.38	19.05	17.54	19.26
Kufri Lalit*	16.67	15.38	17.03	19.07	17.25	18.58
CD (0.05)	0.19	0.19	0.12	0.27	0.24	0.13

*Kufri Pukhraj in place of Kufri Lalit (2021-22)

Table 4. Performance of MS/14-1381 in AICRP replicated yield trials at Pune (*Kharif* Season, Mean of 2021-22, 2022-23 and 2023-24)

Genotypes	75 days			90 days		
	Tuber yield (t/ha)		Dry matter (%)	Tuber yield (t/ha)		Dry matter (%)
	Total	Marketable		Total	Marketable	
MS/14-1381	19.38	18.60	18.98	21.61	20.50	20.41
Kufri Lohit *	17.26	16.21	18.43	19.02	17.63	19.77
Kufri Lalit**	17.10	15.68	17.24	19.61	17.62	19.09
CD (0.05):	0.15	0.14	0.07	0.20	0.17	0.13

*Kufri Neelkanth in place of K Lohit (2022-23), **Kufri Pukhraj in place of Kufri Lalit (2021-22 & 2022-23)

Table 5. Performance of MS/14-1381 in AICRP replicated yield trials at Dharwad (*Kharif* Season, Mean of 2022-23 and 2023-24)

Genotypes	75 days			90 days		
	Tuber yield (t/ha)		Dry matter (%)	Tuber yield (t/ha)		Dry matter (%)
	Total	Marketable		Total	Marketable	
MS/14-1381	15.19	12.82	18.84	17.21	14.65	19.15
Kufri Lohit	12.05	10.05	17.77	14.26	12.00	18.89
Kufri Lalit	13.47	11.68	19.89	15.60	13.16	20.81
Kufri Lalima	14.13	12.16	17.82	15.92	13.79	19.38
CD (0.05)	1.64	1.39	0.97	1.19	1.18	1.10

dry matter content was 19% at 75 days and 20% at 90 days in the plateau regions (Table 7).

Evaluation of MS/14-1381 under natural farming production system at Modipuram: The trial was conducted during 2021-22, 2022-23 and 2023-24 on a plot fixed for a natural farming system and nutrition equivalent to inorganic doses of 180-80-100 N-P_2O_5-K_2O kg/ha was applied through FYM, Green manuring, vermi-compost and bio-fertilizers. The selection parameters under the natural farming system were yield, tuber shape, size, skin colour, texture etc. MS/14-1381 (27.6 t/ha) showed 23 and 33% superiority for total tuber yield (Table 8) over Kufri Lohit (22.4 t/ha) and Kufri Jamunia (20.8 t/ha). MS/14-1381 produced 78% marketable tuber yield than Kufri Lohit (79%) and Kufri Jamunia (74%) under the natural farming system. The tuber dry matter (21%) was toward the high side in MS/14-1381 as compared to Kufri Lohit (20%) and Kufri Jamuia (18%).

Evaluation of MS/14-1381 for export oriented production at Modipuram: The trial for export oriented production was conducted during 2021-22, 2022-23 and 2023-24 by applying nutrition through inorganic doses of 180-80-100 N-P_2O_5-K_2O kg/ha. The selection parameters included tuber shape (oblong, round), Size (>40 mm), tuber dry matter

Table 6. Performance of MS/14-1381 in AICRP replicated yield trials at Hassan (*Kharif*, Mean of 2021-22, 2022-23 and 2023-24)

Genotypes	75 days			90 days		
	Tuber yield (t/ha)		Dry matter (%)	Tuber yield (t/ha)		Dry matter (%)
	Total	Marketable		Total	Marketable	
MS/14-1381	19.12	16.49	17.69	24.10	21.21	19.18
Kufri Lohit	16.52	13.91	18.49	21.63	19.06	20.11
Kufri Lalit	14.44	11.82	20.95	18.81	15.93	21.61
Kufri Lalima*	17.01	13.74	18.09	21.10	18.23	19.14
CD (0.05)	2.23	2.10	0.75	2.52	2.38	0.72

*Kufri Manik in place of Kufri Lalima (2021-22)

Table 7. Overall performance of MS/14-381 in plateau regions* at 75 and 90 days

Genotypes	75 days			90 days		
	Tuber yield (t/ha)		Dry matter (%)	Tuber yield (t/ha)		Dry matter (%)
	Total	Marketable		Total	Marketable	
MS/14-1381	18.50	16.85	18.54	21.40	19.49	19.67
Kufri Lohit	15.74 (18%)	14.04 (20%)	18.27	18.49 (16%)	16.56 (18%)	19.51
Kufri Lalit	15.42 (20%)	13.64 (24%)	18.78	18.27 (17%)	15.99 (22%)	20.02

Value in parenthesis-yield enhancement over respective control; *Means of Pune (*Rabi* & *Kharif*), Dharwad and Hassan (*Kharif*)

Table 8. Evaluation of MS/14-1381 under natural farming production system at Modipuram.

Genotypes	Tuber yield (t/ha)		Yield increase (%)		Tuber dry matter (%)	Tuber dry matter yield (t/ha)
	Marketable	Total	Marketable	Total		
MS/14-1381	21.5	27.6			20.7	5.71
Kufri. Lohit	17.8	22.4	20.79	23.21	19.8	4.44
Kufri Jamunia	15.4	20.8	39.61	32.69	18.4	3.81
CD (0.05)	2.65	3.54			1.56	0.83

(>18%), cosmetic value skin colour, shine, texture etc). MS/14-1381 (36.9 t/ha) showed 6 and 19% superiority for exportable tuber yield (Table 9) as compared to Kufri Lohit (34.6 t/ha) and Kufri Jamunia (31.0 t/ha). MS/14-1381 produced a 90% marketable tuber yield than Kufri Lohit (85%) and Kufri Jamunia (84%). MS/14-1381 possessed 19% tuber dry matter as compared to Kufri Lohit (18%) and Kufri Jamuia (19%).

Tuber dry matter content

Advanced clone MS/14-1381 possessed comparable mean tuber dry matter content of 17% and 18% at 75 and 90 days crop duration, respectively in comparison to controls Kufri Manik (17 and 18%), Kufri Lohit (17 and 18%), Kufri Lalit (18 and 19%) and Kufri Lalima (19 and 21%) in multi-location AICRP (Potato) trials during 2021-22, 2022-23 and 2023-24 (Table 10).

Table 9. Evaluation of MS/14-1381 for export oriented production at Modipuram

Genotypes	Tuber yield (t/ha)		Yield increase (%)		Tuber dry matter (%)	Tuber dry matter yield (t/ha)
	Exportable	Total	Exportable	Total		
MS/14-1381	36.9	41.0			18.7	7.67
Kufri Lohit	34.9	41.0	5.73	0.00	17.8	7.28
Kufri Jamunia	31.0	37.0	19.03	10.81	18.7	6.89
CD (0.05)	4.02	3.8			1.36	0.68

Table 10. Tuber dry matter (%) content in AICRP trials (Mean of 2021-22, 2022-23 and 2023-24) at 75 days and 90 days

Regions	Locations	MS/14-1381	Kufri Manik	Kufri Lohit	Kufri Lalit	Kufri Lalima	MS/14-1381	Kufri Manik	Kufri Lohit	Kufri Lalit	Kufri Lalima
Northern plains	Hisar	17.48	16.93	15.55	16.49	17.81	18.43	17.89	16.60	17.48	18.71
	Jalandhar	14.08	15.16	14.63	16.42	17.58	14.79	15.54	15.31	17.46	18.99
	Modipuram	13.50	15.54	13.71	15.26	16.92	14.44	16.11	14.39	17.82	19.12
	Mean	15.02	15.88	14.63	16.06	17.44	15.89	16.51	15.43	17.59	18.94
Central plains	Chhindwara	17.43	18.28	18.63	18.03	18.33	18.30	18.98	18.86	18.84	33.38
	Deesa	16.48	17.63	17.28	17.64	19.08	17.76	18.74	18.37	18.68	21.57
	Gwalior	15.34	15.12	15.76	16.74	20.04	16.72	16.28	16.95	18.41	19.80
	Kanpur	14.66	14.99	14.42	15.31	15.66	18.03	16.46	15.78	17.18	17.58
	Kota	18.46	17.60	18.21	18.71	18.33	19.53	18.70	18.86	19.65	20.09
	Raipur	18.70	19.13	18.79	17.81	18.84	20.11	19.94	20.35	19.43	19.88
	Mean	16.84	17.12	17.18	17.37	18.38	18.41	18.18	18.19	18.70	22.05
Eastern plains	Ayodhya	17.59	17.56	17.65	17.41	17.51	18.55	18.26	18.41	18.37	18.37
	Bhubaneshwar	17.74	18.58	18.22	17.56	18.98	18.59	19.34	18.66	18.61	19.62
	Dholi	18.02	17.95	16.59	18.63	20.66	18.51	18.48	17.43	19.53	21.38
	Jorhat	22.32	22.36	22.43	22.33	22.39	22.22	22.44	22.25	22.26	21.90
	Kalyani	18.51	16.55	15.14	17.79	18.52	19.28	17.80	17.89	19.73	19.61
	Patna	14.00	14.89	14.56	14.89	16.28	15.83	16.06	16.39	16.06	17.17
	Pasighat	16.64	18.00	20.18	20.20	20.54	18.65	19.85	20.25	23.91	22.94
	Mean	18.03	17.98	17.43	18.10	19.06	18.83	18.73	18.50	19.09	19.67
Overall	Mean	16.93	17.27	16.98	17.57	18.59	18.11	18.18	17.92	18.96	20.63
CD(0.05)	Genotype:0.14; Location × Genotype:0.53						Genotype:1.12; Location × Genotype:1.94				

Keeping quality

Advanced clone MS/14-1381 adjudged to be of very good keeper as it exhibited medium tuber dormancy (6-8 weeks), comparatively less total weight loss (<10%), rottage, sprout weight and firm tuber appearance after 75 days of on-farm storage in station trials (Table 11). In AICRP (Potato) trials (Table 12), the advanced clone showed lower total weight loss (18.25%) along with Kufri Lalima (17.57%) which was lower than other controls Kufri Manik (23.93%), Kufri Lalit (20.71%) and Kufri Lohit (20.40%). Medium tuber dormancy (6-8 weeks) and very good keeping quality of the variety will help farmers to store produce under ambient conditions for up to two months to tide over glut situations in the market.

Nutritional quality: MS/14-1381 possessed medium anthocyanins (6.32 mg/100 G FW), low carotenoids (26.13 µg/100 g FW), medium ascorbic Acid (33.3 mg/100 g FW), high zinc (27.68 ppm) and medium iron (41.78 ppm) in tuber flesh

Usage

Kufri Ratan is suitable for table purpose with attractive red coloured ovoid tubers having shallow-medium eyes, which leads to less peeling losses in comparison to Kufri Lalima and Kufri Sindhuri as both have round shaped tubers with deep eyes and their peeling losses are high (Luthra *et al.*, 2006 and Kumar *et al.*, 2014). Tubers of this clone seldom exhibit external/internal defects and are not susceptible to skin damage at harvest. The tubers are easy to cook (15-20 minutes) and cooked/boiled tubers are free from any kind of discolouration. The new variety possesses pleasant flavour, mealy texture and good organoleptic taste. Thus, the desirable tuber characters, very good keeping and culinary quality of this clone will favour its acceptance.

Disease resistance

Advanced clone MS/14-1381 has field resistance to late blight (AUDPC: 412) as compared to the red-skinned varieties like Kufri Lalima (AUDPC: 827), Kufri Lalit (754), Kufri Manik (1019) and Kufri Lohit (722)

Table 12. Keeping quality (Total weight loss %) of MS/14-1381 in AICRP Locations (Mean of 2021-22, 2022-23 and 2023-24; *one year, **2 year, ***3 year)

Locations	MS/14-1381	Kufri Manik	Kufri Lalit	Kufri Lohit	Kufri Lalima
Ayodhya***	14.47	15.27	14.53	14.50	15.03
Bhubaneshwar**	20.38	11.75	31.35	19.67	19.62
Deesa**	20.11	26.73	30.32	42.24	19.13
Dholi*	18.05	20.58	17.60	18.73	12.10
Hisar***	17.30	16.00	21.90	21.60	18.70
Kanpur**	33.00	17.70	28.75	29.60	21.10
Modipuram***	11.97	15.47	14.35	13.73	9.60
Pasighat***	17.86	16.05	15.51	13.01	15.80
Pune (*Rabi*)**	9.64	-	10.83	11.78	-
Raipur**	27.85	64.57	27.89	25.23	27.59
Dharwad **	16.24	35.00	30.13	27.07	18.38
Hassan**	20.37	13.09	14.79	18.82	16.18
Pune (*Kharif*)*	10.05	-	11.23	9.21	-
Mean	18.25	22.93	20.71	20.40	17.57

Table 11. Keeping quality of MS/14-1381 (Mean of 2017-18, 2018-19, 2019-20) at Modipuram

Genotypes	Dormancy (<or>) than 6 weeks	Sprouting (%)		Weight loss (%) after 75 days of storage				Tuber appearance at 75 days
		At 6 weeks	At 75 days	Rottage	Sprouting	Physio logical	Total	
MS/14-1381	6-8 weeks	49.69	96.48	0.79	0.59	6.83	8.21	4.63
Kufri Lalima	>10 weeks	2.41	42.85	0.96	0.17	5.47	6.59	4.77
Kufri Lalit	>10 weeks	18.47	65.61	2.67	0.18	5.70	8.56	4.79

under field conditions. (Table 13). In AICRP (Potato) trials (Table 14), the variety showed comparatively less late blight infection (7%) as compared to Kufri Manik and Kufri Lalit (12%), Kufri Lohit (11%) and Kufri Lalima (22%).

Production technology

***Crop management*:** The optimal total tuber yield of 36-38 t/ha can be achieved in the advanced clone MS/14-1381 by adhering to the recommended fertilizere doses and package of practices. In North Indian plains, the ideal planting period is from the second fortnight of October to the first fortnight of November, when the daily maximum temperature decreases to approximately 32°C. Conversely, in plateau regions, the planting period during the *rabi* season is from October 15th to November 5th, and during the *kharif* season, it occurs in June/July. For seed-sized tubers (40-60g), planting at a spacing of 20 cm within 60 cm rows yields optimal tuber production, with a seed rate of approximately 3.5-4.0 t/ha. Seed tubers should be removed from cold storage at least 10 days before planting. It is crucial to avoid exposing seed bags to direct sunlight to prevent rotting due to sudden temperature increases. Tubers should be spread in a thin layer under shade in diffused light to promote sprouting, allowing sprouts to reach a length of 0.5-1.0 cm, becoming thick and green. Transport sprouted tubers to the fields in seed trays or baskets to prevent sprout damage. At the trial site in Modipuram, Nitrogen, Phosphorus, and Potassium levels were 180, 80, and 100 kg/ha, respectively, for a 90-day crop duration of ware potatoes. For seed crops, it is recommended to apply 150 kg of nitrogen (N), 60 kg of phosphorus (P_2O_5), and 80 kg of potassium (K_2O) per hectare. Green manuring prior to potato cultivation is advantageous for crop nutrition. At planting, 10-15 t/ha of well-rotted farmyard manure (FYM) may be applied to enhance soil tilth and nutrition for the potato crop. These crop management practices can reduce nitrogen application by approximately one-third and phosphorus and potassium by half. Consequently, a half-adjusted dose of nitrogen and full-adjusted doses of P_2O_5 and K_2O should be applied at planting. The remaining half-adjusted dose of nitrogen should be administered 20-25 days post-planting, coinciding with inter-cultivation and earthing. Nutrient management may vary across different agro-ecological zones; therefore, regional recommendations should be refined and adopted to achieve optimal productivity of this clone. Pre-sowing irrigation is essential to ensure uniform emergence. In its absence, the first irrigation should occur 4-6 days after planting. Subsequent post-planting

Table 13. Late blight resistance at Modipruam (Mean of 2018-19, 2019-20, 2022-23 and 2023-24, **2 years, ***3 years, ****4 years)

Genotypes	Late blight screening under field conditions	
	AUDPC	rAUDPC
MS/14-1381****	411.61	0.21
Kufri Lalima***	826.67	0.37
Kufri Lalit***	753.60	0.40
Kufri Manik***	1019.05	0.47
Kufri Lohit **	722.00	0.29

Table 14. Late blight (%) in MS/14-1381 at AICRP locations at 90 days (Mean of 2021-22, 2022-23 and 2023-24; *one year, **2 year, ***3 year)

Locations	MS/14-1381	Kufri Manik	Kufri Lalit	Kufri Lohit	Kufri Lalima
Bhubaneshwar*	6.00	15.00	10.00	18.00	20.00
Dholi**	2.50	0.00	9.00	0.00	9.00
Chhindwara*	2.20	-	3.20	2.20	3.40
Gwalior*	0.00	0.00	0.50	0.00	0.00
Kalyani***	14.28	15.10	16.73	15.85	16.70
Kanpur**	11.00	30.00	35.00	30.00	80.00
Kota**	6.50	12.50	6.50	-	-
Pune***	14.03	-	15.25	12.53	-
Mean	7.06	12.10	12.02	11.23	21.52

irrigations should be light and applied at 7-10 day intervals in sandy loam soil and 10-12 days in heavy soil. It is imperative to prevent potato ridges from submerging under water, and drainage systems should be established to manage unseasonal rains during the crop season (Rawal *et al.*, 2021).

Plant Protection Measures: For management of cutworms, white grubs, beetles and *leaf-eating* caterpillars, apply cartap hydrochloride 4G @20 kg/ha during earthing-up. It will also take care of sucking *pests* like leaf *hoppers* and aphids. For seed *crops*, place yellow sticky traps (15x30 cm^2 size) just above the canopy height @ 60 traps/ha at equidistance from each other for mass trapping of white flies/aphids. Seed treatment is done with imidacloprid (200SL) @ 0.04% (4 ml/10 l water) for 10 minutes before planting. The first spray of imidacloprid (200SL) @ 0.03% (3 ml/10 l water) is completed at 85% crop emergence followed by a second spray with thiamethoxam (25 WG) @ 0.05% (5 gm/10 l water) 10-15 days after the first spray. Although the variety is field resistant to late blight, however, prophylactic spray just at the time of canopy closure with mancozeb or propineb or chlorothalonil @ 0.2% (2 gm/l water) followed by *need-based* application of cymoxanil + mancozeb or dimethomorph + mancozeb or fenamidone + mancozeb @ 0.3% (3 gm/l water) is required for effective management of late blight. Insecticide sprays are not required in the case of table *crops* and integrated pest and disease management recommended by the institute should be followed (Rawal *et al.*, 2021).

Harvesting: Irrigation should be stopped 10-12 days before haulm killing and harvesting may be done 10-15 days after haulm cutting at proper soil moisture. After harvest, produce should be kept under shade in heaps covered with 30 cm thick available straw or crop residue for 10-15 days. Both of these measures shall help in curing tuber skin. All damaged and rotten tubers are removed and graded to fetch better prices in the market. Potatoes are packed in 45-50 kg capacity gunny or leno bags and labeled either for selling in the market or storing in cold storage (Rawal *et al.*, 2021).

Adaptability

The newly developed red-skinned potato variety, Kufri Ratan, has demonstrated good performance in multi-location trials conducted under the All India Coordinated Research Project (AICRP) on Potato. Consequently, it has been recommended for cultivation in the North Indian plains (Haryana, Punjab, the plains of Uttarakhand, Uttar Pradesh, Madhya Pradesh, Rajasthan, Gujarat, Chhattisgarh, Odisha, Bihar, West Bengal, Assam, and Arunachal Pradesh) and the Plateau regions (Maharashtra (for both *Rabi* and *Kharif* crops) and Karnataka (for Kharif crops)). Kufri Ratan presents an advantageous option for farmers and consumers in areas where red-skinned potatoes are favoured. Furthermore, its export potential can be strategically leveraged in the future for markets such as Bangladesh, Bhutan, Nepal, Pakistan, and the Philippines, where there is a traditional preference for red-skinned tubers (Pandey *et al.*, 2000; Luthra *et al.*, 2004).

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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KUFRI BHASKAR: A CLIMATE-RESILIENT POTATO VARIETY WITH STABLE YIELD UNDER HEAT STRESS CONDITIONS

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ABSTRACT: Kufri Bhaskar is a heat tolerant table potato variety suitable for early planting in Northern plains and for main season planting in Central plains. It is a cross of Kufri Khyati and Kufri Surya. Its plants are tall and vigorous with tolerance to mite and hopperburn. It produces attractive white-cream, ovoid tubers with shallow eyes and cream flesh, possesses 20% tuber dry matter and very good keeping quality. Kufri Bhaskar was trialed across the major growing regions of India along with popular heat tolerant check varieties Kufri Surya and Kufri Kiran. Kufri Bhaskar has ability to produce up to 11% higher tuber yield than heat tolerant variety Kufri Kiran and 17% over popular variety Kufri Surya across potato growing regions of country.

Key words: Kufri Bhaskar, heat tolerance, mite and hopper burn, early planting.

INTRODUCTION

Potato (*Solanum tuberosum* L.) plays a vital role in global food and nutritional security and is cultivated across a broad range of agro-ecologies. In India, it is predominantly grown in subtropical regions under short-season conditions, in the Indo-Gangetic plains. As a cool-season crop, the expansion of potatoes into developing countries—especially in tropical and subtropical regions—has raised concerns among producers. This is particularly relevant where average temperatures exceed optimal levels, leading to issues of heat stress (Demirel *et al.*, 2017). This potentially exposes the crop to high temperatures during the initial growth stages, (Minhas *et al.*, 2011; George *et al.*, 2017). This can adversely affect tuber initiation, bulking, delayed canopy development, reduced photosynthetic efficiency, and ultimately poor tuber yields and quality (Levy and Veilleux, 2007; Tang *et al.*, 2018).

The projected increase in global mean temperatures necessitates the development of heat tolerant potato varieties, mainly in lowland and subtropical areas where ambient temperatures exceed the optimum threshold of 20–25°C (Adekanmbi *et al.*, 2024; George *et al.*, 2017). Under such conditions, most of the released varieties showed reduced leaf expansion, disrupted source-sink relationships, suppressed stolon formation, and in severe cases, no tuber initiation (Tang *et al.*, 2018; Demirel *et al.*, 2017). In these instances, crucial physiological indicators—such as reduced canopy temperature, increased leaf chlorophyll retention, and consistent photosynthetic performance—can assist breeders in more effectively identifying heat-tolerant genotypes within their breeding programs. (Demirel *et al.*, 2017; Al Mahmud *et al.*, 2021). Morphophysiological traits like haulm dry weight, stomatal conductance,

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and SPAD value have also been positively associated with tuber yield under heat stress (Demirel *et al*., 2017). To mitigate the impact of heat stress, breeding strategies should focus on the selection of early maturing, robust canopy architecture, strong root systems, and stable tuberization under fluctuating thermal regimes (George *et al*., 2018; Subba and Dukpa, 2019). Screening of seedlings and advanced potato clone under stress environments is essential to identify climate-resilient potato genotypes which can withstand higher temperatures. Along with this, genotypes with combined tolerance to heat and foliage-feeding pests are also needed in heat tolerance potato breeding programs. Such traits are essential in any ideal heat tolerant potato variety under fluctuating climatic conditions and minimizing reliance on chemical pest control (Raj *et al*., 2004).

The development of heat-tolerant varieties by ICAR-CPRI such as Kufri Surya, Kufri Kiran, and Kufri Lima already demonstrated the feasibility of these cultivars suited for early planting and warmer climates (Gupta *et al*., 2023; Luthra *et al*., 2020; Minhas *et al*. 2006). These varieties enabled the successful diversification of different cropping systems through the inclusion of potato as a short-duration crop (Singh *et al*., 2005; Rana *et al*., 2011). Despite the development of these varieties in the past, temperature variability in the different agroecologies in India demands the continuous development of improved cultivars with enhanced heat tolerance, yield stability, and adaptability (Kumar *et al*., 2021; Muhie, 2022).

In this context, the development of new heat-tolerant variety, Kufri Bhaskar (HT/11-3), which is specifically aimed at enhancing productivity under early planting and high-temperature conditions in subtropical India. This variety promises to address the challenges posed by rising temperatures and ensure sustainable agricultural practices in our region. *Kufri Bhaskar* was evaluated across multi-location trials for its adaptability and agronomic performance in the name of advanced clone HT/11-3.

MATERIALS AND METHODS

The heat-tolerant potato variety *Kufri Bhaskar* (advanced clone HT/11-3) was developed through cross between *Kufri Khyati* (short duration variety) and *Kufri Surya* (heat tolerant variety) made in 2010. The true potato seeds (TPS) were initially grown under high-temperature conditions (24°C temperature during day and night) in a glasshouse at ICAR-CPRI, Shimla, and only few clones that formed tubers under heat stress were further selected for clonal advancement. Following this, systematic clonal selection was carried out at the ICAR-CPRI, Regional Station, Modipuram. The clone HT/11-3 was identified in 2011 for its promising performance under high-temperature conditions at glasshouse, followed by five-hill plot evaluation (2012–13), 30-hill plot (2013–14), multi-row trials (2014–15), and replicated yield trials (2015-17) at Modipuram. During replicated trial under irrigated conditions this clone was evaluated at Modipuram under two different planting dates: early planting (September) to evaluate the performance of clone under high temperature stress during crop establishment and tuber initiation, along with this main season planting in the month of October to evaluate its yield potential under optimal conditions.

After its initial evaluation at Modipuram under early planting (September) and main season planting (October), the clone HT/11-3 was introduced in All India Coordinated Research Project (AICRP) on Potato for multilocation trial. These trials were conducted over a three-year period from 2019–20 to 2021–22 at eight locations (each date): Northern plains zone (Hisar, Jalandhar, Pantnagar), Central plains zone (Deesa, Kanpur, Kota and Raipur) and Eastern plains zone (Faizabad and

Kalyani). All the trials were conducted under both 75- and 90-days crop durations except Kota location (only 90 days). The performance of Kufri Bhaskar was compared with national checks Kufri Surya and Kufri Kiran.

At each AICRP location, the trials were conducted in a randomized complete block design (RCBD) with three replications. Each plot consisted of five rows of 3 meters in length, and plant spacing was maintained at 60 cm between rows and 20 cm within rows. Standard agronomic practices were followed uniformly across locations. The performance of HT/11-3 (*Kufri Bhaskar*) was compared against two previously released nationally recognized heat-tolerant check varieties, *Kufri Kiran* and *Kufri Surya*.

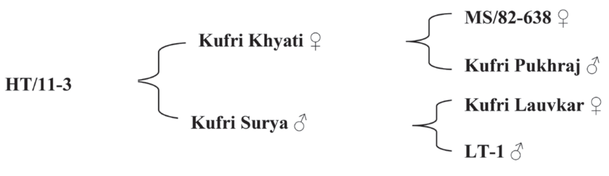
Based on consistent superior performance of HT/11-3 under heat-stress conditions, HT/11-3 was recommended for release as *Kufri Bhaskar* during the 40th group meeting of the AICRP (Potato), held at SKUAST, Srinagar, from 7–9 October 2022.

RESULT

Varietal description

Parentage with details of its pedigree

Plant: Tall, plant canopy compact, stem medium-thick, predominantly green, wings poorly developed and straight.



Foliage: Gray green leaves intermediate, leaf width medium, leaflets ovate-lanceolate, leaflet coalescence absent, rachis green, midrib green.

Flower: Flowering medium, inflorescence medium, floral stalk green, floral stalk-pedicle articulation clearly visible and located above the middle, calyx green, corolla white, corolla shape pentagonal, anther yellow, anther cone normally developed, stylar length longer than stamen column and stigma bi-lobed.

Tubers: Tubers (7-8), ovoid, skin white-cream, eyes shallow, eyebrows normal, flesh cream, texture mealy.

Sprout: Sprout red purple, shape cylindrical, pubescence at sprout base is medium (Fig. 1).

DNA fingerprinting: The fingerprint of clone, HT/11-3 was generated using 2 SSR markers viz., STU and STIKA using a genetic analyzer, ABI 3500. The fingerprints are clearly unique and do not match any of the existing indigenous varieties (Fig 2).

Yield performance

Yield performance in station trials at Modipuram (2014-16)

The advanced clone HT/11-3 was evaluated over three consecutive years (2014–15 to 2016–17) in station trials which were conducted

Fig. 1. Morphological features of Kufri Bhaskar (HT/11-3)

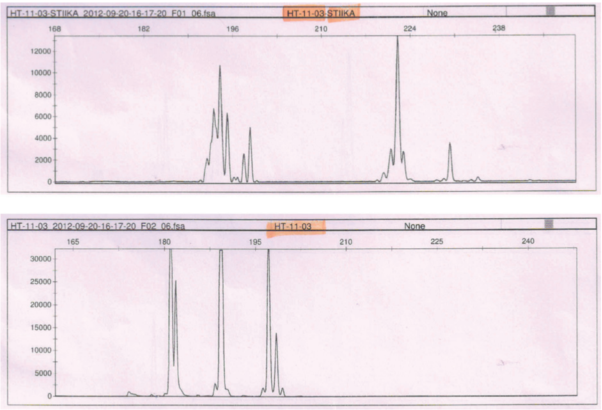


Fig. 2. DNA Fingerprint profile of Kufri Bhaskar (HT/11-3)

at ICAR-CPRI RS Modipuram at 75-day crop duration (Last week of September planting). The genotype HT/11-3 consistently outperformed the national check Kufri Surya in total and marketable tuber yield across all years (Table 1). The mean total tuber yield (TTY) of HT/11-3 was 15.9 t/ha, which was 24.2% higher than Kufri Surya (12.8 t/ha). In 2014, 2015 and 2016, HT/11-3 recorded 36.0%, 16.7% and 26.4% TTY advantage over the Kufri Surya. Along with this, HT/11-3 also exhibited significant superior yield advantage over other check Kufri Lauvkar under high temperature conditions. The mean dry matter content of HT/11-3 was recorded as 16.5% at 75 days crop duration.

Multi-location performance (2019-22) in AICRP trials (75 days)

The advanced clone HT/11-3 was evaluated at eight AICRP centres which represents the northern, central, and eastern plains over three years (2019–20 to 2021–22) under 75-days and 90 days crop duration (Table 2 and 3). The genotype showed consistent superior performance in total tuber yield across locations compared with national checks Kufri Kiran and Kufri Surya. At 75 days crop duration (Table 2), HT/11-3 showed 33.7 t/ha total tuber yield over eight locations, which was 17.6% and 11.6% higher than Kufri Surya (28.6 t/ha) and Kufri Kiran (30.2 t/ha), respectively. At Deesa location, HT/11-3 recorded highest total tuber yield 42.9 t/ha, as compared to Kufri Surya and Kufri Kiran which exhibited 37.9 t/ha and 36.9 t/ha, respectively. HT/11-3 showed minimum yield of 27.2 t/ha at Jalandhar location but it was still higher from Kufri Surya (26.6 t/ha) and Kufri Kiran (25.1 t/ha). This pattern was also observed in marketable tuber yield where HT/11-3 showed 10.8% and 16.6% yield advantages over Kufri Kiran and Kufri Surya, respectively.

At 90 days crop duration (Table 3), the pooled mean total tuber yield of HT/11-3 was 40.6 t/ha, which was 11.2% and 17.2% higher than Kufri Kiran (36.5 t/ha) and Kufri Surya (34.6 t/ha), respectively. The highest yield of HT/11-3 was recorded at Deesa (50.3 t/ha) and lowest yield at Jalandhar (37.1 t/ha). Except Hissar location where Kufri Kiran (41.6 t/ha) slightly outperform over HT/11-3 (41.4 t/ha), HT/11-3 recorded consistent higher yield in all the locations of Northern, Central and Eastern plains.

Table 1: Performance of HT/11-3 in station trials (early season) at Modipuram (2014-15 to 2016-17)

Genotypes	MTY/ha (75 days)			Mean	TTY/ha (75 days)			Mean	Mean DM%
	2014	2015	2016		2014	2015	2016		
HT/11-3	10.2	17.0	14.5	13.9	11.3	18.1	18.2	15.9	16.5
Kufri Lauvkar	6.9	11.0	7.1	8.3	7.8	12.7	9.2	9.9	17.6
Kufri Surya	7.4	14.4	13.7	11.8	8.3	15.6	14.4	12.8	18.3
CD (0.05)	1.3	2.0	2.1		1.3	2.2	2.3		
Yield increase (%) over Kufri Surya	38.6	18.1	5.8	17.8	36.0	16.7	26.4	24.2	

*TTY – Total tuber yield; MTY – Marketable tuber yield

Table 2: Yield performance of HT/11-3 (Pooled means of 2019-20 to 2021-22) at 75 days in AICRP locations

Regions	Locations	Total tuber yield t/ha			Marketable tuber yield t/ha		
		HT/11-3	K Kiran	K Surya	HT/11-3	K Kiran	K Surya
Northern plains	Hissar	36.6	34.3	32.8	33.9	29.3	28.1
	Jalandhar	27.2	25.1	26.6	25.8	24.0	25.6
	Pantnagar	31.0	27.0	24.5	28.1	24.9	22.3
Central plains	Deesa	42.9	36.9	37.9	41.3	35.4	36.9
	Kanpur	35.4	32.6	29.0	27.4	26.4	23.7
	Raipur	36.6	29.3	30.3	33.4	25.6	25.6
Eastern plains	Faizabad	29.8	29.2	24.8	26.8	26.4	22.5
	Kalyani	29.7	26.9	23.1	24.4	25.4	21.9
Overall mean		33.7	30.2	28.6	30.1	27.2	25.8
Mean yield increase (%)			11.6	17.6		10.8	16.6
CD (0.05)		Var: 0.67; Var Location year: 3.22			Var: 0.73; Var Location year: 3.55		

Table 3: Yield performance of HT/11-3 (Pooled means of 2019-20 to 2021-22) at 90 days in AICRP locations

Regions	Locations	Total tuber yield t/ha			Marketable tuber yield t/ha		
		HT/11-3	K Kiran	K Surya	HT/11-3	K Kiran	K Surya
Northern plains	Hissar	41.4	41.6	37.8	37.3	35.8	32.7
	Jalandhar	37.1	31.5	32.5	34.9	29.4	31.5
	Pantnagar	33.8	29.5	26.8	31.2	27.9	24.7
Central plains	Deesa	50.3	48.6	46.4	49.0	47.2	44.7
	Kanpur	45.7	39.6	34.4	39.9	33.5	28.8
	Kota	34.4	30.0	28.9	33.0	28.9	27.8
	Raipur	41.4	34.7	35.4	37.9	30.6	32.0
Eastern plains	Faizabad	35.0	32.8	29.1	32.2	30.5	27.1
Overall mean		40.6	36.5	34.6	37.6	33.3	31.7
Mean yield increase (%)			11.2	17.2		12.8	18.5
CD (0.05)		Var: 0.94; Var × Location × Year: 4.66			Var: 0.94; Var × Location × Year: 4.6		

Zone-wise performance (Pooled across locations)

The pooled performance of HT/11-3 (Kufri Bhaskar) across the northern, central, and eastern plains during AICRP trials (2019–20 to 2021–22) under the 75- and 90-days crop duration revealed consistent yield advantages over the national checks Kufri Kiran and Kufri Surya (Table 4).

At 75 days in the northern plains, HT/11-3 recorded a total tuber yield (TTY) of 31.6 t/ha and marketable tuber yield (MTY) of 29.3 t/ha, with yield advantage of 9.7% and 12.3% over Kufri Kiran, and 13.0% and 15.5% over Kufri Surya. In the central plains, HT/11-3 exhibited the highest TTY of 38.3 t/ha with a yield advantage of 18.2% over Kufri Surya, and 16.3% over Kufri Kiran. In the eastern plains also Kufri Bhaskar performed better than national checks (Table 4).

At 90 days crop duration, in the northern plains, HT/11-3 recorded a mean TTY of 37.4 t/ha and MTY of 34.5 t/ha and showed yield advantage of 15.7% (TTY) and 16.3% (MTY) over Kufri Surya, and 9.5% and 11.1% over Kufri Kiran. In the central plains, HT/11-3 exhibited the highest total tuber yield of 43.0 t/ha. It recorded a yield gain of 18.4% over Kufri Surya, and 12.4% over Kufri Kiran. In the eastern plains, HT/11-3 exhibited a total tuber yield of 35.0 t/ha, with 20.3% higher yield over Kufri Surya, and 6.7% over Kufri Kiran (Table 5).

Performance at Modipuram under AICRP trials (75 and 90 days)

The performance of HT/11-3 was evaluated at Modipuram under AICRP trials during 2020–21 and 2021–22, under both 75-day and 90-day crop durations. This genotype consistently outperformed all standard checks used in the study like Kufri Kiran, Kufri Surya, Kufri Lima, and Kufri Bahar, in total and marketable tuber yield (Tables 6 and 7).

At 75 days (Table 6), HT/11-3 recorded a mean total tuber yield of 23.9 t/ha, which were 8.7% higher than Kufri Kiran (22.0 t/ha), 16% over Kufri Surya (20.6 t/ha), and 21.9% over Kufri Lima (19.6 t/ha). Under the 90-days crop duration (Table 7), HT/11-3 showed similar trend with tuber yield of 25.4 t/ha, which was 7.8% higher than Kufri Kiran (23.7 t/ha) and 18.7% higher than Kufri Surya (21.4 t/ha). Yield advantages over Kufri Lima and Kufri Bahar were 12.4% and 27.7%, respectively. These results indicated the consistent yield superiority of HT/11-3 under both early and full-season conditions at Modipuram.

Table 4: Performance of HT/11-3 in AICRP trials at 75 days (pooled over location)

Regions	HT/11-3 (Kufri Bhaskar)			Kufri Kiran			Kufri Surya		
	TTY	MTY	DM%	TTY	MTY	DM%	TTY	MTY	DM%
Northern plains	31.6	29.3	14.9	28.8	26.1	16.8	28.0	25.3	17.1
	Yield increase (%)			9.7	12.3		13.0	15.5	
Central plains	38.3	34.0	16.1	32.9	29.1	17.6	32.4	28.7	18.2
	Yield increase (%)			16.3	16.6		18.2	18.4	
Eastern plains	29.8	25.6	16.7	28.1	25.9	16.7	24.0	22.2	16.9
	Yield increase (%)			6.1	-1.2		24.2	15.3	
Overall Mean	33.7	30.1	15.8	30.2	27.2	17.2	28.6	25.8	17.6
	Yield increase (%)			11.6	10.8		17.6	16.6	

TTY-Total Tuber Yield, MTY- Marketable Tuber Yield, DM%- Tuber Dry matter content %

Table 5: Performance of HT/11-3 in AICRP trials at 90 days (pooled over location)

Regions	HT/11-3 (Kufri Bhaskar)			Kufri Kiran			Kufri Surya		
	TTY	MTY	DM%	TTY	MTY	DM%	TTY	MTY	DM%
Northern plains	37.4	34.5	16.5	34.2	31.0	18.3	32.4	29.6	18.1
	Yield increase (%)			9.5	11.1		15.7	16.3	
Central plains	43.0	40.0	19.3	38.2	35.1	19.7	36.3	33.3	20.7
	Yield increase (%)			12.4	14.0		18.4	19.9	
Eastern plains	35.0	32.2	19.5	32.8	30.5	20.5	29.1	27.1	20.3
	Yield increase (%)			6.7	5.6		20.3	18.8	
Overall Mean	40.6	37.6	18.5	36.5	33.3	19.4	34.6	31.7	19.9
	Yield increase (%)			11.2	12.8		17.2	18.5	

TTY-Total Tuber Yield, MTY- Marketable Tuber Yield, DM%- Tuber Dry matter content %

Tuber dry matter content

Across AICRP locations, HT/11-3 exhibited moderate dry matter content, with pooled means of 15.8% at 75 days and 18.5% at 90 days (Table 8). The highest dry matter was observed at Raipur (22.4% at 90 days), followed by Kanpur (19.8%) and Faizabad (19.5%). In AICRP trials at Modipuram location, HT/11-3 recorded a mean dry matter content of 17.9% at 75 days and 19.8% at 90 days (Table 9). HT/11-3 has acceptable (16-19%) tuber dry matter content at all locations.

Foliage senescence at Modipuram

HT/11-3 exhibited mean foliage senescence of 52.5% at 75 days and 60.0% at 90 days at Modipuram (Table 10).

Keeping quality and dormancy

HT/11-3 exhibited very good storage

Table 6: Performance of HT/11-3 in AICRP trial at Modipuram at 75 days

Genotypes	Total tuber yield (t/ha)			% Yield increase	Marketable tuber yield (t/ha)			% Yield increase
	2020-21	2021-22	Mean		2020-21	2021-22	Mean	
HT/11-3	20.4	27.3	23.9		19.6	25.9	22.7	
Kufri Kiran	19.5	24.5	22.0	8.7	18.9	22.8	20.8	9.1
Kufri Lima	15.3	23.9	19.6	21.9	14.5	22.3	18.4	23.4
Kufri Surya	17.2	23.9	20.6	16.0	16.5	22.1	19.3	17.6
Kufri Bahar	14.3	18.8	16.6	44.0	13.6	16.9	15.3	48.4
CD (0.05)	1.9	2.7			1.8	2.8		

Table 7: Performance of HT/11-3 in AICRP trial at Modipuram at 90 days

Genotypes	Total Tuber yield (t/ha)			% Yield increase	Marketable Tuber yield (t/ha)			% Yield increase
	2020-21	2021-22	Mean		2020-21	2021-22	Mean	
HT/11-3	22.0	28.8	25.4		20.9	27.6	24.3	
K Kiran	21.6	25.8	23.7	7.8	20.5	24.4	22.5	8.0
K Lima	17.7	27.5	22.6	12.4	16.7	26.3	21.5	13.0
K Surya	19.3	23.6	21.4	18.7	18.3	22.8	20.6	17.9
K Bahar	16.6	23.1	19.9	27.7	15.4	22.3	18.8	29.3
CD (0.05)	1.6	3.1			1.6	3.4		

Table 8: Tuber dry matter (%) of HT/11-3 (Pooled means of 2019-20 -2021-22) in AICRP locations

Regions	Locations	75 days			90 days		
		HT/11-3	K Kiran	K Surya	HT/11-3	K Kiran	K Surya
Northern plains	Hissar	14.8	16.9	16.3	17.5	18.2	17.8
	Jalandhar	15.0	16.7	17.8	15.5	18.3	18.4
Central plains	Deesa	15.1	17.2	18.7	17.4	20.5	22.5
	Kanpur	14.7	16.0	16.9	19.8	18.8	20.2
	Raipur	18.4	19.5	19.1	22.4	21.7	22.2
	Kota	-	-	-	17.7	17.8	17.9
Eastern plains	Faizabad	16.7	16.7	16.9	19.5	20.5	20.3
Overall mean		15.8	17.2	17.6	18.5	19.4	19.9
CD (0.05)		Var: 0.21; Var × Location × Year: 0.88			Var: 0.18; Var × Location × Year: 0.84		

Table 9: Tuber dry matter of HT/11-3 in AICRP trial at Modipuram

Genotypes	75 days			90 days		
	2020-21	2021-22	Mean	2020-21	2021-22	Mean
HT/11-3	17.4	18.4	17.9	19.4	20.1	19.8
K Kiran	20.3	17.6	19.0	21.5	21.4	21.5
K Lima	18.8	16.3	17.6	22.1	18.4	20.3
K Surya	20.0	20.5	20.3	21.1	22.0	21.6
K Bahar	20.0	19.9	20.0	19.2	20.5	19.9

Table 10: Foliage senescence of HT/11-3 in AICRP trial at Modipuram

Genotypes	75 days			90 days		
	2020-21	2021-22	Mean	2020-21	2021-22	Mean
HT/11-3	65.0	40.0	52.5	70.0	50.0	60.0
K Kiran	60.0	40.0	50.0	70.0	45.0	57.5
K Lima	50.0	30.0	40.0	55.0	40.0	47.5
K Surya	65.0	45.0	55.0	70.0	50.0	60.0
K Bahar	70.0	50.0	60.0	80.0	80.0	80.0

Table 11: Keeping quality of HT/11-3 at Modipuram during 2014-16

Genotypes	Dormancy	Sprouting (%)		Weight loss due to Sprout (%)	Wight loss due to rottage (%)	Total weight loss (%)
		45 days	75 days			
HT/11-3	>10 weeks	24.6	34.5	0.1	0.3	11.1
K. Lauvkar	>10 weeks	46.9	55.7	0.2	0.0	8.9
K. Surya	> 10 weeks	12.5	28.0	0.0	0.0	9.9

Table 12: Mite and hopper tolerance of HT/11-3 in station trials at Modipuram

Genotypes	% Mite burn			Mean	%Hopper burn			Mean
	2014	2015	2016		2014	2015	2016	
HT/11-3	10.0	18.3	15.0	14.4	0.0	0.0	1.0	0.3
K. Lauvkar	50.0	80.0	38.3	56.1	0.0	0.0	20.0	6.7
K. Surya	15.0	30.0	16.7	20.6	0.0	0.0	1.7	0.6

behaviour with a dormancy period exceeding 10 weeks, similar to the check variety Kufri Lauvkar and Kufri Surya (Table 11). Sprouting % in HT/11-3 was 24.6% at 45 days and 34.5% at 75 days, higher than Kufri Surya (12.5%, 28.0%) and lower than Kufri Lauvkar (46.9%, 55.7%). Total weight loss in HT/11-3 during storage was 11.1%, which is comparable to other genotypes.

Tolerance to mite and hopper burn

In our station trials, HT/11-3 exhibited moderate tolerance to mite infestation, with a mean foliage damage of only 14.4% (Table 12). In the same trial check variety Kufri Lauvkar and Kufri Surya showed 56.1% and 20.6%, mite infestation. For hopper burn also, HT/11-3 showed very little damage (0.3%) across all three years, which were lower as compared to Kufri Surya (0.6%) and Kufri Lauvkar (6.7%).

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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MOLECULAR CHARACTERIZATION OF POTATO PARENTAL LINES FOR ENHANCED RESISTANCE TO POTATO CYST NEMATODES

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ABSTRACT: Potato cyst nematodes (*Globodera pallida* and *G. rostochiensis*), are major pests that significantly reduce potato yields worldwide. Developing potato varieties resistant to cyst nematodes is essential to sustain potato production worldwide especially in temperate areas. In this study, we did molecular characterization of 85 potato accessions using linked markers/genes to PCN resistance. We used three QTLs/gene-linked markers for each species: *G. rostochiensis* (*H1*, *GroVI*, and *Grp1*) and *G. pallida* (*Gpa2*, *Gpa5*, *GpaIV*^{s}*adg*). The screening results revealed diverse resistance levels among the accessions based on presence and absence of the marker bands. For *G. pallida*, 22 accessions carried both Gpa2-1 and Gpa2-2 markers, while only three showed the presence of *SPUD1636* marker associated with *Gpa5*. Most accessions, except one, tested positive for the Contig237 marker linked to *GpaIV*^{s}*adg*. Likewise, for *G. rostochiensis*, 21 accessions had the *H1* gene marker TG689, while 14 showed the presence of 57R marker. The *GroVI* markers U14 and X02 were found in 33 and 57 accessions, respectively, and the *Grp1* marker TG432 was present in 12 accessions only. Notably, two accessions, CP4052 and CP4057, exhibited seven resistance markers, making them prime candidates for breeding programs aimed at developing durable PCN resistant potato varieties. The use of molecular markers improves the efficiency of selecting resistant plants and is more cost-effective and quicker than traditional methods. This approach helps in early identification of parental lines with multiple resistance genes, aiding in gene stacking and enhancing the overall breeding process for PCN-resistant potatoes.

KEYWORDS: *Globodera rostochiensis*; *Globodera pallida*; Molecular Characterization; PCN-Resistant Genotypes; PCR Amplification; Resistance Genes

INTRODUCTION

Potatoes hold immense significance as a non-grain food crop on a global scale. They exhibit substantial nutritional value and remarkable productivity, making them highly advantageous in less developed nations (Islam *et al.*, 2022). Similar to numerous other agricultural crops, potatoes face difficulties from a variety of pests and diseases. Among these, the presence of potato cyst nematodes (PCN) poses a significant challenge to this crop, such as yellowing of the leaves, wilting, stunted growth, resulting in substantial yield losses annually (Meiyalaghan *et al.*, 2018; Varandas *et al.*, 2020).

Two commercially significant PCN species, namely *Globodera rostochiensis* (golden cyst nematode) and *G. pallida* (pale cyst nematode), are responsible for significant losses in potato yields worldwide (Gavrilenko

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et al., 2021). They can cause yield losses ranging from 19% to 80%, which depends on the potato variety, environmental conditions, and nematode population levels in the field. PCN can be traced back to the Andes region in South America and were introduced to Europe in the 1850s after severe Great Irish Famine (1840s) and now expanded their reach to at least 80 countries. The first detection of *G. rostochiensis* occurred in India (Ooty in Nilgiri hills) in 1961 (Prasad, 1996), while the finding of *G. pallida* occurred in 1996 (Spychalla & De Jong, 2024). Many regions of the world have imposed stringent quarantine laws in an effort to control and stop the spread of PCN once it has been detected in the field (Price *et al.,* 2021). Today, 5 pathotypes of *G. rostochiensis* (*Ro1*, *Ro2*, *Ro3*, *Ro4*, and *Ro5*) and 3 pathotypes of *Globodera pallida* (*Pa1*, *Pa2*, and *Pa3*) are known in the world *(Bairwa et al.,* 2023). As of right now, there are no chemicals on the market that are intended specially to regulate PCN except some generic nematicide.

The best way to manage PCN is to make use of host resistance (Price *et al.,* 2024). Different levels of resistance to PCN have been found in a large number of genes/QTLs and by introducing these genes/QTLs into the cultivars, potatoes with resistance levels to PCN can be produced effectively (Islam *et al.,* 2024). Since 1948, genes for resistance to PCN have been discovered in a range of wild potato species. A few genes have been introgressed in breeding lines and cultivars (Gebhardt & Valkonen, 2001). The potato has many loci of resistance to PCN on chromosomes III (*Gro1.4_QTL*), IV (*Gpa4_QTL*), V (*Gpa_QTL*, *GpaM1*, *Gpa5*, *H1*, and *Grp1_QTL*), IV (*GpaM2*), VII (*Gro1-4*), IX (*Gpa6 QTL*), X (*Gro1.2 QTL*), IX (*GpaXI* and *Gro1.3 QTL*) and XII (*GpaM3* and *Gpa2*) (Barone *et al.,* 1990; Pineda *et al.,* 1993; Gebhardt *et al.,* 1993; Kreike *et al.,* 1993, 1994, 1996; Leister *et al.,* 1996; Jacobs *et al.,* 1996; Rouppe Van Der Voort *et al.,* 1997, 1998; Bradshaw *et al.,* 1998; Caromel *et al.,* 2003, 2005; Adillah Tan *et al.,* 2009). The loci *Gpa*, *Gpa2*, *Gpa4*, *Gpa5*, *Gpa6*, *GpaXI*, *GpaM1*, *GpaM2*, and *GpaM3* provides resistance to *G. pallida*. The genes/QTLs *H1*, *GroVI*, *Gro1*, *Gro1.2*, *Gro1.3*, and *Gro1.4* provides resistance to *G. rostochiensis*. *H1* gene mapped from *Solanum tuberosum* ssp. andigena (CPC1673) located on distal end of long arm of chromosome 5 show hypersensitive reaction to *G. rostochiensis* pathotype Ro1 and Ro4. Molecular marker linked to these above resistance genes helped in the identification of lines having these genes. SCAR marker N146, N195, TG689, 57R linked to *H1* gene (Asano *et al.,* 2012; Mori *et al.,* 2011) SPUD1636 for *Gpa5* (Bryan *et al.,* 2002), TG432 for *Grp1*, X02 for *GroVI* (Jacobs *et al.,* 1996), Contig237 for *GpaIV*^{S}adg etc. were developed which can be used in the marker-assisted selection (MAS). The *H1* resistance gene has proven to be durable for more than 50 years against *G. rostochiensis* (Price *et al.,* 2024).

While bioassays provide the most conclusive evidence of resistance, MAS is a considerably more pragmatic approach for detecting resistant clones in the initial phases of the breeding pipeline (Spychalla & De Jong, 2024). Evaluating the breeding material's phenotype is a lengthy process that is influenced by environmental conditions and necessitates the preliminary vernalization of tubers (Ivanova-Pozdejeva *et al.,* 2023). Studies have demonstrated that genetic marker analysis is over ten times more cost-effective than artificial inoculation with PCN. Therefore, MAS for PCN-resistant cultivars is a primary goal in numerous potato breeding programmes. Nonetheless, there has been some observed decrease in the correlation between the predicted marker allele and the resistance phenotype. DNA markers have made it possible to identify complex loci containing several resistance genes (Totsky *et al.*, 2021). For cultivars with an unknown source of resistance, markers can be used to identify genes within their genomes. When it comes to potato breeding, MAS utilizes a more cost-effective selection technique compared to traditional phenotypic screening in the field (Slater *et al.*, 2020). Molecular markers can be employed in selecting parent plants to enhance the efficient use of existing potato germplasm. Additionally, it can facilitate the advancement of cultivars harbouring numerous resistance genes, a process known as gene stacking or pyramiding (Bhardwaj *et al.*, 2019). Determining the pedigrees of specific varieties can be challenging at times, primarily because the parental forms that were utilized in the early stages of breeding are often obscure. Consequently, it is challenging to ascertain the specific wild species from which resistance to PCN was acquired. DNA markers can be used to trace the introgression of genetic material from wild Solanum species to cultivated potatoes. In this study our objective was to perform an initial molecular screening on the existing germplasm and parent material in a potato breeding programme.

MATERIAL AND METHODS

Experimental material and site

The plant material comprising 85 potato germplasm [parental lines for biotic stress (late blight, virus and PCN) resistance breeding programme maintained at the ICAR-Central Potato Research Institute (CPRI), Shimla, Himachal Pradesh, India, were used for molecular characterization using PCN resistance genes linked markers. The collection comprised exotic potato accessions imported from various countries, advanced breeding lines, and indigenous developed potato varieties (Table 1).

Isolation, quantification and PCR amplification of genomic DNA

The total genomic DNA isolation from young leaves (50 to 100 mg of leaf tissue) was carried out using a Qiagen's DNAeasy Plant Mini Kit. DNA concentration was determined using agarose gel electrophoresis on 0.8% agarose gel and a nanodrop spectrophotometer (Thermo Scientific, US). *G. pallida* resistance was carried out using SPUD1636, Gpa2-1, Gpa2-2, and Contig237 markers, whereas *G.*

Table 1. List of potato genotypes used for the molecular characterization.

S. No.	Genotype	Source (Variety/clone number)	S. No.	Genotype	Source (Variety/clone number)
1.	CP1911	USA (B 6558-16)	44.	CP1971	NET (SATURNA)
2.	CP3774	Peru (CIP 393385.39)	45.	Kufri Neelkanth	Biofortified variety (ICAR-CPRI)
3.	CP3771	Peru (CIP 393371159)	46.	CP4630	Processing variety, Kufri Chipsona-4 (ICAR-CPRI)
4.	HR9-5	Advanced breeding clone for late blight resistance (ICAR-CPRI, Shimla)	47.	CP4105	Late blight resistant variety, Kufri Girdhari (ICAR-CPRI)
5.	CP4311	Denmark (SARPO MIRA)	48.	CP4070	Hill variety, Kufri Himalini (ICAR-CPRI)
6.	LBY-24	Advanced breeding clone for late blight resistance (ICAR-CPRI, Shimla)	49.	CP3400	Table purpose variety, Kufri Jawahar (ICAR-CPRI)
7.	CP4039	Peru (MARIELA × XY9)	50.	MP/09-68	Advanced breeding clone for processing purpose (ICAR-CPRI, Shimla)
8.	CP2186	USA (Norchip)	51.	CP2350	Canada (GEMSEG)
9.	CP3773	Peru (CIP 393371.58)	52.	CP4087	Netherlands (CMK 1997-022-017)

S. No.	Genotype	Source (Variety/clone number)	S. No.	Genotype	Source (Variety/clone number)
10.	CP4046	Peru (C 91.612 × C 92.044)	53.	CP2416	Peru (CIP 720124)
11.	LBY-15	Advanced breeding clone for late blight resistance (ICAR-CPRI, Shimla)	54.	CP2372	Peru (CIP 379706.34/LT-9)
12.	CP4505	Peru (CIP 397079.6)	55.	CP3180	Polland (ATOL)
13.	CP4494	304387.17	56.	CP2067	Peru (CIP 573275/ ASN69-1)
14.	CP4052	Peru (CIP 397029.21)	57.	CP4085	Netherlands (MELODY)
15.	SM/92-338	Bacterial wilt resistant advanced clone (HB/82-372/JEX/C-166 (Kufri Pukhraj))	58.	MP/09-73	Advanced breeding clone for processing purpose (ICAR-CPRI, Shimla)
16.	CP4042	Peru (394611.112)	59.	CP3134	Peru (CIP 720136/ SANTA CECILIA)
17.	HR9-3	Advanced breeding clone for late blight resistance (ICAR-CPRI, Shimla)	60.	CP3640	Canada (A84420-5)
18.	CP3402	Early bulking variety, Kufri Pukhraj (ICAR-CPRI)	61.	CP2419	Peru (CIP 720131/ MANTIQUEIRA)
19.	CP4057	Peru (CIP397079.6)	62.	CP1945	USA (K 194-3)
20.	Farida	Netherlands	63.	CP3646	Canada (KENNEBECK)
21.	CP4437	Ivory russet	64.	CP1917	USA (B 6581-4)
22.	Atlantic	USA	65.	CP3647	Canada (SHEPODY)
23.	CP3702	Innovator	66.	CP2294	Peru (CIP 377369.7/P-4)
24.	CP4300	USA (FL2215)	67.	CP4500	Peru (CIP 393073.197)
25.	CP4433	Colomba	68.	CP2379	Peru (CIP 575049/ CEW-69-1)
26.	CP4301	USA (FL2221)	69.	MP/2K-424	Advanced breeding clone for processing purpose (ICAR-CPRI, Shimla)
27.	Heraclea	Netherlands	70.	CP4075	USA (FL 1533)
28.	Navigator	-	71.	CP2067	Peru (CIP 573275/ ASN69-1)
29.	CP3920	CHN (Santana)	72.	HT/97-727	Advanced breeding clone for Heat tolerance (ICAR-CPRI, Shimla)
30.	CP4430	VMT 5-1	73.	CP1940	USA (K 85-6)
31.	CP4175	Peru (CIP 397006.18)	74.	CP2418	Peru (CIP 720130/ CHIQUITA)
32.	CP3636	Peru (CIP 801020/ KAGIRI)	75.	CP1909	USA (B 6532-10)
33.	CP2011	Mexico (CIP676082)	76.	CP1980	GFR (ANETT)
34.	CP4045	Peru (CIP 395112.6 (391686.15 × 393079.4))	77.	CP4398	Peru (CIP 304394.56)
35.	CP3470	Peru (CIP 385280.2/ XY.3)	78.	CP4439	Netherlands
36.	MS/08-1148	Advanced clone of Kufri Surya × CP3125 cross combination	79.	CP2379	Peru (CIP 575049/ CEW-69-1)
37.	CP2379	Peru (CIP 575049/ CEW-69-1)	80.	CP1717	France (ROSEVAL)
38.	SM/95-43	Advanced breeding clone for late blight resistance (ICAR-CPRI, Shimla)	81.	QBA/92-4	Advanced breeding clone for processing purpose (ICAR-CPRI, Shimla)
39.	CP4496	Peru (CIP 390478.6)	82.	CP2069	Peru (CIP 800144/ DTO-2)
40.	CP4043	Peru (CIP 395017.229 (393085.13 × 392639.8))	83.	CP4568	USA (LR)
41.	CP2370	Peru (CIP 378711.5/ MUZIRANZARA)	84.	MP/98-31	Advanced breeding clone for processing purpose (ICAR-CPRI, Shimla)
42.	CP4047	Peru (CIP 395193.6 (C 91.612 × C 92.030))	85.	CP3173	Polland (ELBA)
43.	CP4084	NET (CYCLOON)			

rostochiensis resistance was evaluated using TG689, 57R, U14, XO2, and TG432 markers. PCR amplification was performed in 20 µl reaction comprising: 10 µl of EmeraldAmp GT PCR Master Mix (2x Premix), 1 µl each of forward and reverse primers, 6 µl of nuclease free water and 2 µl of template DNA. Details of the markers, marker type, product size, and PCR conditions used for screening are given in Table 2.

Electrophoresis and gel documentation of amplified DNA

The amplified DNA products were separated using horizontal gel electrophoresis in an agarose gel containing ethidium bromide (10 mg/µl). The gel was run at 70 mA for 2 hours in 1× TBE buffer (pH 8.0) and visualized using a gel documentation system (BioSpectrum® Imaging System™, UK).

Data analysis

The screening was conducted by checking for the presence or absence of the desired bands. The presence of the band was scored as plus (+) and absence was scored as minus (-) and total number of genes amplified genotype wise are given in Table 3.

RESULTS AND DISCUSSION

In total, 85 potato accessions were characterized for the presence of genes/QTLs for resistance to PCN (*Gpa2*, *Gpa5*, *GpaIV*^{s}*adg*, *H1*, *GroVI* and *Grp1*) using specific marker assays (Gpa2-1, Gpa2-2, SPUD1636, Contig237, TG689, 57R, U14, X02, and TG432) (Table 1). The results obtained with molecular markers developed for the different resistant genes/ QTLs are presented below and in Table 3.

Molecular characterization of genotypes for *G. pallida* resistance

Screening 85 accessions with the marker Gpa2-1 (fragment size of 1120 bp) and Gpa2-2 (452 bp) revealed 22 accessions positive for both the DNA markers that is diagnostic for the *Gpa2* resistant locus (Fig. 1). Both markers were amplified in PCR conditions recommended by Asano *et al.*, (2012). The locus *Gpa2* identified in *S. tuberosum* ssp. andigena CPC1673 was mapped on distal end of chromosome 12 which confers resistance to *Globodera pallida* (Pa2) (Rouppe Van Der Voort *et al.*, 1997).

Only three accessions (Atlantic, CP4439 and Heraclea) showed the presence of SPUD1636, marker linked to the QTL *Gpa5.* This call attention to the importance of

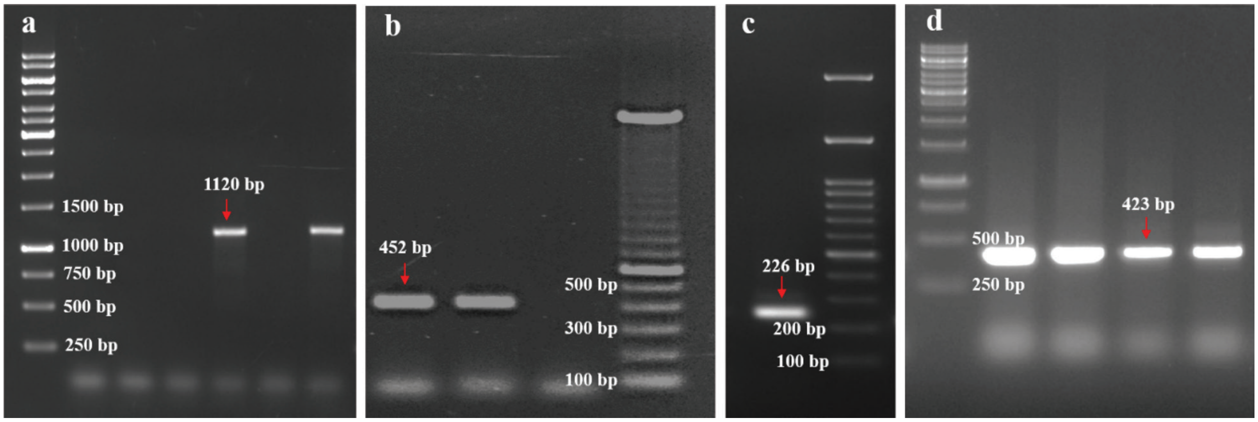

Fig. 1. Agarose gel electrophoresis showing amplification of different PCN resistant genes. a) Gpa2-1 marker-1120 bp, 1 kb ladder; b) Gpa2-2 marker-452 bp, 100 bp ladder; c) SPUD1636 marker-226 bp, 100 bp ladder; and d) Contig 237 marker-423 bp, 1 kb ladder.

Table 2. Details of the molecular markers used for characterization.

Potato cyst nematodes	Genes/ QTL	Marker	Marker type	Fragment size (bp)	Primer sequence (5′ to 3′)	PCR conditions	Reference
G. pallida	Gpa2	Gpa2-1	STS	1120	F- TTTAGCACGGAATGTGGGGA R- GTTTCCCCATCAAAACTCAC	94°C-10 min, (94°C-45 s, 60°C-1 min, 72°C-1 min) 35 cycles, 72°C-5 min	Asano *et al.*, 2012
		Gpa2-2	STS	452	F- GCACTTAGAGACTCATTCCA R- ACAGATTGTTGGCAGCGAAA	94°C-10 min, (94°C-45 s, 60°C-1 min, 72°C-1 min) 35 cycles, 72°C-5 min	Asano *et al.*, 2012
	Gpa5	SPUD 1636	PCR	226	F-GTGCGCACAGGGTAAAACC R-ACCTTAGCGGATGAAAGCC	94°C-3 min, 94°C-30 s, 65°C-1 min, 72°C-1 min, (94°C, 30 s, 65°C decreasing the annealing temp. to 60°C by 1°C per cycle, 30 s; 72°C 30 s) 5 cycles, (94°C, 30 s, 60°C, 30 s, 72°C 30 s) 24 cycles; 72°C, 3 min	Bryan *et al.*, 2002
	GpaIV^{s} adg	Contig 237	CAPS/ TaqI	423	F- GCAGTCCTAATTGCACGTAACA R- CTTACTTGGGCAACCCAGAAT	94°C-10 min, (94°C-1 min, 54°C-1 min, 72°C-1 min) 35 cycles, 72°C-5 min	Asano *et al.*, 2012
G. rostochiensis	H1	TG689	SCAR	141	F-TAAAACTCTTGGTTATAGCCTAT R-CAATAGAATGTGTTGTTTCACCAA	94°C-2 min, (94°C-20s, 55°C-20s, 72°C-30s) 35 cycles, 72°C-5 min	Milczarek *et al.*, 2011
		57R	SCAR	450R	F-TGCCTGCCTCTCCGATTTCT R-GGTTCAGCAAAAGCAAGGACGTG	95°C-3 min, (94°C-30 s, 63°C-20 s, 72°C-1 min) 35 cycles, 72°C-3 min	Milczarek *et al.*, 2014
	GroV1	U14	SCAR	366	F-GGGCTTGTATAAGACCTCCGAGAGG R-CCCTTCCTTGGGTAGTTTGAGCG	92°C-7 min, (92°C-1 min, 57°C-1 min, 72°C-2 min) 25 cycles, 72°C-5 min	Jacobs *et al.*, 1996
		XO2	SCAR	854	F-CCACCAAACCCATAAAGCTGC R-TGTGAATTGGTATGAATCTGCAACC	92°C-7 min, (92°C-1 min, 55°C-1 min, 72°C-2 min) 25 cycles, 72°C-5 min	Jacobs *et al.*, 1996
	Grp1	TG432	CAPS/ RsaI	1900	F-GGACAGTCATCAGATTGTGG R-GTACTCCTGCTTGAGCCATT	94°C-3 min, (94°C-30 s, 66°C-45 s, 72°C-2 min) 35 cycles, 72°C-5 min	Asano *et al.*, 2012

Table 3. Evaluation of genotypes based on molecular markers.

Accession Number	Markers linked to *G. pallida* resistance genes				Markers linked to *G. rostochiensis* resistance genes					Total No of marker
	Gpa2_ QTL-Gpa2-1	Gpa2_ QTL-Gpa2-2	Gpa5-SPUD 1636	Contig237	H1-TG689	H1-57R	GroVI_ Ro1-U14	GroV1 -xo2	Grp1_ QTL-TG432	
CP-1911	-	-	-	+	-	-	-	+	-	2
CP-3774	-	-	-	+	-	-	-	-	-	1
CP-3771	+	+	-	+	-	-	-	-	+	4
HR9-5	+	+	-	+	-	-	-	+	+	5
CP-4311	-	-	-	+	-	-	+	+	+	4
LBY-24	+	+	-	+	-	-	+	-	-	4
CP-4039	-	-	-	+	-	-	+	+	-	3
Norchip	+	+	-	+	-	-	-	+	-	4
CP-3773	-	-	-	+	-	-	+	+	-	3
CP-4046	-	-	-	+	+	+	+	+	-	5
LBY-15	-	-	-	+	-	-	-	-	-	1
CP-4505	+	+	-	+	-	-	-	-	-	3
CP-4494	-	-	-	+	-	-	-	+	-	2
CP-4052	+	+	-	+	+	+	+	+	-	7
SM/92-338	-	-	-	+	-	-	+	+	-	3
CP-4042	-	-	-	+	+	+	-	+	-	4
HR9-3	+	+	-	+	-	-	-	+	-	4
K.Pukhraj	-	-	-	+	-	-	+	+	-	3
CP-4057	+	+	-	+	+	+	+	+	-	7
Farida	-	-	-	+	-	+	-	+	-	3
Ivory russet	+	+	-	+	-	+	+	+	-	6
ATL	-	-	+	+	+	-	-	+	-	4
Innovator	-	-	-	+	-	-	-	+	-	2
FL-2215	-	-	-	+	+	-	-	+	-	3
Colomba	-	-	-	+	+	-	-	+	-	3
FL-2221	+	+	-	+	+	-	-	+	-	5
Heraclea	-	-	+	+	+	-	-	+	-	4
Navigator	-	-	-	+	+	-	-	+	-	3
Santana	-	-	-	+	-	-	-	-	-	1
VMT 5-1	-	-	-	+	-	-	+	+	-	3
CP-4175	+	+	-	+	-	-	+	-	-	4
CP-3636	-	-	-	+	-	-	-	+	-	2
CP-2011	-	-	-	+	-	-	-	+	-	2
CP-4045	+	+	-	+	-	-	-	-	-	3
CP-3470	+	+	-	+	-	-	+	-	-	4
MS/08-1148	-	-	-	+	-	-	-	+	-	2
CP-2379	-	-	-	+	+	-	-	-	-	2

Accession Number	Markers linked to *G. pallida* resistance genes				Markers linked to *G. rostochiensis* resistance genes					Total No of marker
	Gpa2_ QTL-Gpa2-1	Gpa2_ QTL-Gpa2-2	Gpa5-SPUD 1636	Contig237	H1-TG689	H1-57R	GroVI_ Ro1-U14	GroV1 -xo2	Grp1_ QTL-TG432	
SM/95-43	-	-	-	+	-	-	-	-	-	1
CP-4496	+	+	-	+	-	-	+	+	-	5
CP-4043	-	-	-	+	-	-	+	-	-	2
CP-2370	+	+	-	+	-	-	-	+	-	4
CP-4047	+	+	-	+	-	-	-	+	-	4
CP-4084	-	-	-	+	-	-	+	+	-	3
K. Neelkanth	-	-	-	+	-	-	+	-	-	2
CP4630 (K. Chipona-4)	-	-	-	+	+	-	-	+	-	3
CP4105 (K. Girdhari)	-	-	-	+	-	-	+	-	-	2
CP4070 (K. Himalini)	-	-	-	+	-	-	+	+	-	3
CP3400 (K. Jawahar)	-	-	-	-	+	-	-	+	-	2
MP/09-68	-	-	-	+	-	-	+	-	-	2
CP-2350	-	-	-	+	-	-	+	-	-	2
CP-4087	+	+	-	+	+	+	-	-	+	6
CP-2416	-	-	-	+	-	-	-	+	-	2
CP-2372	-	-	-	+	-	-	-	-	+	2
CP-3180	-	-	-	+	-	-	+	+	-	3
CP-2067	-	-	-	+	-	-	+	-	-	2
CP-4085	-	-	-	+	-	-	+	+	-	3
MP/09-73	-	-	-	+	-	-	-	+	-	2
CP-3134	-	-	-	+	+	+	+	-	-	4
CP-3640	-	-	-	+	-	-	+	+	-	3
CP-2419	-	-	-	+	+	+	-	+	+	5
CP-1971	-	-	-	+	-	-	-	+	-	2
CP-3646	-	-	-	+	-	-	-	-	-	1
CP-1917	+	+	-	+	+	-	-	-	-	4
CP-3647	-	-	-	+	-	+	+	+	+	5
CP-2294	-	-	-	+	-	-	+	+	-	3
CP-4500	-	-	-	+	-	-	-	-	-	1
CP-2379	-	-	-	+	-	-	-	+	-	2
MP/2K-424	-	-	-	+	-	-	-	+	+	3
CP-4075	+	+	-	+	+	-	+	+	-	6
CP-2067	-	-	-	+	-	+	-	-	-	2
HT/97-727	-	-	-	+	-	-	+	+	-	3
CP-1940	-	-	-	+	-	-	+	-	-	2
CP-2418	+	+	-	+	+	+	-	+	-	6
CP-1909	-	-	-	+	-	-	-	+	-	2
CP-1980	+	+	-	+	-	-	-	-	-	3

Accession Number	Markers linked to *G. pallida* resistance genes				Markers linked to *G. rostochiensis* resistance genes					Total No of marker
	Gpa2_ QTL-Gpa2-1	Gpa2_ QTL-Gpa2-2	Gpa5-SPUD 1636	Contig237	H1-TG689	H1-57R	GroVI_ Ro1-U14	GroV1 -xo2	Grp1_ QTL-TG432	
CP-4398	-	-	-	+	-	-	-	+	-	2
CP-4439	-	-	+	+	-	-	+	+	-	4
CP-2379	-	-	-	+	-	-	-	+	-	2
CP-1717	-	-	-	+	-	-	-	-	+	2
QBA/92-4	-	-	-	+	-	-	-	+	+	3
CP-2069	-	-	-	+	+	-	+	+	-	4
LR/4568	-	-	-	+	-	+	-	-	-	2
MP/98-31	-	-	-	+	-	-	-	+	-	2
CP-3173	+	+	-	+	-	-	-	+	+	5
CP-1945	-	-	-	+	+	+	-	+	+	5
Total number of breeding germplasm with markers	22	22	03	85	21	14	33	57	12	

introduction of varieties having SPUD1636. *Gpa5* locus maps to chromosome 5 which acts additively with *Gpa6* locus (chromosome 9) to confer durable resistance to *G. pallida*. (Bryan *et al.*, 2002a) developed PCR-based marker, SPUD 1636 (Fig. 1) from AFLP marker which can detect the *Gpa5* locus and detect the chromosomal segment carrying the *S. vernei* derived QTL conferring resistance to *G. pallida*.

Except one variety Kufri Jawahar, all the accessions were positive for the Contig237 marker, linked to *GpaIV*^{s}*adg* resistance locus. This indicates that this QTL has been widely used in resistant breeding programme. QTL mapping of resistance to *G. pallida* allocated a QTL (*Gpa4*) to chromosome IV (Bradshaw *et al.*, 1998; Gebhardt & Valkonen, 2001). SNP based marker Contig237 (Fig. 1) is linked to *GpaIV*^{s}*adg*, imparting resistance against *G. pallida* pathotype Pa2/3 (Moloney *et al.*, 2010).

For molecular screening purposes we have used 5 markers linked to *G. pallida* resistance genes (4 exclusively for *G. pallida* and one for both PCN species). In the present study, out of all accessions four accessions (CP3771, HR9-5, CP4087 and CP3173) exhibited presence of 4 marker (except SPUD1636) linked to *G. pallida* resistance genes. Likewise, 18 accessions were positive for either 3 markers. One accession (Kufri Jawahar) was found having no resistance gene linked to *G. pallida*. In our previous study we have found multiple accessions showing the presence of 2 or more marker for *G. pallida* resistance (Mangal *et al.*, 2023). To search for potato cultivars bred in Russia with multiple resistance to PCN, Gavrilenko *et al.*, (2021) used marker associated with four loci: *Gpa2*, *GpaVvrn_QTL*, *GpaVs spl_QTL*, *Grp1_QTL* and found several domestic cultivars with multiple PCN resistance. Dalamu *et al.*, (2017) used two markers (HC and SPUD1636) which were linked to *G. pallida* resistance genes/QTL and observed many genotypes having both markers together.

Molecular characterization of genotypes for *G. rostochiensis* resistance

In our study, applying the specific primers TG689 and 57R for the resistance gene *H1* gave the presence of expected product size for 21 and 14 accessions respectively out of 85 tested accessions (Fig. 2). The *H1* gene was derived from *S. tuberosum* ssp. andigena (CPC1673) in 1952 which confers nearly complete or durable resistance to *G. rostochiensis* pathotypes Ro1 and Ro4 (Gebhardt *et al*., 1993) and has been extensively introgressed into commercial potato cultivars. According to Finkers-Tomczak *et al.* (2011) the molecular marker 57R was found to be closely linked to *H1* in a cross between the diploids SH83–92-488 and RH89–039-16. Similarly, marker TG689 has been utilized for *H1* PCN resistance screening, demonstrating a high congruence between the marker assay and the PCN-resistance phenotype (Biryukova *et al.,* 2008). Milczarek *et al.* (2014) found that the 57R and TG689 markers showed over 90% agreement with phenotypic tests, confirming their effectiveness in selection but the use of 57R leads to a reduction in the number of susceptible recombinants as compared with TG689. This is advantageous for breeding purposes because it is preferable to discard susceptible clones early on rather than mistakenly classify them as resistant and maintain them for further selection.

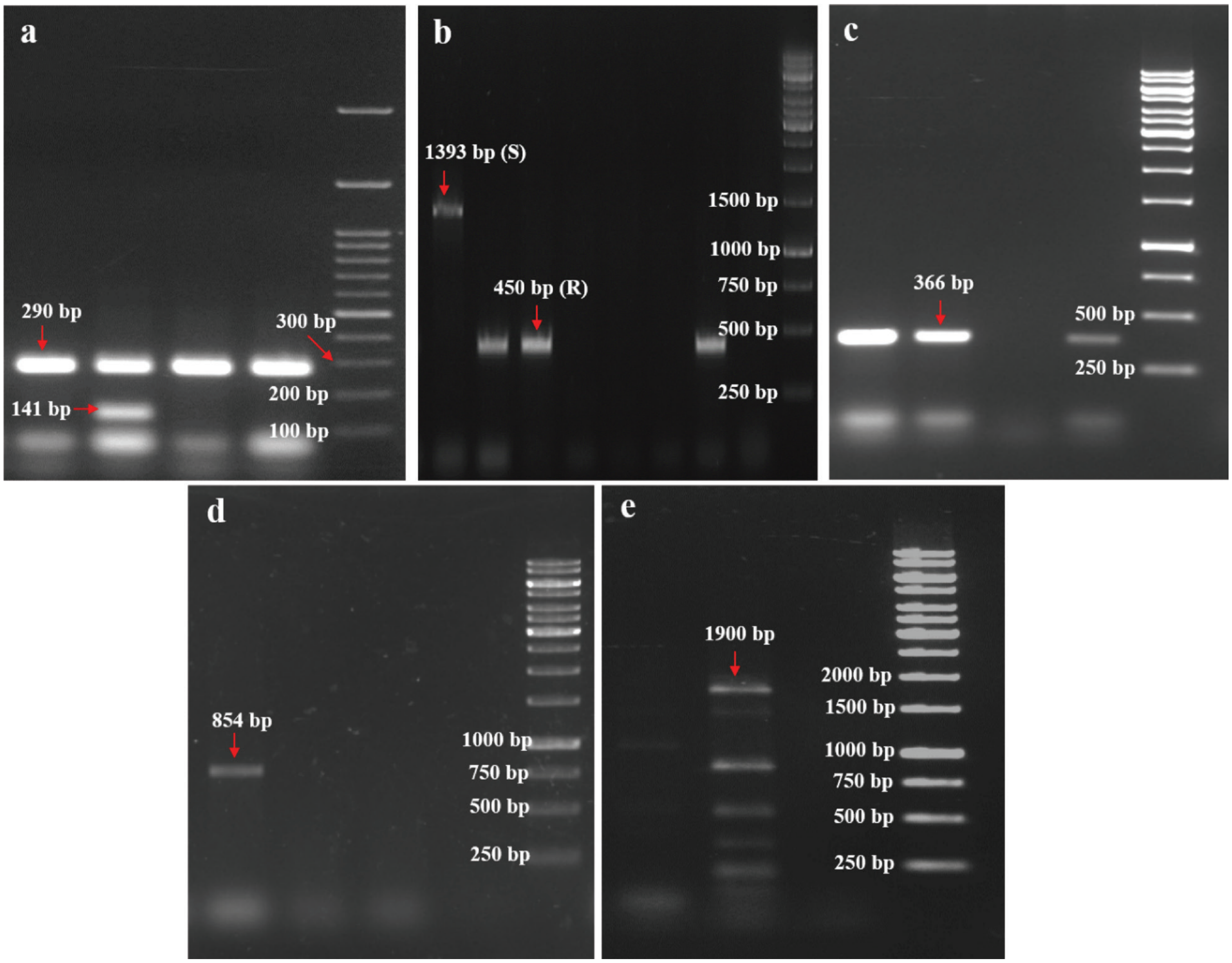

Fig. 2. Agarose gel electrophoresis showing amplification of different PCN resistant genes. a) TG689 marker-141, BCH (positive control)-290 bp, 100 bp ladder; b) 57R marker-450 bp (Resistant) and 1393 bp (Susceptible), 1kb ladder; c) U14 marker-366 bp, 1 kb ladder; d) XO2 marker-854 bp, 1 kb ladder; and e) TG432 marker-1900 bp, 1kb ladder.

Similarly, Schultz *et al.* (2012) used these markers in Australian and Scottish potato breeding programmes, Park *et al.* (2018) in New York breeding clones, and Whitworth *et al.* (2018) in advanced breeding population and observed same results. Zoteyeva *et al.* (2020) identified the good correlation of the marker 57R with resistance to PCN in the screening of interspecific potato hybrids. Ivanova-Pozdejeva *et al.* (2023) compared the applicability of *H1* gene markers TG689 and 57R in Estonian cultivars and other breeding clones and found 57R marker suitable for implementing genetic testing for nematode resistance. Meiyalaghan *et al.* (2018) designed and used two probe-based HRM markers (57R_1P and TG689_1P) for identifying resistance to *G. rostochiensis* pathotype Ro1 in 155 potato accessions. From this study they concluded that the HRM markers were more effective in screening as compared to conventional SCAR (57R and TG689) marker and found poor transferability for the SCAR markers. Totsky *et al.* (2021) screened GenAgro potato collection of ICG SB RAS using known diagnostic PCR markers and found 57R, a highly reliable marker and also suggests the need to use this marker when selecting samples resistant to PCN. Marker TG689 was successfully amplified in 47 out of 60 resistant cultivars (Milczarek *et al.*, 2011b). Additional studies have confirmed that 57R is a valuable marker, demonstrating over 90% concordance in various analyses. Dalamu *et al.,* (2023) screened 94 native potato accessions and observed 3 and 5 accessions positive for TG689 and 57R, respectively. Galek *et al.* (2011) demonstrated that testing for the presence of *H1* gene is highly useful before conducting bioassays, as the marker is much simpler to utilize.

Marker U14 and X02 linked with the gene *GroVI* was amplified in 33 and 57 accessions, respectively (Fig. 2). The *S. vernei* derived *GroV1* locus (long arm of chromosome 5) was found in the same region of the potato genome as the *H1* nematode resistance locus (Jacobs *et al*., 1996). Two reported SCAR markers were developed by converting the RAPD markers X02 and U14, which flank *GroVI*, generating amplicons of 854 bp and 366 bp, respectively (Gartner *et al*., 2021; Jacobs *et al*., 1996). The DNA marker of gene *GroVI* can be used as an indicator of the presence of genetic material of *S. vernei* in potato varieties. Bhardwaj *et al*. (2019) found 6 genotypes positive for X02 marker out of 12 genotypes studied.

CAPS marker TG432 (linked to *Grp1* locus located on short arm of chromosome V) was detected in 12 accessions out of 85 tested accessions with broad spectrum resistance levels to both *G. rostochiensis* (Ro5) and *G. pallida* (Pa2/3) pathotype (Finkers-Tomczak *et al*., 2009; Rouppe Van Der Voort *et al*., 1998).

For molecular screening of accessions having *G. rostochiensis* resistance genes we have used 5 markers (4 exclusively for *G. rostochiensis* and one for both PCN species). Out of all accessions six accessions (CP4046, CP4052, CP4057, CP2419, CP3647 and CP1945) exhibited presence of either 4 markers linked to *G. rostochiensis* resistance genes. Likewise, 8 accessions were positive for either 3 markers. Ten accessions were found having no resistance gene linked to *G. rostochiensis*. In our previous study we have found multiple accessions showing the presence of 2 or more marker for *G. rostochiensis* resistance (Mangal *et al*., 2023). Out of 60 *G. rostochiensis* resistant cultivar screened, Milczarek *et al*., (2011) found 18 cultivars which exhibited presence of at least two marker linked to resistance genes.

Combined resistance to both PCN species

In the present investigation total nine markers linked to PCN were used for molecular screening purpose. Based on molecular markers analyses we have identified two accessions CP4052 and CP4057 which exhibited presence of seven resistance markers. Four accessions (Ivory russet, CP4087, CP4075 and CP2418) showed the presence of either 6 markers. Likewise, seven, sixteen, twenty-two, twenty-seven, and seven accessions showed presence of 5, 4, 3, 2 and 1 markers, respectively. Similarly, Dalamu *et al*. (2017) identified elite potato genotypes CP1843, CP1879, and JEX/A-267 that can be utilized as parental lines for introgression of multiple resistant genes against both PCN species. Sharma *et al*. (2014), Slater *et al*. (2016), Bhardwaj *et al*. (2019), Mangal *et al*. (2023) used different markers in their breeding programme linked to PCN resistance genes and found genotypes having multiple resistance genes.

CONCLUSION

PCN are a significant global pest. Breeding potato cultivars with resistance to these pests is the most sustainable method of control. Before choosing parents for PCN resistance breeding programme, their molecular characterization with resistance genes linked marker will improve the efficiency of breeding programme. It will not only the save the time but it will help in the identification of parental lines having multiple resistance genes. This strategy is particularly valuable for resistance breeding against *G. pallida* due to the absence of any identified single dominant gene that provides high levels of resistance against this species. The genotypes identified in the current study having maximum resistance genes can be used in the hybridization programme. These genotypes also can be used for cultivar development after evaluation of their agronomic and yield characters. While using DNA markers for only a few genes cannot entirely replace extensive laboratory testing, it does provide a simple and reliable method for selecting potato forms resistant to this parasite in a shorter time. This approach significantly reduces the number of genotypes in the sample for further breeding. Various researchers have used different markers linked to PCN resistance genes in their breeding programmes, resulting in improved selection efficiency. They recommend elite potato genotypes that can be used as parental lines for the introgression of resistance genes against both PCN species.

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AUTHOR CONTRIBUTION

Conceptualized, experimental design and materials: SS, VB and VM, Genotyping: BD, AK and BS, Facilitation: BraS, VK and AKS, Manuscript Writing: VM and RS, Editing: SS. All authors read and approved the manuscript.

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DECLARATIONS

Consent for publication: Consent for publication is not applicable to this article as it does not contain any studies with human participants or animals performed by any of the authors.

Competing interests: The authors declare that they have no competing interests.

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ANALYSIS OF CONTRACT FARMING AND ITS IMPLICATION ON PROFITABILITY; EVIDENCE FROM POTATO FARMERS IN PUNJAB, INDIA

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ABSTRACT: Contract farming has become an essential institution for modern value chains but with controversies. Hence, the present study sought to understand whether contract farming is a boon or a bane for farmers. To unravel this, 120 farmers were sampled from the Moga district of Punjab state, India. The data was subjected to inferential analysis, profitability analysis, and qualitative discussion. It was found that areas under potato cultivation, potato farming experience, and having a secondary school education positively affect farmers' decision to participate in contract farming. The profitability estimates revealed that potato cultivation under no contract is more profitable than cultivation under a contract. Likewise, the impact assessment revealed that contract farming negatively affects farmer's gross returns. The qualitative discussion revealed myriad terms and conditions followed by the potato farmers under contract, including pre-price fixation, written contract, farm size requirement, quality and quantity requirement, input supply, no credit, farm visits, and cheque payment. Therefore, compensation in the event of crop failures, the provision of crop insurance, credit facilities, and advance payments needs immediate attention from policymakers.

KEYWORDS: Contract farming, Potatoes, Profitability, Impact assessment

INTRODUCTION

India holds 2.3% of the world's land and 4.2% of its freshwater resources, making agriculture a crucial sector contributing over 20% of the GDP in 2020-21. Despite its importance, the sector faces challenges, particularly for smallholder farmers who dominate the landscape but are often trapped in low-yield, subsistence farming cycles. These farmers struggle with low bargaining power, unstable markets, fluctuating prices, and exploitation by intermediaries, leading to limited profits and investment capacity. The adoption of modern inputs, better market access, and infrastructure have the potential to enhance agricultural growth.

Globalization and privatization have increased private sector involvement, shifting focus from low-value subsistence crops to higher-value commercial crops. However, Indian agricultural markets remain largely unorganized, with inadequate infrastructure limiting their ability to meet urban consumers' demands. Addressing these challenges requires reducing transaction costs and intermediary influence, which can lead to a more efficient and profitable supply chain. Collaboration among producers, consumers, and public-private partnerships is essential

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for tackling future challenges and ensuring sustainability in the agricultural sector. This multi-faceted approach can drive growth, improve productivity, and benefit all stakeholders involved in the agricultural economy.

Market-oriented production is a key component of rural development strategies, particularly in developing countries where agriculture remains a major source of income and employment for rural populations (Girma and Gardebroek, 2015). In addition, market access is also a critical factor in determining the income of agricultural households and incentivizing the cultivation of diverse crops. The diversification of traditional cereal-based agriculture into high-value food commodities has led to the emergence of both horizontal and vertical integration (Mishra *et al*., 2018). Producing these commodities requires significant capital investment and access to information, but small-scale farmers typically lack resources such as technology, quality inputs, and agricultural extension services. To address this issue, it is crucial to strengthen institutional mechanisms such as contract farming. Contract farming is a system where farmers enter into agreements with agribusiness companies to produce a specific crop or livestock product according to certain quality and quantity standards (Narayanan, 2025). In exchange, the company typically provides the farmers with inputs such as seeds, fertilizers, credit, insurance and technical assistance and offers guarantees a price for their crops (Patil *et al*., 2011b; Balram *et al*., 2012; Ray *et al*., 2020). Most often the contract company provides extension specialists that relay good agronomic practices and technologies to farmers (Biswas, Singh, and Singh, 2014). This company intervention makes the farmers more skilled and technologically sound in crop production.

After the National Agricultural Policy was released in 2000 by the Union Government, contract farming has been supported by successive governments and international development agencies. They view it as an important way to encourage private-sector investment in Indian agriculture. The policy aims to promote private sector involvement through contract farming, land leasing, direct marketing, and setting up private markets. These efforts are intended to speed up technology transfer, bring in more capital, and provide secure markets for crop production. Since 2015, policy reforms have been implemented in 16 Indian states to legalize and promote contract farming by the private sector (Vicol, 2018). This has paved the way for greater private capital investment in the agricultural sector, which was previously highly protected.

By the early 1990s, contract farming had been established in Punjab following the involvement of multinational corporation PepsiCo’s subsidiary, Pepsi Foods, in tomato and chilli production, as well as the participation of local company Nijjer Agro Foods Limited in tomato farming (Singh, 2020). Under the Punjab Contract Farming Act of 2013, farmers can enter into contracts with companies to produce crops. The state government of Punjab has been actively promoting contract farming to enhance agricultural productivity and improve farmers’ incomes through cropping patterns, production techniques, and crop diversification (Kaur and Singla, 2021). The Department of Agriculture and Farmers Welfare reported that the Government of India, India produced 60.14 million tons of potato in 2022-23. Punjab was India’s sixth largest producer of potatoes after Uttar Pradesh, West Bengal, Bihar, Gujarat, and Madhya Pradesh, and accounted for 5 % of total production in the country.

Since the inception of contract farming, it has emerged as a contentious and widely discussed subject in India. Therefore, an in-depth analysis of the terms of contracts in contract farming is essential to understand the potential benefits and drawbacks of these agreements promote fair, sustainable agricultural practices, and improve the agricultural landscape in general. It can provide a comprehensive understanding of the contractual obligations, rights, and responsibilities of each party involved in the agreement. This evidence can help identify potential areas of conflict or disagreement between farmers and buyers, and enable stakeholders to develop strategies for addressing these issues. It will also provide insights into the level of risk and uncertainty associated with contract farming for farmers and the potential benefits and drawbacks of participating in these agreements. Analyzing the cost and return structure between contract and non-contract farming methods will provide insights into the profitability of different farming methods, help identify potential areas for cost savings or efficiency improvements, and inform decision-making about whether to engage in contract farming or pursue alternative farming methods. Furthermore, this analysis can assist policymakers in understanding the benefits and drawbacks of contract farming for farmers and the overall agricultural sector, and guide the development of policies and regulations to ensure fair and equitable outcomes for all stakeholders involved.

MATERIALS AND METHODS

Study area and sampling

A multistage sampling approach was used to select the study area and the participants. Initially, the Moga district in the state of Punjab was selected purposively due to the predominance of potato production under contract and non-contract regimes. Afterwards, a list of potato farmers under contract was obtained from a contract farming company (name withheld for confidentiality). From the list, 60 potato farmers were selected randomly. Similarly, the same number of farmers who cultivated potatoes under no contract were sampled from the district. In this way, 120 farmers were selected for this study. It is worth noting sample size of 120 or more is sufficient for empirical analysis according to the central limit theorem (Bannor et al., 2020). Therefore, the sample unit used in this study is justified. Cross-sectional data was sourced from the sampled participants with the aid of a well-designed and pre-tested questionnaire.

Method of data analysis

Binary logit regression

The determinants of farmer's participation in potato contract farming were examined using logistic regression. Thus, the outcome variable is binary, to participate in contract farming or otherwise. Rooted in the utility maximization theory, this study posits that farmers will prefer contract farming supposing participating will provide satisfaction better than non-participation. In econometric modelling involving binary outcome variables, the binary probit or logit regressions are considered suitable (Gujarati *et al.*, 2022). However, the two models provide almost similar parameter estimates. Hence, the choice of either model is subjective. In this study, the binary logit regression was used to examine the determinants of participating in contract farming. The binary logit model is specified as:

$$p = P(Y_i = 1|X_i = x_i) \quad (1)$$

$$= \frac{\exp(\beta_0+\beta_1 x_i)}{1+\exp(\beta_0+\beta_i x_i)} \quad (2)$$

$$P_i = F(Z_i) = F(\alpha + \beta x_i) = \frac{1}{1+e^{-Zi}} = \frac{1}{1+e^{-(\alpha+\beta x_i)}} \quad (3)$$

Where e denotes the base of natural logarithms. Pi is the likelihood of participating in contract farming; *Xi* is the set of covariates that predict contract farm participation. β is the coefficient of the covariates to be estimated. Equation (3) can be restated as:

$$\log_e \frac{P_i}{1-P_i} = Z_i = \alpha + \beta x_i \quad (4)$$

The binary logistic model estimated in this study is given as;

Contract farming = β_1 Age + β_2 Education + β_3 Marital status + β_4 Family size + β_5 log Income + β_6 Experience + β_6 Farm size + β_7 Borrowed (5)

Profitability and Risk Analysis

Profitability

The tabular analysis was employed for estimating the costs and returns under various regimes of contract farming. The formula for various cost and returns concepts used in the study are as follows:

1. Gross Returns = Yield * Price
2. Net Return over Variable Cost = Gross Returns – Total Variable Cost
3. Net Returns over Total Cost = Gross Returns – Total Costs
4. Cost of production per kg= Total Variable Cost / Yield
5. Net Returns over Variable Cost per kg = Total Variable Cost / Yield
6. Net Returns over Total Cost per kg = Net Returns Over Total Cost / Yield
7. Returns per Rupee of Expenditure= Gross Returns / Total Cost
8. Return per Rupee on Variable Cost= Gross returns / Total Cost
9. Return per Rupee on Total Cost= Gross Return / Total Cost

Production and Price Risk

To analyze the extent of production and price differences between contract and non-contract farmers, their respective production and price risks were estimated. The pricing and production risks were determined by calculating the standard deviation (SD) and coefficient of variation (CV) using the following formula:

$$s = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}} \quad (6)$$

Where x = the value in the data distribution, $\bar{x}$ = the sample mean, and n = total number of observations.

$$\text{Coefficient of Variation} = \frac{Standard\ deviation}{Mean} * 100 \quad (7)$$

Inverse Probability Weighted Regression Adjustment Model (IPWRA)

The IPWRA model was used to assess the impact of contract farming on the gross profit of potato farmers. Since its proposal by Wooldridge (2010), this approach has been widely applied to impact evaluations (Lu *et al*., 2021; Israel *et al*., 2020). Reweighting and joint regression-adjustment techniques are used by the IPWRA, which is recognized as a doubly robust estimator, to estimate the mean treatment effects on the treated (ATT) and possible mean outcomes (Lu *et al*., 2021). Two sturdy properties make up the IPWRA estimator, which offers a dependable remedy for potentially skewed estimations (Israel *et al*., 2020). Furthermore, IPWRA remains consistent with at least one correctly described result even in cases when an outcome or treatment is misspecified (Bannor *et al*., 2023). The IPW and RA components make up the IPWRA model. Weighing the data according to the inverse probability that is being handled yields the inverse probability weights (IPWs). The likelihood of receiving treatment or propensity scores in the IPW is expressed as follows:

$$p(G) = \Pr(W_i = 1 \mid G) = H\{z(G)\} = E(W_i \mid G) \quad (8)$$

Where *G* represents pre-treatment covariates' multidimensional vector from observable attributes and *H{z(G)}* represents the function of cumulative distribution. The vector *G* represents farmers observed characteristics used in attaining treatment effects.

In addition, the RA part uses linear regression for treated and non-treated units (contract farmers and non-contract farmers) and averages the estimated outcome (gross profit) to obtain treatment effects. In simple terms, RA focuses on outcomes, and IPW emphasizes more on treatment in computing treatment effects. Following Lu *et al*. (2021), the RA model for the ATT is stated as follows:

$$ATT_R = a_S^{-1}\sum_{i=1}^{a} W_i[r_S(G,\varphi_S) - r_J(G,\varphi_J)] \quad (9)$$

Where ${}^{a}s$ represents contract farmers, $r^{(G)}$ denotes the regression model for producers and non-producers anchored on observed covariates ^{G} and parameters $\varphi_i = (\delta_i, \nu_i)$. The IPWRA model is established after merging the IPW and RA models. Thus, the IPWRA estimator expresses the ATT as:

$$ATT_{IPWRA} = a_S^{-1}\sum_{i=1}^{a} W_i[r_S^*(G^*,\varphi_S^*) - r_J^*(G,\varphi_J^*)] \quad (10)$$

Where $\varphi_S^* = (\delta_S^*, \nu_S^*)$ is attained from a procedure in estimating the weighted regression.

$$\min_{\varphi_S^*,\nu_S^*} \sum_{i=1}^{a} \frac{W_i(f_i - \varphi_S^* - G\nu_S^*)^2}{\hat{p}(G,\hat{\beta})} \quad (11)$$

$$\min_{\varphi_J^*,\nu_J^*} \sum_{i=1}^{a} \frac{(1-W)_i(f_i - \varphi_J^* - G\nu_J^*)^2}{\hat{p}(G,\hat{\beta})} \quad (12)$$

RESULTS AND DISCUSSION

Socioeconomic profile of farmers

Table 1 presents the background information of the sampled respondents. Accordingly, all the farmers were males. Again, the contract farmers are slightly older than their counterparts. However, the test statistics show that the average ages of these categories of farmers do not differ. Again, contract farmers have relatively smaller family sizes than their counterparts but the test statistics prove otherwise. Moreover, there are more married contract farmers than non-contract farmers but the test statistic refutes this claim. Further, there are more illiterate non-contract farmers than contract farmers. Relatively, contract farmers have less land holding than their counterparts but the test statistic disapproves this claim. Importantly, the test statistics revealed that there are no significant

Table 1. Background information of farmers

Variable	Description	Contract farmers (60)	Non-contract farmers (60)	Test statistics	Aggregate (120)
Gender	Male	60 (100)	60 (100)	NA	120 (100)
	Female	0 (0.00)	0 (0.00)		0 (0.00)
Age	Mean	38.57	38.16	7.17	38.367
	Std. dev.	9.37	9.54		9.377
Family size	Mean	7.23	8.93	2.93	8.083
	Std. dev.	2.93	3.57		3.351
Marital status	Single	14 (23.23)	10 (16.67)	0.10	24 (20)
	Married	46 (76.67)	50 (83.33)		96 (80)
Education	Illiterate	32 (53.33)	38 (63.33)	0.93	70 (58.33)
	Primary/metric	4 (6.67)	8 (13.33)		12 (10)
	Secondary	14 (23.33)	4 (6.67)		18 (15)
	Graduation	10 (16.67)	10 (16.67)		20 (16.67)
Landholding	Mean	11.63	12.03	0.09	11.83
	Std. dev.	5.01	7.41		6.27
Potato farm size	Mean	7.68	6.80	3.601	7.24
	Std. dev.	3.01	4.64		3.91
Experience	Mean	2.23	2.80	3.53***	2.52
	Std. dev.	0.97	0.89		0.97

Notes: *, ** and *** denote significance at 10%, 5% and 1% respectively. Figures in brackets are percentages.

differences in the acreages of potato cultivation for contract farmers and non-contract farmers. In addition, contract farmers have fewer years of experience in potato cultivation than non-contract farmers.

The terms and conditions surrounding the potato contract farming are presented in Table 2. It was stated that a formal contract governs their business relationship. Once more, there were no middlemen in the contractual procedure between the firm and the farmers. The contractual agreement stipulated the predetermined quality, quantity, and price of the output. Farmers needed to have access to suitable irrigation infrastructure and produce potatoes on a minimum of 5 acres to be eligible for the company's contract farming programme. Additionally, the business gave the farmers access to virus-resistant and high-yielding potato seed variants. The requirement was for the farmers to pay for half of the seeds up front; the other half would be subtracted from their earnings. The company offer packages like fungicides, insecticides, and herbicides to control weeds, pests, and illnesses. The pre-agreed pricing and quality parameters were disclosed to the farmers before assenting to the contract.

Table 2. Terms and modalities surrounding the contract farming

No.	Term/modality	Description
1.	The requirement to allow farmers to enter into a contract	Farmers need to cultivate potatoes on a minimum of 5 acres of land and must have proper irrigation facilities
2.	Method of approaching farmers	Direct meeting with farmers
3.	Any middleman between the farmer and the company	No
4.	Type of contract (Oral/Written)	Written
5.	Supply of agri inputs to the farmers	Seeds, Kit (Weedicide, Insecticide, and Fungicide) on a demand basis.
6.	Pre-agreed price fixation	Yes
7.	Prices range for various grades.	Grade A and B = Rs. 14.35/Kg Grade C = Rs. 10.75 /Kg Grade D = Rs. 7.5/Kg Grade Z = Rs. 1/Kg All the produce of every grade was procured from the farmers.
8.	Facilities Provided by the company	Seed, grading machine, transportation, technical guidance, bags.
9.	Frequency of visits by company officials	Two times a week (Also addresses farmers queries over the phone)
10.	Quality parameters considered by the company	Yes
11.	Planned quantity of procurement obtained by the company	Yes
12.	Payment mode	Payment is made through a bank.
13.	Form of payment	Cheque
14.	Advance payment	No
15.	Credit amenities provided by the company	No
16.	Action if the farmer refuses to supply produce to the company	Legal action be taken against that farmer
17.	Compensation in the event of failure	The farmer is responsible for the loss.
18.	Incentive	50 paisa/kg, if farmers had adopted the drip irrigation method 50 paisa/kg, if farmers had stored their potatoes in sheds immediately after harvest 25 paisa/kg, if a farmer had used a grading machine Rs 1/kg, if the yield of grade A and B potatoes exceeded 80%

The firm supplied seeds, grading equipment, bags, transportation, and technical advice, among other things. Twice a week, a technical expert would visit farmers' fields to assess crop conditions, recommend appropriate agronomical techniques, identify and prevent pests and diseases, etc. The firm only pays farmers via cheque. The company did not provide a credit facility or advance payment. If the crop failed, there was no compensation. To entice farmers to produce high-quality potatoes, the contracting firm provided them with four different kinds of incentives. The initial incentive was a payout to the farmers of 50 paisa for every kilogram of potatoes produced under drip irrigation. A reward of 50 paisa was given to farmers who put their potatoes in sheds right after harvesting as the second incentive. For the third incentive, a payout of 25 paisa per kg was offered to farmers who graded their crops using grading equipment that the firm provided. Finally, the company offered a payment of Rs 1/kg if the yield of grade A+B potatoes exceeded 80%.

Determinants of Contract Farming Participation

Table 3 presents the determinants of participating in potato contract farming by farmers in the Moga district of Punjab. The model diagnostics show that the model is fit under various specifications. Thus, the Chi-square is significant which shows the model fits the data well. Again, the Pseudo R-square indicates that farmers’ socioeconomic variables explain around 26% of the decision to enrol in potato contract farming. Variables like education, farming experience, and potato farm size were significant determinants of contract farming participation at a 5% level or less. Specifically, secondary education is significant and positively predicts participation in potato contract farming. This is plausible because most of the contract agents require farmers to document and have records of their routine activities on the farm. As such, farmers who have secondary education can fulfil this requirement unlike those who are illiterate. Likewise, education has been reported to influence contract farming (Ganewo *et al.*, 2022; Bidzakin *et al.*, 2019). Further, farming experience is significant and positively influences participation in potato contract farming. This means that experienced farmers are more likely to participate in contract farming. Probably, experienced farmers have the knowledge and understanding of contract farming policies and requirements and can produce to meet the quality requirement of the contract. Hence, farmers who possess higher experience are likely to participate in contract farming. Elsewhere, it has similarly been asserted that the farming experience favours contract farming (Loquias *et al.*, 2022; Ganewo *et al.*, 2022). Lastly, potato farm size is significant and positively influences participation in contract farming. Thus, potato farmers with large farm sizes are more likely

Table 3. Determinants of participation in potato contract farming

	Coef.	St. Err.	p-value
Age (years)	1.031	0.052	0.54
Education			
Primary/metric	1.997	2.545	0.587
Secondary	7.758	8.609	0.050*
Graduation	0.855	0.861	0.876
Marital status (1=Married)	0.459	0.559	0.522
Family size (number)	0.853	0.089	0.127
Income (Rs)	1.189	0.65	0.751
Experience (years)	0.304	0.131	0.006***
Potato farm size (acres)	4.359	3.336	0.049**
Borrowed (1= Yes)	0.523	0.361	0.348
Log-likelihood	-30.769		
Pseudo R-squared	0.260		
Chi-square	21.639		
Prob > Chi^2	0.017**		

Note: *, **, and ***denote significance at 10%, 5%, and 1% respectively. The reference category for education is illitera to participate in contract farming. An intuitive reason could be that contract companies give preferences to commercial farmers. This finding is congruent to the assertion of Bidzakin *et al*. (2019).

Profitability analysis of potato production

Table 4 illustrates the profitability analysis of potato cultivation under contract and non-contract regimes. The highest contribution to the total cost of production was from seed cost, which accounted for 58.98% in contract farming and 41.62% in non-contract farming. In potato farming, contract farmers used seeds supplied by the contract company, requiring 1173 kg per acre, compared to 1312 kg used by non-contract farmers. While the contract farmers received high-quality seeds, their costs were higher at Rs. 35,186, versus Rs. 25,041 spent by non-contract farmers who bought seeds from the market. The higher

Table 4: Cost and returns for contract and non-contract farming (per acre)

S. No.	Particulars	Units	Contract farming		Non-Contract farming	
			Qty	Amt (Rs.)	Qty	Amt (Rs.)
A	Returns					
1	Production	Quintal	65.86		132.1	
2	Price per kg of Potato	Rs.	12.33		6.96	
3	Gross returns	Rs.	81234		91801	
4	Net returns over variable cost	Rs.	23200		32737	
5	Net returns over the total cost	Rs.	21574		31646	
6	Cost of production per kg	Rs.	9.06		4.55	
7	Net returns over total cost per kg	Rs.	3.28		2.39	
8	Returns per rupee of variable cost	Rs.	1.34		1.55	
9	Returns per rupee of the total cost	Rs.	1.36		1.53	
B	Cost					
1	Land preparation and seed sowing cost	Rs.		2718		2230
2	Seed (50 Kg Bag)	Bags	23.46	35186	26.23	25041
3	FYM	Trolley	4.6	4613	3.97	3173
4	Chemical fertilizer	Kg	435	6409	417	6068
5	Fertilizer application	Rs		435		417
6	Irrigation labor	Rs.		595		595
7	Pesticides	Rs./acre	-	1932	-	2497
8	Pesticide application	Day	-	673	-	657
9	Harvesting cost	Rs.	-	4485	-	8213
10	Transportation cost	Rs.	-	0	-	855
11	Bag cost	Rs./Bag	-	0	31	8190
12	Interest on W. C.(7% of VC)	Rs.	-	984	-	1125
13	Variable costs	Rs.	-	58034	-	59064
14	Depreciation	Rs.	-	1626	-	1101
15	Fixed cost	Rs.	-	1626	-	1101
16	Total cost	Rs.	-	59660	-	60166

Note: WC = working capital, Rs= rupees, Qty= Quantity, Amt= Amount, VC= variable cost, FYM= farmyard manure cost for contract farmers likely reflects factors such as seed quality, transportation, storage, handling, and research and development. In contract farming, chemical fertilizers, farmyard manure, harvesting costs, and land preparation and seed sowing costs contributed to the total cost of production of potatoes by 10.74%, 7.73%, 7.52%, and 4.56%, respectively. On the other hand, in non-contract farming, harvesting, bag, chemical fertilizer, and FYM contributed to the total cost of production of potatoes by 13.65%, 13.61%, 10.09%, and 5.27%, respectively. Contract farmers used more FYM (4.6 trolleys) than non-contract farmers (3.97 trolleys) due to guidance from the company, which promoted organic farming and reduced chemical fertilizers. This increased FYM use was encouraged to enhance crop size and quality, although it was not mandatory. Moreover, non-contract farmers spent more on pesticides, incurring Rs. 2,497 per acre, compared to Rs. 1,932 for contract farmers. This cost difference arose because the contracting firm supplied pesticide kits at a 20% discount. Again, contract farming yielded lower harvests (65.86 quintals/acre) and reduced harvesting costs (Rs. 4,485) compared with their counterparts. Moreover, the noticeable differences in the cost of bags and transportation could be attributed to the fact that contract farmers had their bags and transportation costs covered by the company, unlike non-contract farmers, who spent Rs. 35-40 per bag and required 200-220 bags. The company also eliminated transportation costs by purchasing produce directly from the farm gate.

Overall, contract farmers experienced a lower total cost of production (Rs. 59,660) compared to non-contract farmers (Rs. 60,165), benefiting from better technology, technical guidance, and economies of scale. Despite producing lower yields (65.86 quintals per acre) due to earlier harvesting as instructed by the company, contract farmers received a significantly higher price per kg of potatoes (Rs. 12.33) than non-contract farmers (Rs. 6.96), who harvested later (Geetanjali *et al.*, 2021). This higher price was due to pre-determined contract prices, shielding contract farmers from market price volatility. However, non-contract farmers achieved higher gross returns (Rs. 91,801) and net returns over variable cost (Rs. 32,737) and total cost (Rs. 31,646), compared to contract farmers (Rs. 81,234 gross returns, Rs. 23,200 net returns over variable cost, and Rs. 21,574 net returns over total cost). Non-contract farmers incurred higher costs due to increased pesticide use and harvesting expenses, and they bore the costs of bags and transportation. Despite lower net returns, contract farmers benefited from stable prices, guaranteed markets, access to quality inputs, and reduced risks, fostering loyalty and a willingness to expand contract farming (Patil *et al.*, 2011a). The findings highlight that while non-contract farmers might earn more during favourable market conditions, contract farming offers stability and reduced risk, crucial for farmers facing market inefficiencies and price volatility.

Implication of contract farming on gross profit

The impact of contract farming participation on potato farmer's gross profit is presented in Table 5. Figure 1 shows the overlap test. The overlap assumption is not violated since the propensity scores show a fair distribution. In addition, the results revealed that participating in contract farming aggravates farmer's gross profit. In other words, contract farming decreases a farmer's gross margin. Specifically, participants of contract farming have an average gross profit of Rs 81296 ($975)

Table 5. Impact of contract farming on potato farmer's gross profit

Outcome variable	Outcome means		ATE
	Contract farmers	Non-contract farmers	
Gross profit	81296.92 (348.1887)***	94581.05 (2680.937)***	-13284.13 (2667.13)***

Note: Numbers in parentheses are standard errors. ****denotes significance at 1%.

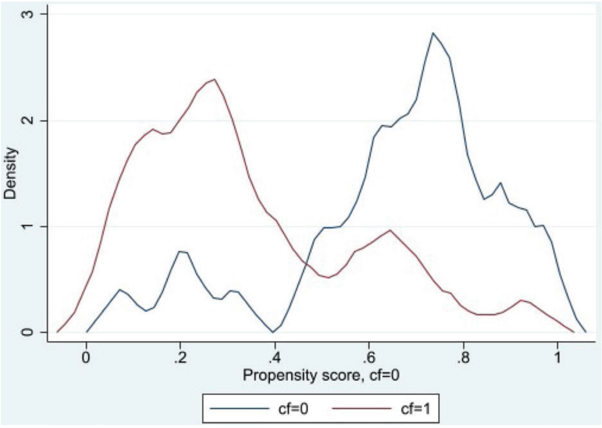

Fig. 1. Overlapping test results

relative to a gross profit of Rs 94581 ($1135[1]) for non-participants. The average treatment effects revealed that participating in contract farming decreases farmers' gross profit by Rs 13284 ($159). Generally, contract farming has been attributed to an increase in profitability and farm performance (Bannor *et al.*, 2022; Kosoe and Ahmed, 2022). However, the current finding is contradictory. Intuitively, contract farmers are slapped with numerous production requirements and instructions, which are usually costly. For instance, contract farmers are required to purchase recommended seeds, which are costly. Likewise, they are requested to apply more FYM, which is also costly. The costly requirements at the end inflate contract farmer's cost of production and decrease their anticipated profits.

Risk assessment for potatoes under contract and non-contract regime

Table 6 shows that non-contract farmers face greater production risk compared to contract farmers, with a coefficient of variation of 11.87 % and 3.76 % respectively. Similarly, the results for price risk demonstrate that non-contract farmers face higher risk compared to contract farmers, with a coefficient of variation of 9.07 % and 3.40 % respectively. It must be understood that contract farming has become a vital strategy for farmers to reduce exposure to market risks. The current findings highlight its role in mitigating production and price risks, ensuring better income security and stability. Studies by Ray *et al*. (2021) and Behera et al. (2021) confirm that contract farming offers protection against price fluctuations, while Paul *et al*. (2019) emphasize its role in minimizing risks of price volatility and crop failure.

CONCLUSION

Contract farming has become an essential institution for modern value chains in India, helping to increase efficiency, reduce transaction costs, and promote the integration of farmers into global supply chains. The present study was an attempt to understand whether contract farming is a boon or a bane for the farmers. To unravel this, 30 contract

Table 6. Production and price risk for contract and non-contract farmers

Particulars	Contract farmers	Non-Contract farmers
	Production risk	
Mean (Quintal)	65.87	132.1
SD (kg)	2.47	15.68
CV (%)	3.76	11.87
	Price risk	
Mean Rs. (kg)	12.34	6.96
SD Rs. (kg)	0.42	0.63
CV Rs.(%)	3.40	9.07

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[1] Note: $1 = Rs 83.35 as at 05/04/2024

and non-contract farmers making 60 farmers were sampled from the Moga district of Punjab state, India. Inferential analysis, profitability analysis, and qualitative discussion were used to make meaning from the cross-sectional data gathered. The results showed that potato farm size, farming experience, and having a secondary school education have significant and positive influences on a farmer's decision to participate in contract farming. The profitability analysis revealed that contract farming offers lower total production costs compared to non-contract farming, despite higher seed expenses. In addition, contract farmers benefit from reduced pesticide costs, free bags, and transportation and also receive higher prices per kg. Nonetheless, non-contract farmers achieve higher gross and net returns. The impact assessment shows that participation in contract farming harms farmer's gross returns. Thus, contract farming reduces farmer's potential gross returns. It was observed that farmers with less than 5 acres of land are generally excluded from contract farming since the minimum requirement for participation is 5 acres of irrigated land. To manoeuvre this barrier, small and marginal farmers are allowed to join contract farming by forming groups of 2 or 3 to collectively meet the 5-acre land requirement, with one farmer handling the contractual agreements and transactions. In addition, it was noted that prices are pre-agreed before cultivation with the company supporting with inputs like seeds. Concerning risk, contract farmers have lower production and price risk compared to non-contract farmers. This suggests that while non-contract farmers tend to earn more than their counterparts, contract farming provides stable production and guaranteed markets.

It is therefore recommended that provisions should be made to compensate farmers in the event of crop failure. In addition, there is a need to enhance support mechanisms within contract farming to boost farmer returns. This could involve policies promoting more favourable contract terms, such as better pricing structures, increased transparency, and shared benefits from market premiums. Additionally, integrating farmer training on yield optimization and sustainable practices could improve productivity and profitability, aligning contract farming returns better than with those of non-contract farming.

CONFLICT OF INTEREST

All authors declare no conflict of interest with this article.

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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EVALUATION OF POTATO GERMPLASM IN NORTHERN PLAINS OF INDIA

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ABSTRACT: The research experiments were conducted at ICAR-Central Potato Research Institute, Regional Station, Modipuram, Meerut, Uttar Pradesh during the early (2022) and main (2022-23) crop season to evaluate 50 potato (*Solanum tuberosum*) germplasm for tuber yield components in the North-central plains of India. On the pooled basis, the highest germination (%) was recorded for 12 genotypes namely, CP1454, CP1631, CP1651, CP3252, CP3334, CP3355, CP3414, CP3464, Kufri Bahar, Kufri Mohan, Kufri Garima and Kufri Ganga. The best performance for plant vigour was observed in Kufri Lima (4.3) followed by Kufri Mohan (4), Kufri Arun (3.9), Kufri Bahar, Kufri Garima, Kufri Surya and CP3085 (3.8). Early maturity was observed in CP3469 (3.75) followed by the genotypes namely, CP3469, CP1454, CP1471, CP3255, CP1651, CP2094, CP3266, CP3048, CP3050, CP3326, CP1648, CP3361, CP3252, CP3288, Kufri Mohan, Kufri Bahar, Kufri Surya, Kufri Pukhraj and Kufri Neelkanth (3.5). The highest marketable tuber numbers/plant were recorded for CP3353 (7) followed by CP3469, CP1651 and Kufri Sinduri (6). The highest total tuber number/plant was found in CP3353 (13) followed by CP3469, Kufri Sinduri, CP3385, CP3464 and Kufri Lalit (9), Kufri Ganga and CP1651 (8), Kufri Pukhraj, Kufri Lima, Kufri Garima, Kufri Mohan, Kufri Arun and CP3361 (7). The genotype Kufri Lima (310.8g) produced highest marketable yield/plant followed by Kufri Mohan (306g), Kufri Ganga (302g), Kufri Garima (294g), CP3294 (293g) and CP3413 (290g), Kufri Lalit (274g), CP3326, CP3469 (268g), Kufri Pukhraj (257g). The genotype like Kufri Mohan (360g) produced highest total tuber yield/ plant followed by Kufri Arun (358g), Kufri Lima (352g), Kufri Ganga (344g), Kufri Garima (336g), Kufri Lalit (323g), CP3413 (308g), Kufri Pukhraj (307g) and CP3294 (304g), CP3469 (288g) and CP3326 (277g). Overall, four genotypes CP3294, CP3469, CP3353 and Kufri Mohan were found promising genotypes in terms of germination, marketable tuber number/ plant, total tuber yield/plant and total tuber numbers /plant.

KEYWORDS: Potato, germplasm, plant characters, tuber yield, North-central plains

INTRODUCTION

Potato (*Solanum tuberosum*) plays a significant role in human food security and it is a crop with fascinating genetic traits and cultural history (Swaminathan, 1999). Potato is the third most important food crop after wheat and rice in the world (FAOSTAT 2020). Potato is used as a staple food among the vegetables and is utilized throughout the year in India. It belongs to family Solanaceae with chromosome number 2n=48. Due to its great utility, the potato is acknowledged as the "King of Vegetables". Due to its high yield potential in a short time, it is one of the most profitable and remunerative crop (Kashyap *et al.* 2021). Potato is also rich in several micronutrients, iron and potassium. It is a good source of dietary antioxidants, which may play a preventing role in diseases

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related to ageing and a source of dietary fiber (Mulatu *et al*. 2005). It contains minerals and vitamins B1, B3, B6 and C and composition of 20.6% carbs, 2.1% protein, 0.3% fat, 1.1% crude fiber along with tryptophane and isoleucine. Potato produces more energy and protein per unit area and per unit time than other food crops (Lutaladio & Castaldi, 2009). Potato is a cheap food of human diet. During 1948-1949, India produced 1.54 million tonnes of potatoes from 0.234 million ha area at an average productivity level of 6.58 t/ ha. Now India produces nearly 60.14 million tonnes of potatoes (Department of Agriculture & Farmers Welfare, Government of India) from 2.3 million ha with a productivity of 25.79 t/ha (2022-23). The latest (2022) global annual production of potatoes is 375 million tonnes, with an average productivity of 21.1 t/ha. (FAOSTAT, 2022), and thus average productivity of potatoes in India is higher than that of the world's average potato productivity. Presently, India is the second largest annual producer of potatoes after China. Together, six states *viz*. Uttar Pradesh, West Bengal, Bihar, Gujarat, Madhya Pradesh and Punjab contribute more than 90% of total potato production in India. In terms of total production, Uttar Pradesh, West Bengal and Bihar, occupy the top three positions with total annual potato production of 20.126 million tonnes (33.46%), 14.508 million tonnes (24.12%), and 9075 million tonnes (15.09%), respectively.

In India, 90% of potatoes are produced in sub-tropical plains during the winter season. High temperature during crop growth and tuberization restricts the adoption of potatoes in early planting conditions of north-western plains and peninsular India (Luthra *et al*. 2006). The early planted crop is vulnerable to attack of sucking pests like leafhoppers (*Amrasca biguttula* Ishida) and mite (*Polyphagotorsonemus latus* Banks) resulting in significant yield reduction (Malik and Luthra 2007). The yield and quality of potatoes are very sensitive to high temperatures (Bodlaender 1963; Ewing 1981). Minimum night temperature plays a crucial role during tuberization, which is reduced at night temperatures above 20°C with complete inhibition of tuberization above 25°C. Optimum temperatures for tuber formation are widely regarded as being in the range of 10-17°C (Bodlaender 1963; Moorby and Milthorpe 1975). Climate change is likely to lead to an overall temperature increase of 1-1.4 °C (Hijmans 2003) and the development of potato cultivars with increased heat tolerance appears to be important to cope with climate change. To expand potato cultivation in non-traditional warmer areas, there is a need to evolve varieties that could germinate, grow and tuberize well under high temperature (Luthra *et al*. 2013). The objective of the study was to evaluate potato genotypes for tuber yield components under early and main planting seasons for use in varietal development programme.

MATERIALS AND METHODS

The present investigation was carried at the experimental field of ICAR-Central Potato Research Institute Modipuram, Meerut, Uttar Pradesh (altitude of 230m amsl) during the early season of 2022 and the main season of 2022-23. The experimental materials was comprised of 50 germplasm CP1454, CP1471, CP1631, CP1648, CP1651, CP2094, CP3048, CP3050, CP3085, CP3247, CP3252, CP3255, CP3259, CP3266, CP3270, CP3288, CP3294, CP3326, CP3334, CP3337, CP3353, CP3355, CP3360, CP3361, CP3365, CP3385, CP89, CP3395, CP3413, CP3414, CP3415, CP3421, CP3437, CP3437, CP3438, CP3464, CP3465, CP3469 along with controls namely, Kufri Lalima, Kufri Surya, Kufri Sinduri, Kufri Pukhraj, Kufri Neelkanth, Kufri Mohan, Kufri Lima, Kufri Lalit, Kufri Garima, Kufri Ganga, Kufri Chipsona, Kufri Bahar and Kufri Arun. The data on 12 traits such as germination percentage, plant vigour (1-5 scale where 1 is very poor & 5 is highly vigorous), foliage maturity (1-5 scale where 1 is very late & 5 is very early), marketable tuber number per plant, marketable tuber yield per plant, total tuber number per plant, total tuber yield per plant were recorded to understand the yield potential of genotypes. Tuber characters like tuber colour, shape, eye depth and flesh colour were also observed. The data was recorded on plant vigour at 60 days after planting, however foliage maturity and tuber yield components were recorded at 75 days after planting in early crop and 90 days in main season crop.

The annual rainfall averages between 0.1–4.2 mm during the period from September to February. The average temperature ranged from 6.5-33.4°C in January to 33.4°C in September. Relative humidity varied from 50.7% to 94.9% during the crop season. The research field had clay loam soil, and the soil pH ranged from 6.9–7.4. The experiment was planted in last week of September, 2022 in early season and the second fortnight of October during 2022-2023 in main crop season. The row-to-row distance of 60cm and the plant to plant distance of 20 cm were maintained. The 15 tubers of each genotype were planted in a row of 3 meters. The crop was harvested after 75 days in the early season and 90 days in the main crop season.

RESULTS AND DISCUSSION

Performance of genotypes under early planting season

In early season 50 potato germplasm lines were evaluated at 75 days (Table 1). Plant stand ranged from 53-100% and 42 genotypes achieved full germination with 100% followed by CP3415, CP3438, and Kufri Sinduri with 93% germination. The data of foliage maturity was recorded at 75 days on the scale of 1 (late)-5 (very early) and ranged from 3 to 4. Two genotypes CP1648 and CP3288 emerged as early maturing with a score of 4. The plant vigour was recorded on scale of 1 (poor)-5 (very good) and ranged from 2 to 4. The genotypes namely, CP3085, Kufri Surya, Kufri Mohan, Kufri Arun and Kufri Lima showed good plant vigour with scale 4. The highest total tuber yield ranged from 26 to 267 g/plant and high total tuber yield was recorded in Kufri Lima (267g)

Table 1. Germplasm evaluation in early sowing season (2022)

S. No.	Genotypes	PS (%)	PV	FM	Tubers/plant		Tuber yield (g/plant)		hopper burn (%)	Mite damage (%)
					Marketable	Total	Marketable	Total		
1	CP1454	100	3.5	3.5	3.0	3.7	80.9	88.2	40	0
2	CP1471	100	3.5	3.5	2.7	3.8	83.3	94.7	20	0
3	CP1631	100	3.0	3.5	2.1	3.5	74.7	89.3	20	0
4	CP1648	87	2.5	4.0	3.5	8.5	62.9	99.3	20	0
5	CP1651	100	3.0	3.5	3.1	4.5	76.8	89.1	40	0
6	CP2094	100	3.0	3.5	2.5	3.7	82.0	94.1	40	0
7	CP3048	100	2.0	3.5	2.7	5.7	73.3	89.3	40	0
8	CP3050	100	2.0	3.5	1.6	3.3	36.0	48.4	60	0
9	CP3085	100	4.0	3.0	2.3	2.7	62.7	68.1	20	0
10	CP3247	87	2.5	3.5	1.8	4.2	29.7	54.5	60	0
11	CP3252	100	2.5	3.5	1.8	2.8	69.4	78.0	80	0

S. No.	Genotypes	PS (%)	PV	FM	Tubers/plant		Tuber yield (g/plant)		hopper burn (%)	Mite damage (%)
					Marketable	Total	Marketable	Total		
12	CP3255	100	3.5	3.5	2.6	4.5	71.8	88.7	40	0
13	CP3259	73	3.0	3.5	2.0	3.8	65.9	86.1	80	0
14	CP3266	100	2.5	3.5	2.1	3.9	61.3	74.7	80	0
15	CP3270	100	2.5	3.5	1.5	4.3	35.3	57.2	80	0
16	CP3288	100	2.0	4.0	2.0	3.5	47.0	62.3	100	0
17	CP3294	100	3.0	3.0	2.9	3.1	109.1	112.4	40	0
18	CP3326	100	3.0	3.0	3.1	4.0	116.5	128.3	60	0
19	CP3334	100	3.0	3.0	2.7	4.5	62.9	81.3	60	0
20	CP3337	100	3.0	3.0	2.3	4.9	76.8	96.8	60	0
21	CP3353	100	3.5	2.5	3.0	10.9	55.1	111.7	20	0
22	CP3355	100	2.5	3.0	1.7	5.3	35.8	68.1	100	0
23	CP3360	100	2.5	3.0	1.5	4.0	26.1	44.9	100	0
24	CP3361	100	2.5	3.0	0.8	4.7	15.3	40.0	100	0
25	CP3365	100	3.0	3.0	0.5	3.3	10.7	25.5	40	0
26	CP3385	100	3.0	3.0	2.0	9.3	33.6	85.1	20	0
27	CP3389	100	3.0	3.0	2.1	5.3	42.5	58.9	40	0
28	CP3395	100	3.0	3.0	3.6	5.1	82.2	95.2	80	0
29	CP3413	100	3.5	2.5	2.8	4.9	113.7	136.5	40	0
30	CP3414	100	3.0	2.5	3.1	4.7	112.5	128.0	40	0
31	CP3415	93	3.0	2.5	2.1	2.6	100.0	103.9	40	0
32	CP3421	100	3.5	3.0	3.7	5.3	98.7	109.5	40	0
33	CP3437	53	3.0	3.0	3.0	4.3	100.0	112.5	20	0
34	CP3438	93	3.0	3.0	3.3	4.7	77.9	90.6	20	0
35	CP3464	100	3.5	2.5	2.9	5.7	86.2	103.5	20	0
36	CP3465	100	2.5	2.5	1.6	3.6	30.1	43.5	40	0
37	CP3469	100	3.5	3.0	3.9	7.5	108.7	120.8	20	0
38	K Arun	100	4.0	3.5	3.0	4.7	233.3	254.7	20	0
39	K Bahar	100	3.5	3.5	2.7	4.2	73.5	87.5	100	0
40	K Chipsona 3	100	3.0	3.5	2.0	3.7	75.8	96.4	40	0
41	K Ganga	100	3.5	3.0	4.8	7.4	216.7	241.3	20	0
42	K Garima	100	3.5	2.5	4.3	5.9	195.2	212.1	0	0
43	K Lalima	100	3.0	3.0	5.3	7.9	151.8	173.5	20	0
44	K Lalit	100	3.5	3.0	5.4	9.0	170.3	208.3	40	0
45	K Lima	73	4.0	3.5	5.0	6.2	257.3	267.3	20	0
46	K Mohan	100	4.0	3.5	4.0	5.7	198.0	213.8	20	0
47	K Neelkanth	100	3.0	3.5	4.0	6.2	129.3	149.3	60	0
48	K Pukhraj	100	3.0	3.5	3.7	5.8	128.3	152.1	60	0
49	K Sinduri	93	3.0	2.5	4.9	6.4	136.4	154.6	60	0
50	K Surya	100	4.0	3.5	3.3	4.3	116.6	128.1	20	0

followed by Kufri Arun (255g), Kufri Ganga (241g), Kufri Mohan (214g), Kufri Garima (212g), Kufri Lalit (208g), Kufri Lalima (174g) Kufri Sinduri (155g), Kufri Pukhraj (152g) and Kufri Neelkanth (149g). The Marketable tuber yield (g/plant) ranged from 11 to 257 and high marketable tuber yield found in Kufri Lima (257g) followed by Kufri Arun (233g), Kufri Ganga (217g), Kufri Mohan (198g), Kufri Garima (195g), Kufri Lalit (170g), Kufri Lalima (152g), Kufri Sinduri (136g), Kufri Neelkanth (129g) and Kufri Pukhraj (128g) respectively.

The total tuber/plant ranged from 3 to 11. The highest total tuber number was recorded for Kufri Sinduri and CP3353 (11), CP3385, Kufri Lalit, CP1648 and Kufri Lalima (9), CP3469 (8), Kufri Ganga (7), Kufri Sinduri, Kufri Neelkanth and Kufri Lima (6). In the case of Marketable tuber number ranged from 0.47 to 5. The highest tuber number/ plant, the highest marketable tuber no. were recorded for Kufri Lalit, Kufri Lalima, Kufri Lima, Kufri Sinduri and Kufri Ganga (5) and Kufri Garima, followed by Kufri Mohan, Kufri Neelkanth, CP3469, CP 3421 and Kufri Pukhraj (4). The incidence of hopper burn ranged from 0 to 100%. Only Kufri Garima showed complete resistance (0%). All 50 genotypes were found highly tolerant with 0% mite damage incidence. A similar kind of study for the evaluation of potato genotypes in the early season for yield and yield traits was conducted by Luthra *et al*. 2008 and Chaudhary *et.al*. 2023.

Performance of genotypes under the main planting season

In the Main sowing season (2022-23) the germplasm lines were evaluated at 90 days (Table 2). The plant stand range of 50 genotypes was 60 to 100%. Total 15 genotypes namely, CP1454, CP1631, CP1648, CP3247, CP3252, CP3334, CP3355, CP3414, CP3415, CP3437, CP3464, Kufri Bahar, Kufri Mohan, Kufri Garima and Kufri Ganga were showed 100% germination followed by 14 genotypes with 93% germination. The plant vigour ranged 3 to 5. The two genotypes CP3048 and Kufri Lima were highly vigorous with value of 5 followed by nine genotypes namely, CP3050, CP3266, CP3355, CP3395, CP3438, CP3465, Kufri Bahar, Kufri Mohan and Kufri Garima with a value 4. The foliage maturity ranges from 3 to 5. One genotype CP3469 (5) was very early maturing followed by 21

Table 2. Germplasm evaluation in main sowing season (2022-23)

S. No.	Genotypes	PS (%)	PV	FM	Tubers/plant		Tuber yield (g/plant)	
					Marketable	Total	Marketable	Total
1	CP1454	100	3.5	3.5	4.3	5.2	253.3	266.7
2	CP1471	87	3.5	3.5	5.9	8.1	314.6	330.0
3	CP1631	100	3.5	3.0	5.0	5.9	307.7	316.7
4	CP1648	100	3.5	3.5	8.8	11.1	283.3	299.5
5	CP1651	93	3.5	3.0	5.5	6.4	364.3	372.1
6	CP2094	93	3.5	3.5	5.0	6.1	353.6	362.9
7	CP3048	67	4.5	3.5	4.6	6.3	235.0	255.0
8	CP3050	87	4.0	3.5	4.8	6.2	261.5	278.5
9	CP3085	80	3.5	3.0	5.1	5.1	333.3	333.3
10	CP3247	100	3.0	3.0	5.5	6.8	260.0	272.0
11	CP3252	100	3.0	3.5	4.0	4.9	277.3	284.0

S. No.	Genotypes	PS (%)	PV	FM	Tubers/plant		Tuber yield (g/plant)	
					Marketable	Total	Marketable	Total
12	CP3255	80	3.5	3.5	5.8	6.8	316.7	329.2
13	CP3259	80	3.5	3.0	4.8	6.7	344.2	363.3
14	CP3266	87	4.0	3.5	5.5	7.1	434.6	452.3
15	CP3270	87	3.0	2.5	4.4	5.0	215.4	230.8
16	CP3288	87	3.5	3.0	7.5	7.5	267.7	267.7
17	CP3294	73	3.0	3.0	6.6	7.2	477.3	495.5
18	CP3326	87	3.0	4.0	5.2	5.7	418.5	426.2
19	CP3334	100	3.5	3.0	5.1	6.2	286.7	300.0
20	CP3337	93	3.5	3.5	5.5	6.4	353.6	361.4
21	CP3353	93	3.5	3.0	10.5	14.4	292.9	314.3
22	CP3355	100	4.0	3.0	4.7	6.7	140.0	160.0
23	CP3360	87	3.5	3.5	6.9	8.5	346.2	361.5
24	CP3361	80	3.5	4.0	7.3	8.7	363.3	378.3
25	CP3365	67	3.5	3.0	3.9	4.9	220.0	230.0
26	CP3385	93	3.5	3.0	6.9	8.7	309.3	330.7
27	CP3389	93	3.5	3.0	4.1	5.6	207.1	228.6
28	CP3395	87	4.0	3.5	4.8	5.5	292.3	300.0
29	CP3413	93	3.0	3.0	4.6	6.4	467.1	479.3
30	CP3414	100	3.0	3.5	4.8	5.7	358.7	374.0
31	CP3415	100	3.0	3.0	4.8	6.8	346.7	360.0
32	CP3421	87	3.0	3.0	6.2	7.3	376.9	386.2
33	CP3437	100	3.5	3.5	4.1	5.9	357.3	378.6
34	CP3438	93	4.0	3.0	5.4	6.9	364.3	378.6
35	CP3464	100	3.0	3.5	6.8	11.8	403.3	450.7
36	CP3465	60	4.0	3.0	5.4	6.0	331.1	337.8
37	CP3469	80	3.5	4.5	8.6	10.8	425.0	455.0
38	K Arun	87	3.8	3.0	4.5	7.2	423.1	461.5
39	K Bahar	100	4.0	3.5	4.4	7.2	373.3	426.7
40	K Chipsona 3	93	3.5	3.3	8.6	10.8	285.7	335.7
41	K Ganga	100	3.8	3.3	4.7	7.7	386.7	446.7
42	K Garima	100	4.0	3.3	4.9	8.2	393.3	460.0
43	K Lalima	93	3.5	3.3	4.6	7.4	307.1	357.1
44	K Lalit	87	3.8	3.3	4.1	7.0	376.9	438.5
45	K Lima	93	4.5	3.3	4.7	7.8	364.3	435.7
46	K Pukhraj	87	3.5	3.5	7.0	11.9	384.6	461.5
47	K Mohan	100	4.0	3.5	3.9	6.7	413.3	506.7
48	K Neelkanth	93	2.5	3.5	5.0	8.3	300.0	357.1
49	K Sinduri	93	3.0	3.5	5.7	7.1	264.3	314.3
50	K Surya	93	3.5	3.5	5.4	8.8	221.4	257.1

genotypes with a value of 4. The range for Marketable tuber number /plant was 4 to 11 tubers. The genotype CP3353 (11) achieved the highest tuber number followed by CP1648, Kufri Chipsona 3 and CP3469 (9), CP3288, CP3361 and Kufri Pukhraj (7). The marketable tuber yield ranged was 140 to 477 g/plant. The highest Marketable tuber yield/plant was produced by the genotype CP3294 (477g) followed by CP3413 (467g), CP3266 (435g), CP3469 (425g), Kufri Arun (423g), CP3326 (415g) and Kufri Mohan (413g).

The total tuber number ranged was 5 to 14/plant. The highest Total tuber number per plant was recorded by only one genotype CP3353 (14) followed by Kufri Pukhraj and CP3464 (12), CP1648, CP3469 and Kufri Chipsona 3 (11). Total tuber yield per plant ranged 160 to 507 g/plant. The Highest Total tuber yield per plant was recorded in Kufri Mohan (507g) followed by CP3294 (477g), CP3413 (467g), Kufri Arun (423g), Kufri Pukhraj (385g) and Kufri Garima (393g).

Performance of genotypes over the season

In pooled data from early (2022) and main sowing season (2022-23), the plant stand ranged from 77-100% (Table 3). As many as 12 genotypes CP1454, CP1631, CP1651, CP3252, CP3334, CP3355, CP3414, CP3464, Kufri Bahar, Kufri Mohan, Kufri Garima and Kufri Ganga were recorded with 100% germination. Plant vigor ranged from 3 to 4. Nine genotypes Kufri Lima, Kufri Mohan, Kufri Arun, Kufri Bahar, Kufri Garima, Kufri Surya, CP3085, Kufri Ganga and Kufri Lalit were highly vigrous (4). Foliage maturity ranged from 3 to 4. Early maturity was found in genotypes namely CP3469, CP1454, CP1471, CP3255, CP1651, CP2094, CP3266, CP3048, CP3050, CP3326, CP1648, CP3361, CP3252, CP3288, Kufri Mohan, Kufri Bahar, Kufri Surya, Kufri Pukhraj and Kufri Neelkanth with a value 4.

Marketable tuber number/plant ranged from 2 to 7/plant. The highest Marketable

Table 3. Mean performance of genotypes in pooled data (2022 and 2022-23)

S. No	Genotypes	PS (%)	PV	FM	Tubers/plant		Tuber yield (g/plant)		Tuber characters
					Marketable	Total	Marketable	Total	
1	CP1454	100	3.5	3.5	4.0	4.0	167.1	177.4	Wc, O, S, W
2	CP1471	93	3.5	3.5	4.0	6.0	199.0	212.3	Wc, O, Md, Cr
3	CP1631	100	3.3	3.3	4.0	5.0	191.2	203.0	Wc, O, S, Cr
4	CP1648	90	3.0	3.5	4.0	7.0	213.6	235.7	Wc, O, Md, Cr
5	CP1651	100	3.3	3.5	6.0	8.0	180.1	194.3	Wc, O, S, W
6	CP2094	97	3.3	3.5	4.0	5.0	217.8	228.5	Cr, O, S, Cr
7	CP3048	83	3.3	3.5	4.0	6.0	154.2	172.2	Cr, O, Md, W
8	CP3050	93	3.0	3.5	3.0	5.0	148.8	163.4	Cr, O, Md, W
9	CP3085	90	3.8	3.0	4.0	4.0	198.0	200.7	Cr, R, S, W
10	CP3247	93	2.8	3.3	4.0	6.0	144.9	163.2	Wc, R, Md, Cr
11	CP3252	100	2.8	3.5	3.0	4.0	173.4	181.0	Y, R, S, Cr
12	CP3255	90	3.5	3.5	4.0	6.0	194.2	209.0	W, R, S, Cr
13	CP3259	77	3.3	3.3	3.0	5.0	205.0	224.7	Cr, R, Md, Cr
14	CP3266	93	3.3	3.5	4.0	5.0	248.0	263.5	P, R, S, Cr
15	CP3270	93	2.8	3.0	3.0	5.0	125.4	144.0	Cr, O, S, W

S. No	Genotypes	PS (%)	PV	FM	Tubers/plant		Tuber yield (g/plant)		Tuber characters
					Marketable	Total	Marketable	Total	
16	CP3288	93	2.8	3.5	5.0	5.0	157.4	165.0	Cr, O, S, Cr
17	CP3294	87	3.0	3.0	5.0	5.0	293.2	303.9	Cr, O, S, W
18	CP3326	93	3.0	3.5	4.0	5.0	267.5	277.2	W, O, S, W
19	CP3334	100	3.3	3.0	4.0	5.0	174.8	190.6	Wc, O, S, W
20	CP3337	97	3.3	3.3	4.0	6.0	215.2	229.1	Y, O, S, Cr
21	CP3353	97	3.5	2.8	7.0	13.0	174.0	213.0	Wc, R, Md, W
22	CP3355	100	3.3	3.0	3.0	6.0	87.9	114.1	Cr, R, D, Cr
23	CP3360	93	3.0	3.3	4.0	6.0	186.1	203.2	Wt, R, Md, W
24	CP3361	90	3.0	3.5	4.0	7.0	189.3	209.2	Wc, R, Md, Cr
25	CP3365	83	3.3	3.0	2.0	4.0	115.3	127.8	Y, R, S, Y
26	CP3385	97	3.3	3.0	4.0	9.0	171.4	207.9	Re, O, Md, Cr
27	CP3389	97	3.3	3.0	3.0	5.0	124.8	143.8	Wc, O, S, W
28	CP3395	93	3.5	3.3	4.0	5.0	187.3	197.6	Cr, O, S, Cr
29	CP3413	97	3.3	2.8	4.0	6.0	290.4	307.9	Cr, Ov, Sl, Wt
30	CP3414	100	3.0	3.0	4.0	5.0	235.6	232.0	Cr, O, Md (pink), Cr
31	CP3415	97	3.0	2.8	3.0	5.0	223.3	247.8	Cr, O, Md (pink), Cr
32	CP3421	93	3.3	3.0	5.0	6.0	237.8	247.8	Wc, O, S, W
33	CP3437	77	3.3	3.3	4.0	5.0	228.7	245.6	Cr, R, S, Cr
34	CP3438	93	3.5	3.0	4.0	6.0	221.1	234.6	Cr, R, Md, Cr
35	CP3464	100	3.3	3.0	5.0	9.0	244.8	277.1	Cr, R, S, W
36	CP3465	80	3.3	2.8	4.0	5.0	180.6	190.6	Cr, O, S, Cr
37	CP3469	90	3.5	3.8	6.0	9.0	266.8	287.9	Wc, O, S, W
38	K Arun	93	3.9	3.3	4.0	7.0	328.2	358.1	Re, R, S, Y (pink VB)
39	K Bahar	100	3.8	3.5	4.0	6.0	223.4	257.1	Cr, R, S, W
40	K Chipsona 3	97	3.3	3.4	3.0	5.0	180.8	216.1	Wc, O, S, W
41	K Ganga	100	3.6	3.1	5.0	8.0	301.7	344.0	Wc, R, S, Cr
42	K Garima	100	3.8	2.9	5.0	7.0	294.3	336.1	Cr, R, S, Y
43	K Lalima	97	3.3	3.1	5.0	7.0	229.5	265.3	Re, R, S, Wc
44	K Lalit	93	3.6	3.1	5.0	9.0	273.6	323.4	Re, R, Md (pink), Y
45	K Lima	83	4.3	3.4	5.0	7.0	310.8	351.5	Cr, R, S, W
46	K Mohan	100	4.0	3.5	4.0	7.0	305.7	360.2	W, R, S, W
47	K Neelkanth	97	2.8	3.5	4.0	6.0	214.7	253.2	P, R, S, Wc
48	K Pukhraj	93	3.3	3.5	4.0	7.0	256.5	306.8	Cr, O, S, Y
49	K Sinduri	93	3.0	3.0	6.0	9.0	200.4	234.4	Re, R, Md, W
50	K Surya	97	3.8	3.5	4.0	6.0	169.0	192.6	Cr, O, S, Cr

PS-Plant Stand%, PV-Plant vigour, FM-Foliage maturity, TTN/P-Total tuber no. per plant, MTN/P-Marketable tuber no. per plant, MTY/P-Marketable tube yield per plant, TTY/P- Total tuber yield per/plant; Tuber traits: Cr-cream, Re-Red, R-Round, S-Shallow, WC- white cream, Md-medium deep, Y-Yellow, O-oval, W-white, D-deep, P-Purple, VB-Vascular bundle tuber number was recorded for CP3353 (7) followed by CP3469, CP1651 and Kufri Sinduri (6) and 8 genotypes namely, Kufri Lalit, CP3421, CP3464, Kufri Lima, Kufri Lalima, CP3294, CP3288 and Kufri Ganga (5). Total tuber number per plant (ranged from 4 to 13/plant). The Total tuber number per plant was recorded highest by CP3353 (13) followed by 9 genotypes CP3469, Kufri Sinduri, CP3385, CP3464 and Kufri Lalit (9), Kufri Ganga and CP1651 (8), Kufri Pukhraj, Kufri Lima, Kufri Garima, Kufri Mohan, Kufri Arun and CP3361 (7).

Marketable tuber yield ranges 88 to 328 g/plant. In Marketable tuber yield per plant, Kufri Arun (328g) produced the highest marketable yield followed by Kufri Lima(311g), Kufri Mohan (306g), Kufri Ganga (302g), Kufri Garima (294g), CP3294 (293g) and CP3413 (290g), Kufri Lalit (274g), CP3326 (268g), CP3469 (268g), Kufri Pukhraj (257g). Total tuber yield ranged from 114-360 g/plant. Total tuber yield per plant was recorded in Kufri Mohan (360g) followed by Kufri Arun (358g), Kufri Lima (352g), Kufri Ganga (344g), Kufri Garima (336g), Kufri Lalit (323g), CP3413 (308g), Kufri Pukhraj (307g) and CP3294 (304g), CP3469 (288g) and CP3326 (277g).

CONCLUSION

During the Early sowing season (2022) overall basis genotypes only Kufri Garima was found promising genotype in terms of germination, total tuber yield, and total tuber number, nil hopper burn and mite damage. During the Main season planting (2022-23) on an overall basis, genotype CP3353 appears to perform the best overall, given its leading position in both marketable and total tuber numbers per plant. Additionally, Kufri Mohan and CP3294 also show exceptional performance in terms of tuber yield, making them strong candidates for high yield potential. Based on the pooled data (2022-23) the performance across all traits, Kufri Mohan emerges as the best overall performer. This genotype demonstrates a 100% germination percentage, indicating robust initial growth. It also exhibits high plant vigor with a rating of 4.0, suggesting strong and healthy plant development. Kufri Mohan excels in yield, producing a high marketable tuber yield per plant of 306 grams and achieving the highest total tuber yield per plant at 360 grams. This consistent performance across multiple important traits makes Kufri Mohan a strong genotype and can be used in further breeding programme.

Overall, the germplasm CP3353, CP3294, Kufri Garmia and Kufri Mohan were the best performers in terms of Germination, total tuber yield, marketable tuber yield, total tuber number and acceptable tuber attributes.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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ECONOMIC ANALYSIS OF POTATO CULTIVATION IN TRANS-GIRI REGION OF HIMACHAL PRADESH

Sapna Bhardwaj[1*] and Brij Bala[2]

ABSTRACT: Potato accounts for 10.85 per cent of the Himachal's total (17.22 lakh MT) vegetable output, which is the highest among all vegetables. In terms of area and output of potato, the state's third-ranked district is Sirmaur, and the Trans-Giri region of Sirmaur is notable for its high-quality potato production. Therefore, in the light of vital importance of potato in the Sirmaur's agrarian economy, this study reports the economic analysis of potato cultivation in Trans-Giri region which was done based on primary survey of 60 farmers grouped into small and large farmers of Sirmaur district during 2022-23. The total variable cost, total cost and net farm income on overall farm came to be Rs. 17,6368/hectare, Rs. 21,4929/hectare and Rs. 17,1618/hectare, respectively. Hired labour and potato seed made up the majority of the expenses which was around 52 per cent of total variable costs. Potato production seemed profitable with an output-input ratio of 1.80. To increase the production and profitability of potato crop, farmers must rationalize the use of inputs in accordance with package of practices.

KEYWORDS: Economics, Potato production, Cultivation, Trans-Giri, Sirmaur district

INTRODUCTION

Potato (*Solanum tuberosum*) is the third top most consumed crop worldwide after rice and wheat (International Potato Centre, 2022). Andes (South America) is the origin place of commercial potato which is derived from the wild species *Solanum tuberosum*. Around 8,000 years ago, it was at first cultivated near the present border separating Bolivia and Peru. In the 16th century, potato was taken from Latin America to Europe by the Spanish people. In earlier days potato was just admired for its floral beauty before being praised for its tubers, and since then, potato became a vital carbohydrate source in human and animal diets around the globe (Spooner and Hawkes, 1990). Potato is cultivated in more than 100 countries, under different conditions such as temperate, sub-tropical and tropical climates. India is the second-largest potato producer in the world after China, contributing about 12.3 % of global production, with Uttar Pradesh, West Bengal and Bihar together accounting for nearly 74 % of national output (*Rana and Anwer, 2018).*

India's agricultural system revealed its resilience amid COVID-19. The only bright sector was the agriculture and allied sectors clocking a growth rate of 3.4 per cent at constant prices during 2020-21. The share of agriculture and allied sectors in Gross Value Added (GVA) of the country was 17.8 per cent for the year 2019-20. (Economic Survey of India, 2020-21). Despite the obstacles caused by COVID-19, a steady supply of agricultural goods, particularly staples such

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as rice, wheat, pulses and vegetables, has been maintained, ensuring food security (Economic Survey of India, 2020-21). Potato contribution to agricultural GDP per unit of cultivable land is approximately 3.7 times higher than rice and 5.4 times higher than wheat (Indian Horticulture, 2019). Some popular potato varieties have been developed by ICAR-Central Potato Research Institute for farmers and cover almost 95 per cent of total area under potato. India produced approximately 45.87 million tonnes of potato annually during the triennium 2014-17 and contributed Rs. 57,512 crores annually to the GVA at current price (Indian Horticulture, 2019). During this period, ICAR-CPRI developed varieties which contributed 54,636 crores annually. Four varieties, viz., Kufri Jyoti, Kufri Pukhraj, Kufri Chipsona and Kufri Bahar, jointly contributed around 75 per cent of total area under potato (Indian Horticulture, 2019). The rise in inflation in the 2020 was due to increase in food inflation, which increased from 0.1 per cent in 2018-19 to 6.7 per cent in 2019-20 and further to 9.1 per cent in 2020-21, owing to build up in vegetable prices. Inflation in vegetables remained high during the period September 2019 to April 2020. It decreased to 4 per cent in June 2020 and remained in double digits from July to November 2020. During the lean season, the increase in vegetable inflation was primarily due to increase in onions and potato prices. (Economic Survey of India, 2020-21). The economy of the Himachal Pradesh is largely dependent on agriculture. About 12.73 per cent of total gross state domestic product (GSDP) is generated through agricultural and allied sectors (Economic Survey of Himachal Pradesh, 2019-20). So, it is an essential sector for the sustained growth of state economy. Although Rice, Wheat, Maize are the major agricultural crops grown in the state yet, Potato is also one of the important commercial crops. Out of total vegetable production in the country, major share goes to potato (28.9 per cent). Out of the total 17.22 lakh MT production of vegetables in state, potato accounts for 1.87 lakh MT i.e. 10.85 per cent, which is largest among all other vegetables (Economic survey of Himachal Pradesh, 2019-20). Potato is among the principal cash crops grown in Himachal Pradesh. The climatic conditions in most of the state provide good opportunity for producing both table potato and disease-free quality seed. Himachali Potato is very popular and is sold in various parts of the country as '*Pahari aloo*' that fetches premium price in the market as it is fresh and does not have sweet taste like the cold-stored potatoes. Potato, being an important crop, is grown throughout Himachal Pradesh. Sirmaur district possesses 3rd rank in area as well as in potato production in the state (Statistical Year Book of Himachal Pradesh, 2019-20). The potato grown in high altitude areas of the state is also in great demand as seed potato. Area under potato cultivation is 12.36 per cent (1500 ha.) of the total area under vegetables in Sirmaur (12134 ha.), which accounts for a production of 19,570 tonnes (District Statistical Abstract of Sirmaur, 2020-21). There are 6 blocks in Sirmaur district and Rajgarh, Shillai and Sangrah blocks, as well as few of the panchayats of Paonta Sahib block, are all part of Sirmaur's Trans-Giri region area. Rajgarh and Sangrah blocks alone accounts for 63.34 per cent of district's total land and 63.24 per cent of its total production (District Statistical Abstract of Sirmaur, 2020-21). In this area, the crop is grown between February-March to July-August. Kufri Jyoti variety of potato is used in the region by the farmers. The prosperity of farmers in the state is linked with the development of agriculture. Since cultivable land in the state is extremely limited due to geographical and topographical factors, farmers must resort to commercial crop cultivation to achieve high returns per unit of land because commercial crops have large input requirement, it is critical to utilize resources efficiently in order to maximize returns per unit of land.

Despite being a major potato-producing region the Trans-Giri area faces difficulties with rising input costs, uneven farm-size productivity, and non-judicious use of resources like labour, fertiliser, and seed. There is not much empirical data on the cost structure, profitability, and resource-use efficiency of potato cultivation in this hilly agroclimatic region, although it greatly boosts farmers' income and the local food supply. It is challenging to develop efficient technological and policy interventions meant to improve the sustainability and profitability of potato farming in the area in the absence of such localised economic analysis. In order to comprehend this, therefore, a systematic economic analysis of potato cultivation in the Trans-Giri region is essential to understand the cost of production, returns, and key factors influencing productivity across different farm categories.

MATERIALS AND METHODS

The study was carried out in the Trans-Giri region of Sirmaur district of Himachal Pradesh in 2022-23. Since, it is well known for its significant potato production and as supplier of high-quality seed potatoes. Two major potato growing blocks, on the basis of area under potato cultivation were selected i.e. Rajgarh and Sangrah. Then, a two-stage random sampling technique was used for the selection of villages and potato growers in two selected blocks. At first stage of sampling, a list of all potato growing villages was prepared for both the selected blocks and a sample of five villages was selected randomly in each of the selected blocks. Finally, a sample of 60 potato growers was selected randomly from ten villages based on the proportional allocation method. Further, the farmers were post-stratified into two categories viz., small (<2 ha.) and large (>2 ha.), on the basis of their total land holding. To accomplish the objectives of the study, both primary and secondary data were utilized. For the study, both tabular and statistical analysis was performed which are as follows:

Cost Concepts

The net returns over various costs were calculated by reducing the different costs from gross returns. The following CACP concepts were used in for working out the costs and returns of potato.

Cost A: Material cost + bullock/tractor charges + hired labour + interest on working capital + miscellaneous charges.

Cost B: Cost A + interest on fixed capital + rental value of owned land.

Cost C: Cost B + imputed value of family labour.

Cost D: Cost C + 10 per cent of Cost C.

The interest on working capital at 6 per cent rate for half of the crop period and also 6 per cent on fixed capital was computed as per the prevailing interest rates during the period under study. Based on the sample survey customary average rental value of land was used.

Farm efficiency measures

For working out profitability of potato in the study areas following farm efficiency measures were worked out:

2.2.1 Gross farm income (GFI)

It is defined as gross value of output including by-product priced at farm harvest rates.

2.2.2 Farm Business Income (FBI)

It is the disposable income of the enterprise. FBI = Gross income - Cost A

2.2.3 *Farm Investment income (FII)*

FII = Net farm income + interest on owned fixed capital + rental value of land

2.2.4 *Farm Family Labour Income (FLI)*

It is the return to family labour (including management).

F.L.I = Gross income – Cost B

2.2.5 *Net Farm Income (NFI)*

It is the net profit after deducting all cost items i.e., variable and fixed costs from gross income.

NFI = Gross income – Total cost (Cost C)

Production function analysis

To examine the extent of use of various resources in production of potato, production functions were estimated using input-output data from individual farmers. To explain the factors affecting the production of potato, multiple linear and log linear functions were fitted. Depending upon the value of R^2 (best fit) and the statistical significance of regression coefficients, multiple log linear production function was employed for analysis and discussion.

The production function used was of the following form:

$$Y = b_0 X_1^{b1} X_2^{b2} X_3^{b3} X_4^{b4} X_5^{b5}$$

Logarithm form of the function is:

$$\text{Log } Y = \text{Log} b_0 + b_1 \text{Log} X_1 + b_2 \text{ Log } X_2 + b_3 \text{ Log } X_3 + b_4 \text{Log} X_4 + b_5 \text{ Log} X_5 + \mu$$

Y = Output of potato (q/ha)

X_1 = Seed rate (kg/ha)

X_2 = Farmyard manure (q/ha)

X_3 = Fertilizers (kg/ha)

X_4 = Human labour (Man days/ha)

X_5 = Operational holding (ha)

b_0 = Constant term

U = Random term

To examine the significance of each parameter, t-test was employed as under:

SE (b_i) = Standard error of regression coefficient, i = 1,2....5

n = Number of sample observations

α = Selected level of probability (1 per cent, 5 per cent or 10 per cent)

k = No. of parameters /coefficients

RESULTS AND DISCUSSIONS

Total Cost of cultivation

Variable cost structure for potato cultivation on sample farms

Variable costs refer to expenditures on inputs that are consumed within a single production cycle, such as seed, fertilizers, pesticides, and hired labour. As shown in Table 1, seed was the largest contributor, accounting for 17 per cent of all variable costs and 58.57 per cent of all material costs (Rs. 51,198). This emphasizes the importance of seed in guaranteeing crops that are both disease-free and productive. Singh (2010) reported similar findings and came to the conclusion that the cost of seed (31 per cent) was the highest of the material costs. Farmyard manure (FYM) was the second most important input, with approximately 31 per cent of material costs and 9 per cent of total variable costs, indicating its significance in managing soil health. Fertiliser and pesticide costs accounted for 7 per cent and 2 per cent of material costs, respectively; small farms spent slightly more per hectare on fertilisers than large farms, while large farms spent more per hectare on pesticides. The hired labour accounted for about 35 per cent of variable costs on overall farms, making it the second largest component after material inputs, highlights about the labour-intensive potato farming is in the hilly area. Human labour

Table 1. Variable cost structure for potato cultivation on sample farms (Rs. /ha)

Sr. No.	Particulars	Small		Large		Overall	
		Per farm	Per ha.	Per farm	Per ha.	Per farm	Per ha.
1	Material cost						
I	Seed	5302	31191 (17.87)	4414	27588 (15.32)	5006	29990 (17.00)
ii	FYM	2847	16750 (9.60)	2493	15584 (8.65)	2729	16361 (9.28)
iii	Fertilizers	628	3696 (2.12)	571	3569 (1.98)	609	3653 (2.07)
iv	Pesticides	188	1109 (0.64)	218	1361 (0.76)	198	1193 (0.68)
	Sub-total	8967	52746 (30.23)	7696	48102 (26.71)	8543	51198 (29.03)
2	Bullock labour/tractor/power tiller	2202	12953 (7.42)	2079	12994 (7.21)	2161	12966 (7.35)
3	Hired Labour	9792	57600 (33.01)	11160	69750 (38.73)	10248	61650 (34.96)
4	Miscellaneous charges (Rs.)	300	1765 (1.01)	380	2375 (1.32)	327	1968 (1.12)
5	Working capital (1+2+3+4)	21261	125063 (71.67)	21315	133221 (73.97)	21279	127782 (72.45)
6	Interest on working capital (@ 6 per cent p.a.)	372	2189 (1.25)	373	2331 (1.29)	372	2236 (1.27)
7	Cash variable expenses	21633	127252 (72.92)	21688	135552 (75.26)	21651	130018 (73.72)
8	Family Labour	8032	47250 (27.08)	7128	44550 (24.74)	7731	46350 (26.28)
	Total variable cost	29665	174502 (100.00)	28816	180102 (100.00)	29382	176368 (100.00)

Note: Figures in parentheses indicate respective percentages to total variable cost

was the second most expensive factor, after seed (31.19 per cent) making the two most expensive part of variable cost (*Srinivas et al., 2007; Singh, 2010; Sinha, 2019).* Tractor, power tiller, and bullock labour costs accounted for roughly 7 per cent of total variable costs. Family labour played an important role for both small (Rs. 47,250/ha) and large farms (Rs. 44,550/ha) and about 26 per cent of variable costs for overall farms. Human labour and seed were found to be the costliest expenses sample farmers faced when growing potatoes. Similar results were given by Lal and Sharma (2006) who also reported potato crop as the most capital and labour intensive due to substantial cost incurred on seed, fertilizer and human labour. The variable cost varies from Rs. 1,74,504 to Rs. 1,80,102 per hectare from small to large farms.

Fixed cost structure for potato cultivation on sample farms

A thorough examination of fixed costs provides important information about the sustainability and underlying profitability of potato farming in the Trans-Giri area. The fixed costs remain constant regardless of yield or cultivation scale typically comprising interest on fixed capital, depreciation, and the rental value of land and are given in Table 2. Small holders allocated 17.48 per cent of total capital costs to their potato crop, while large farms, growing a wider variety of crops, allocated 9.75 per cent.

The average total fixed cost per hectare for the overall farms was Rs. 38,560, with small farms spending Rs. 38,197 and large holdings spending Rs. 39,288. Land rental, which is the biggest contributor stays constant across farm sizes at Rs. 36,458 per hectare, is noteworthy because it establishes the baseline for fixed cost in these hilly agro-ecosystems. The total cost of cultivating potatoes, when variable costs are taken into account, increases from Rs. 2,12,698 per hectare on small farms to Rs. 2,19,390 on large ones, with an average of Rs. 2,14,929 for the overall farms. The ability of

Table 2. Fixed cost structure for potato cultivation on sample farms

(Rs./ha)

Sr. No.	Particulars	Small	Large	Overall
1	Total variable cost	174502	180102	176368
2	Total fixed cost	38197	39288	38560
a)	Interest on fixed capital	886	1710	1161
b)	Depreciation on fixed capital	852	1119	941
c)	Rental value of land	36458	36458	36458
3	Total cost of cultivation (1+2)	212698	219390	214929

larger farms to invest in more sophisticated inputs, such as superior seed, fertilisers, plant protection, and mechanised labour, is what is driving this upward trend (Akter and Akram, 2020).

Different costs and returns for potato cultivation on sample farms according to CACP cost concepts

The CACP cost concepts were applied to small, large, and overall farms sizes in the Trans-Giri region and compiled in Table 3. A detailed evaluation of farm profitability and planning is made possible by these layered costing techniques, which range from operational (Cost A) to fully allocated cost (Cost D).

Table 3. Different costs and returns for potato cultivation on sample farms according to CACP cost concepts

(Rs./ha)

Sr. No.	Particulars	Small	Large	Overall
1	Cost A	127251.67	135552.22	130018.52
2	Cost B	164595.79	173721.03	167637.54
3	Cost C	211845.79	218271.03	213987.54
4	Cost D	233030.37	240098.14	235386.29
5	Gross returns	391382.73	375172.13	385979.20
6	Net returns over			
i	Cost A	264131.06	239619.91	255960.68
ii	Cost B	226786.94	201451.10	218341.66
ii	Cost C	179536.94	156901.10	171991.66
iv	Cost D	158352.36	135073.99	150592.91
7	Output-Input Ratio	1.84	1.71	1.80

Operating costs (Cost A), which account for the primary financial expenditures for every growing season, averaged Rs. 1,30,018 per hectare; large farms had higher costs, which was indicative of their wider use of cutting-edge inputs and technologies. The Cost B includes interest on fixed capital and the land's notional rental value, was Rs. 1,67,638 per hectare for overall farms. Cost C varies from Rs. 2,11,845 to Rs. 2,18,271 per hectare from small to large farms. Singh *et al.*, (2020) also found that large farms had higher Cost C than small farms. Notably, additional non-cash outflows, such as the imputed value of family labour and management, are included with each subsequent cost category (A, B, C, and D), making Cost D on per hectare to be Rs. 2,33,030 on small farms to Rs. 2,40,098 on large farms.

Overall, potato cultivation yielded gross returns of Rs. 3,85,979 per hectare on overall farms. It's interesting to note that small farms reported roughly 4 per cent higher gross returns per hectare than large farms, which is evidence of smallholders' extensive use of family labour and rigorous input management. In terms of net returns, returns over Cost A averaged Rs. 2,55,961 per hectare, with small farms achieving Rs. 2,64,131 and large farms achieving Rs. 2,39,620. Net returns over Cost B and C varies from Rs. 2,18,341 to Rs. 1,71,991 per hectare on overall farms. The benefit for small farms remains, primarily because of increased family labour contributions and more stringent variable cost control in resource-constrained environments, even though this margin decreases as more expenses are taken into account.

These patterns are further supported by the output-input ratio, which is a summary indicator of enterprise efficiency and stands at 1.84 for small farms, 1.71 for large farms, and 1.80 overall (Sapkota, 2019). Small farm holders received the highest returns per unit of investment, with an average return of Rs. 1.80 for every rupee invested in potato cultivation. Despite rising input costs high profitability of potato cultivation was found *(Mohammadi et al., 2018; Raghuvanshi et al., 2018; Kumar et al., 2022).*

Farm efficiency

To better understand the efficiency and profitability of potato farming, Table 4 provides detailed calculations for several key performance indicators such as gross farm income, net farm income, farm family labour income, farm business income, and farm investment income.

Small farms earn slightly more than large farms which is Rs. 3,91,383 and Rs. Rs. 3,75,172, with an overall gross farm income of Rs. 3,85,979 per hectare. This suggests that small farm holders are able to maximise output per unit area by closely managing inputs and frequently using labour from their own families. The average farm's net farm income, which represents earnings after all expenses are excluded, is Rs. 1,50,593 per hectare on overall farms. Small farms have net farm income of Rs. 1,79,537 whereas Rs. 1,35,074 per hectare for large farms. This disparity shows how smallholders have a clear edge in turning work into real profit when they rely on family labour and prudent management. The same pattern can be seen in farm family labour income, which is higher on small farms (Rs. 2,26,787) than on large farms (Rs. 2,01,451) per hectare. Farm family labour income is the returns earned by family labour after major expenses are covered. This is a direct result of family labour being more readily available and frequently used in small-scale businesses where each member's input has a quantifiable impact.

Table 4. Measures of farm business returns for potato on sample farms

(Rs./ha)

Sr. No.	Particulars	Small	Large	Overall
1	Gross farm income	391383	375172	385979
2	Farm business income	264131	239620	255961
3	Farm family labour income	226787	201451	218342
4	Farm investment income	216881	193950	209238
5	Net farm income	179537	135074	150593

The trend continues when looking at farm business income, which is the operating surplus after basic production costs are deducted: small farms report Rs. 2,64,131, while large farms report Rs. 2,39,620 per hectare. Small farms have higher farm investment income (Rs. 2,16,881) than large farms (Rs. 1,93,950), which is indicative of more effective capitalisation and use of owned resources. Additionally, When combined, these metrics consistently show that small potato growers are more profitable and efficient on their farms. It's evident that small farms' resource-conscious, family-cantered business model helps them generate greater profits, highlighting the value of domestic labour, careful input management, and flexible tactics in the particular agricultural environment of the Trans-Giri region.

Production function analysis

To examine the input-output relationship in potato crop under different categories of farmers, regression analysis was carried out with the help of both linear and Cobb-Douglas production functions. The Cobb-Douglas form of the production function was found to be the best fit on the basis of both economic and statistical criteria and was used to study the effects of different factors on output, production elasticities, and resource use efficiency of the different factors. The regression coefficients, their standard errors and the value of adjusted

Table 5. Estimated regression coefficients of different factors influencing potato production

Sr. No.	Particulars	Regression coefficients	Small	Large	Overall
1	Constant	b_o	0.89 (0.31)	-3.94 (1.84)	-0.37 (0.34)
2	Seed (X_1)	b_1	0.41** (0.11)	1.91* (0.83)	0.27** (0.10)
3	FYM (X_2)	b_2	0.01 (0.08)	0.51 (0.27)	0.26** (0.06)
4	Fertilizer (X_3)	b_3	-0.33** (0.08)	0.14 (0.34)	0.05 (0.05)
5	Human Labour (X_4)	b_4	0.95** (0.21)	0.50** (0.18)	0.98** (0.11)
6	Area under potato crop (X_5)	b_5	0.71** (0.12)	1.21** (0.29)	0.36** (0.08)
7	Adjusted coefficients of multiple determination	R^2	0.70	0.78	0.71

Note: Figures in parentheses indicate standard errors
*Significant at 5 per cent level of significance, **Significant at 1 per cent level of significance

coefficients of multiple determinations (R^2) for potato production are given in Table 5. The production function explained approximately 71 per cent of the variation in potato production on the farm as a whole. On overall farm, the value of seed (X_1), human labour (X_4), Farm yard manure (X_2), and the size of the land holding under potato (X_5) had a significant and positive effect on potato production (Sharma *et. al.,* 2017). This implied that one per cent increase in quantity of the seed of potato and human labour resulted in about 0.27 and 0.98 per cent increase in production. This suggests that there was potential for boosting potato production as well as profit. Similar results were also reported by Lal and Sharma (2006). The area under potato crop (X_5) and FYM (X_2) had a positive and significant effect on the production of potatoes on an average farm. This indicates that the production of potatoes could be increased by putting more area under this crop. The table further shows that the fertilizer (X_3) exhibited significance negative effect on production in the case of small farms. One per cent increase in the use of fertilizer resulted in about a 0.33 per cent decrease in production. On small farms, seed (X_1), human labour (X_4) and potato crop area (X_5) all had a significant positive impact on potato production. More specifically, a one per cent increase in quantity of seed and area under potato production was expected to result in 0.41 and 0.71 per cent increase in total production, whereas on large farms, human labour (X_4) and area under potato crop (X_5) exhibited the most positive significant effect on the production of potatoes.

CONCLUSION

The total cost of cultivation of potatoes amounted to Rs. 2,14,929 per hectare on overall farms, with Rs. 2,19,390 per hectare on large farms and Rs. 2,12,698 per hectare on small farms. Total variable cost turned out to be Rs. 1,80,102 per hectare on large farms and Rs. 1,74,502 per hectare on small farms. The major component of the total variable cost was human labour which contributed about 61 per cent to the total variable cost and was comparatively higher on large farms. After human labour, next major component of cost was seed, which accounted for about 17 per cent of the total variable cost of cultivation on overall farms. The total variable cost accounted for 82 per cent of the total cost, while 18 per cent was due to the fixed cost (Rs. 38,560 per hectare). Both the total variable cost and the total fixed cost were found to be higher on large farms than on small farms. The output-input ratio was higher on small farms (1.84) than on large farms (1.71). In overall farms, the output-input ratio was 1.80, which showed that one rupee invested in potato cultivation would return Rs. 1.80. Production function analysis indicated that seed, FYM, fertilizer, and area under potato cultivation were the most important factors affecting the production of potatoes.

COMPETING INTERESTS

We declare that we have no significant competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

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EFFECT OF NUTRIENT OMISSION ON GROWTH AND YIELD OF POTATO (*SOLANUM TUBEROSUM* L.) UNDER RAINFED ECOSYSTEMS OF NORTH EASTERN HILLY REGION, MEGHALAYA

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ABSTRACT: A field experiment was conducted to identify the most limiting nutrients for potato (*Solanum tuberosum* L.) production in Shillong, NEH Region, Meghalaya, India, during 2019-20. The experiment was replicated three times using a factorial randomized complete block design. The study included five nutrient treatments *viz*., control (-NPK), omission of nitrogen (-N), phosphorus (-P), and potassium (-K), recommended NPK (+NPK) and two potato varieties *viz*., K. Girdhari and K. Megha. Results showed that the average potato yield for the nutrient omission treatments were -K (12.67 t ha^{-1}), -P (10.81 t ha^{-1}), -N (7.85 t ha^{-1}), and -NPK (3.53 t ha^{-1}). The recommended NPK treatment resulted in the highest production (16.46 t ha^{-1}) with a net return of ₹160559 ha^{-1} and a B:C ratio of 1.95, indicating its superiority in terms of profitability and sustainability. The agronomic efficiency of nitrogen (AEN), phosphorus (AEP) and potassium (AEK) ranged from 52.17~92.32, 35.97~107.71 and 71.94~215.41 kg yield increase per kg of nutrient applied, respectively. Similarly, the partial factor productivity for nitrogen (PFPN), phosphorus (PFPP), and potassium (PFPK) under the fully fertilized treatment was 117.54, 137.14, and 274.27 kg yield per kg of nutrient input, respectively.

KEYWORDS: Nutrient response, nutrient omission, potato, varieties

INTRODUCTION

Potato (*Solanum tuberosum* L.) is an important food and cash crop in hilly regions of Meghalaya and is widely grown under rainfed conditions. However, Meghalaya's potato production is 1.87 lakh tons from 19,000 hectares with an average productivity of 10 t ha^{-1}, which is lower than the national average of about 23 t ha^{-1} (Kharumnuid *et al*., 2022). In Meghalaya, traditional potato farming often involves using less than the recommended dose of fertilizer, resulting in insufficient nutrients for potato growth and development. Several studies have demonstrated that imbalanced fertilizer use during crop cultivation contributes to low yield and quality, especially when most farmers of Meghalaya ignore nitrogen and potassium (Kadian *et al.,* 2010; Chulet *et al*., 2017).

Potato a heavy feeder that requires a higher quantity of nitrogen (N), phosphorous (P) and potassium (K) and fertilizers are important sources of these nutrients for potato (Koch *et al*., 2020). Nitrogen supply affects the plant growth (Ahmed *et al.,* 2015), tuber bulking rate and weight (Zebarth and Rosen 2007); phosphorous promotes root

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development, tuber initiation and maturity (Hopkins *et al*., 2014), while potassium affects tuber size, yield and quality of Potato (Trehan *et al*., 2009). Balanced fertilization significantly enhanced potato productivity (Gupta *et al.,* 2004). Numerous field trials have been conducted to estimate the amount of fertilizer required by potatoes in different parts of India (Kumar *et al.*, 2005; Kumar *et al.*, 2011; Kumar *et al.*, 2012) as crop productivity depends on the interaction of nutrients (N × P × K and micronutrients). Estimating the role of each nutrient is one of the biggest challenges for site-specific nutrient management. Nutrient omission can be a simple approach to determining the influence of each nutrient on crop growth and development (Yadav *et al*., 2020).

Furthermore, the omission of nutrients (N/P/K) shows the response of the crop and reduces the growth, yield and quality of potatoes (Singh *et al*., 2020; Yadav *et al*., 2020; Mugo *et al*., 2021). Crop yields in nutrient omission and non-omission areas are related to the soil's inherent nutrient supply and crop response to specific nutrients (Singh *et al*., 2020 and Nagar *et al*., 2023). Fertilizer application recommendations based on local climate, soil, and management approaches can significantly boost potato productivity. However, constant dependence on chemical fertilizers can lead to a nutritional imbalance that affects the soil's physical, chemical and biological properties and increases the cost of potato cultivation (Yadav *et al*., 2020). Therefore, to increase potato productivity, it is necessary to improve the nutrient supply capacity of the soil (N, P, K) and the response of the crop to nutrients. The omission trials have shown that potato production can be improved by developing location-specific nutrient recommendations based on soil nutrient-supplying capacity and crop response (Nagar *et al*., 2023). However, the indigenous nutrient supply capacity of soil in this region and the response of potatoes to nutrient omission were unclear. Based on the above facts, a field trial was conducted to identify the main limiting nutrient of potato.

MATERIALS AND METHODS

Experimental site description

The nutrient omission trials were conducted during the summer season of 2019-2020 (February– July) at the research farm of ICAR-Central Potato Research Institute, Regional Station, Shillong, Meghalaya. Shillong is situated in North Eastern India, at 25°54′ N latitudes and 91°84′ E longitudes, at 1738 m above mean sea level. It has a sub-tropical climate, with an annual rainfall of 2647 mm, of which 63% is from February to July. The maximum temperature ranges from 16 to 25°C and the minimum temperature ranges from 7 to 17°C during both cropping seasons (Fig. 1). Two potato cultivars, K. Girdhari and K. Megha, which are late maturing, good yield potential and resistant to late blight, were used in this experiment.

Nutrient omission trials

The soil is a well-drained sandy loam with pH of 5.12, electrical conductivity of 0.21 dS m^{-1}, organic carbon 1.5%, and soil

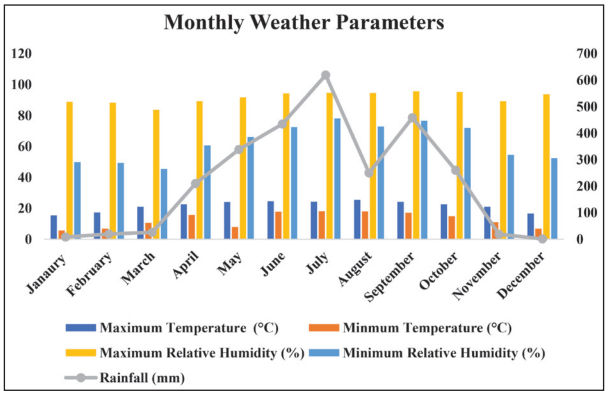

Fig. 1. Average monthly weather parameters (pooled mean of 2019-2020) of experimental site, Upper Shillong, Meghalaya

available N, P, and K at a depth of 0 to 15 cm are 260, 25, 217 kg/ha respectively. The study was laid out in a factorial randomized block of two varieties, five treatments, and three replications. The fertilizer treatments included (T_1) PK (N0PK), (T_2) NK (NP0K), (T_3) NP (NPK0) compared with (T_4) recommended RDF (+NPK) and (T_5) Unfertilized control (-NPK). The recommended dose of fertilizer (RDF) rate for potato in this region is 140:120:60 kg ha^{-1} along with 15 t ha^{-1} farmyard manure (0.90% N, 0.22% P, and 0.93 % K) was applied. All plots were fertilized according to the treatments. Nitrogen, phosphorus, and potassium were applied in the form of urea (46% N), single superphosphate (16% P_2O_5), and muriate of potash (60% K_2O), respectively. All nutrients were applied at the planting time except nitrogen, which was applied in two split applications (i.e., 50% base, 50% at 45 DAP). Uniform cultural practices and plant protection measures were used in all treatments.

Growth and yield determination

Seven plants from each plot were randomly selected for various biometric observations. Leaf chlorophyll content was measured at 35 days after planting (DAP) using an at LEAF+ chlorophyll meter (FT Green LCC, Wilmington, DE, USA). All plants were harvested manually and graded according to their weight and number, categorizing them as large (>75 g), medium (50-75 g), small (25-50 g) and very small (< 25 g) tubers. The tuber yield per plot was calculated and converted into tonnes per hectare.

Estimating yield response (YR), yield loss (%) agronomic efficiency (AE) and partial factor productivity (PFP)

The following formulas were used to compute yield response, yield loss, partial factor productivity and agronomic efficiency.

(i) $YR = Y_{NPK} - Y_0$- expressed in t ha^{-1}

(ii) Yield Loss = $((Y_{NPK} - Y_0) / Y_{NPK}) \times 100$ -expressed in percentage (%)

(iii) $AE = (Y - Y_0)/F$- expressed in kg yield per kg nutrient applied

(iv) $PFP = Y/F$-expressed in kg yield per kg of nutrient applied

Where Y_{NPK} stands for tuber yield of nutrient management practices (+NPK t ha^{-1}); Y_0 is the tuber yield of nutrient omission (N/P/K- t ha^{-1}). Where Y represents the yield of nutrient management practices (+NPK kg ha^{-1}), Y_0 represents the yield in the control plot (kg ha^{-1}), and F represents the quantity of nutrients applied (kg ha^{-1}). The agronomic efficiency (AE) of N, P, and K is represented by the variables AEN, AEP, and AEK, and the partial factor productivity (PFP) of N, P, and K is represented by the variables PFPN, PFPP, and PFPK. For the economics calculation of the 2019-2020 season, the prevailing market prices for inputs and outputs were used (sale of potato @ 20,000/tonne).

Data analysis

Analysis of variance was done for the information generated in FRBD using TNAUSTAT statistical software (Manivannan, 2014). The significance of treatment differences was compared through critical difference at a 5 % level of significance (P = 0.05) and interpretation of treatment results was made according to Gomez and Gomez (1984).

RESULTS AND DISCUSSION

Plant growth characteristics

Potato plant growth parameters, including plant height (cm), number of stems per plant, and number of compound leaves per plant of the potato were significantly affected by nutrient omissions (Table 1) and potato varieties, except for the number of stems per plant. These results were significant for

Table 1. Effect of nutrient omissions on growth attributes of potato.

Treatments	Plant height (cm)	Number of haulms plant^{-1}	Number of compound leaves plant^{-1}	Chlorophyll reading
Fertilizer application rate (N)				
Without N (100% PK)	35.49^{c}	2.68^{bc}	33.43^{c}	40.65^{c}
Without P (100% NK)	41.77^{b}	2.95^{b}	39.00^{b}	46.39^{b}
Without K (100% NP)	42.43^{b}	2.93^{b}	42.19^{b}	49.62^{b}
100% RDF of NPK	49.12^{a}	3.69^{a}	48.48^{a}	55.78^{a}
Unfertilized control (-NPK)	23.02^{d}	2.44^{c}	26.81^{d}	41.56^{c}
Potato variety (V)				
K.Girdhari	41.55^{a}	2.88	39.77^{a}	45.23^{b}
K. Megha	35.19^{b}	3.00	36.19^{b}	48.35^{a}
Analysis of variance				
Nutrients	6.04	0.40	5.11	4.34
Varieties	3.82	NS	3.23	2.75
N × V	NS	NS	NS	NS

Within columns means followed by the same superscripts are not significantly different at p 0.05, NS- non-significant.

both varieties in both seasons ($p < 0.005$). The interaction effect of potato variety and nutrient omission was not significant. The results showed that -NPK omission produced the shortest plants (23.02 cm) with the fewest numbers of stems (2.44) and compound leaves per plant (26.81 number). Conversely, recommended NPK (T_4) recorded the tallest plant (49.12 cm), more stems (3.69 number) and compound leaves per plant (48.48 number). This could be due to the availability of all the essential nutrients that enhance the growth of potato (Jatav *et al*., 2017). The omission of N significantly reduced plant height (35.49 cm) compared to the omission of P and K (41.77 cm and 42.43 cm, respectively). Therefore, the results suggested that nitrogens plays a critical role in cell division and vegetaive growth. This findings are in line with Singh *et al*. (2020) and Yadav *et al*. (2020). Similarly, the number of stems per plant (2.95 and 2.93) and compound leaves per plant (39 and 42.19) un affected by omissions of P and K suggesting these nutrients have less influence on growth parameters.

Further, growth parameters such as plant height, number of stems and number of leaves were significantly lower in treatments where N was omitted (- NPK and -N) compared to those of treatments receiving nitrogen (-P, -K, +NPK). In acidic, erosion-prone soils of Meghalaya's hilly terrains, Nitrogen is the most limiting nutrient for potato cultivation. Continuous farming in these area has led to nitrogen losses due to leaching, denitrification, and ammonia volatilization (Bharti and Ram, 2023). Several authors have found the impact of nutrient omission on potato growth (Singh *et al*., 2020; Yadav *et al*., 2020; and Mugo *et al*., 2021), and these studies explained the importance of N/P/K on potato growth and development. The taller plant (41.55 cm) and maximum number of leaves (39.77) were recorded in K. Girdhari and the shorter (35.19) and minimum number of leaves (36.19) were found in K. Megha. Both varieties had statistically similar numbers of stems per plant production. Since the environmental conditions during the growing period were similar, the different responses of the cultivars reflect the genetic differences between the cultivars (Singh *et al*., 2019).

Soil Plant Analysis Development (SPAD) value

The SPAD readings indicated that chlorophyll content was highest in the fully fertilized treatment (+NPK), followed by -K omission (49.62) and -P omission (46.39) (Table 1). In contrast, -N omission recorded the lowest chlorophyll content (40.65), which was on par with unfertilized control (41.56). These results reflect the nitrogen role in chlorophyll synthesis and photosynthesis efficiency (Jongschaap and Booij, 2004).

SPAD or chlorophyll meter values increased with increasing nitrogen levels (Singh *et al.*, 2019). Interestingly, the variety K. Megha exhibited higher SPAD valus (48.35) than K. Girdhari (45.23) suggesting varital differences in nitrogen use efficiency.

Potato yield and yield components respond to applied nutrients.

Potato tuber yield and its components were significantly influenced by nutrient omissions and different varieties used. There was no significant interaction between these factors, indicating that the response to nutrients was consistent across the varieties. The omission of N, P, and K had a significant reduction in potato tuber yield (Fig. 2). The ranking of total tuber yield and marketable tuber yield under different nutrient treatments was as follows: + NPK> -K >-P >-N > -NPK. This indicates nitrogen is the most yield-limiting nutrient for yield, followed by phosphorus and potassium. Soil incorporation of recommended NPK combined with farm yard manure recorded the highest total tuber yield (16.46 t ha^{-1}) and marketable tuber yield (12.32 t ha^{-1}), highlighting the benefits of integrated nutrient management in this region. Conversely,the lowest total and marketable tuber yield was found in -NPK (3.53 and 1.76 t ha^{-1}) and -N (7.85 and 5.44 t ha^{-1}) treatments, highlighting nitrogen deficiency, consistent with earlier studies (Singh *et al.*, 2020; Yadav *et al.*, 2020).

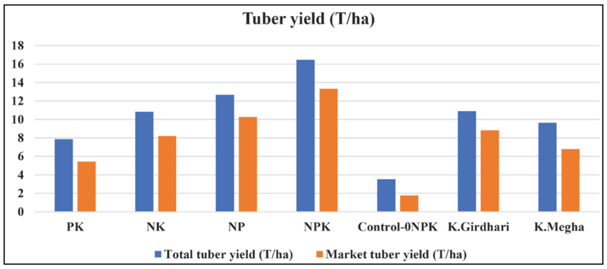

Fig. 2. Effects of nutrient omission on total and marketable tuber yield(t ha^{-1}) of potato

K. Girdhari produced a higher total and marketable potato tuber yield(10.89 and 8.43) compared to K. Megha (9.64 and 6.37 t ha^{-1}). However, K. Girdhari recorded a lowest non-marketable tuber yield (2.46 t ha-1) than K. Megha (3.27 t ha^{-1}). These varietal differences in yield and their components emphasize the importance of selecting varieties that are well adapted to local conditions. Overall, K. Girdhari consistently outperforms K. Megha.

Both the total and marketable tuber numbers showed the same pattern and their characteristics were significantly lower in -NPK omission and higher in no omission (+NPK) treatment (Fig. 3). The recommended NPK (T_4) had the highest total number of tubers (560.48 thousand ha^{-1}) and marketable tubers (339.68 thousand ha^{-1}) than -K (479.18 thousand ha^{-1} and 218.01 thousand ha^{-1}), -P (199.99 thousand ha^{-1} and 209.22 thousand ha^{-1}), -N (128.36 thousand ha^{-1} and 230.07 thousand ha^{-1}), and -NPK (231.02 thousand ha^{-1} and 50.46 thousand ha^{-1}) omission. The appropriate and timely use of nutrients and their combinations can improve plant growth and yield (Kumar *et al.*, 2023).

Yield response (t/ha) and yield loss (%) of nutrients

The omission of nutrients significantly influenced the tuber yield. Fig. 4 shows the

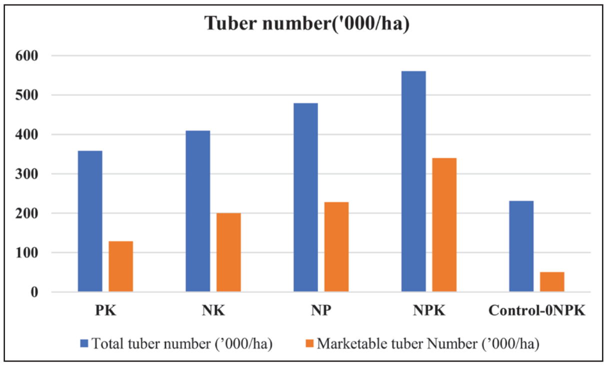

Fig. 3. Effects of nutrient omission on total and marketable tuber number ('000 ha^{-1}) of potato

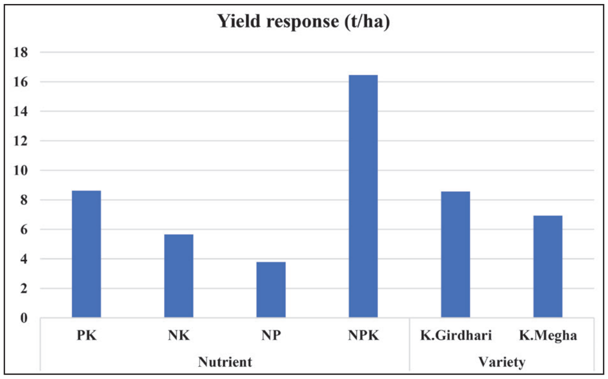

Fig. 4. Potato yield response (t ha^{-1}) as influenced by nutrient omission and potato varieties.

differences in yield responses to different nutrients across the seasons and varieties. The total tuber yield of recommended NPK was used as the target yield (16.46 t ha^{-1}). The highest yield response (yield reduction in nutrients omission) was recorded as -N omission (8.61 t ha^{-1}), followed by -P omission (5.65 t ha^{-1}) and -K omission (3.78 t ha^{-1}). The nutrient response of K. Girdhari (8.56 t/ha) was higher than K. Megha (6.92 t ha^{-1}) in the unfertilized control compared to the optimum fertilized treatment. This may be due to K. Girdhari cultivar produces higher yields than K. Megha with recommended fertilization

The substanical yield loss observed in -NPK (%) and -N (53%) omission indication crital role of nitrogen in potato (Fig. 5). Phosphorous and potassium omissions caused moderate yield reductions (34 and 23%) reflecting their secondary but still important roles. In Meghalaya, 81% of the total cultivated area is acidic and phosphorus (P) is the yield-limiting nutrient as it tends to fix P in the form of iron and aluminium phosphate (Sharma *et al.*, 2006). Available potassium status was low to medium in soils of the northeastern region of India (Mandal *et al.*, 2013). These findings suggested that site specific nutrient management is important for optimizing yiled.

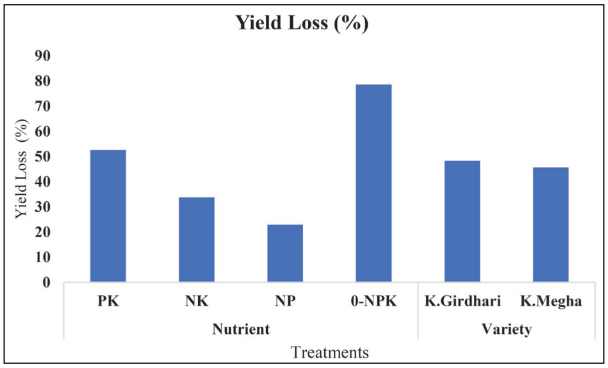

Fig. 5. Potato yield loss (%) as influenced by nutrient omission and potato varieties.

Agronomic efficiency (AE) and Partial factor productivity (PFP) of nutrients

Indigenous soil productivity can be estimated by using tuber yield from nutrient omission treatments, highlighting nutrient use efficiency and partial factor productivity (PFP). The mean agronomic efficiency of N (AEN) ranges from 52.17 to 92.32 kg tuber kg^{-1} N applied (Fig. 6). The AEN of -K omission (NP) was higher than -P omission (NK). Phosphorus plays a crucial role for enhancing AEN, as confirmed by Dua *et al.* (2007), who found the optimal potato AEN to be between 48-135 kg tuber kg^{-1} nitrogen. The mean agronomic efficiency for phosphorus (AEP) ranged from 35.97 to 107.17 kg tuber kg^{-1} P_2O_5, while potassium (AEK) ranged from 71.94 to 215.41 kg tuber kg^{-1} K_2O and the lowest AEP and AEK were recorded in

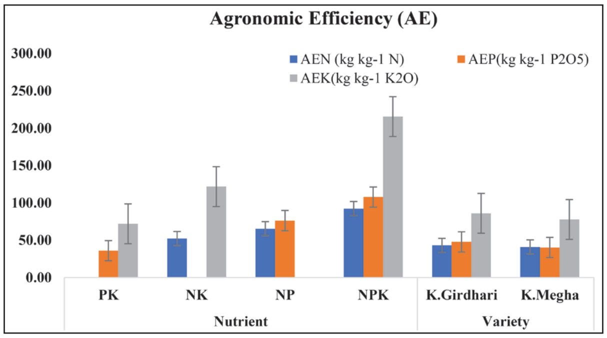

Fig. 6. Agronomic Efficiency (AE) as influenced by nutrient omission and potato varieties.

–N omissions. Fully fertilization (+NPK) led to the highest AEN, AEP, and AEK values of 92.32, 107.71, and 217.41 kg kg^{-1}, respectively. Similar results on the agronomic efficiency of potato by Singh *et al.* (2020) confirmed the highest reduction of AEP and AEK in nitrogen-omitted soils in Gwalior, India.

Partial factor productivity (PFP) measures crop productivity per unit of nutrient applied. Balanced fertilization (+NPK) increased PFP of N, P, and K (117.54, 137.14,274.27 kg kg^{-1}) (Fig. 7). The PFP of nitrogen was higher when potassium was omitted (90.53 kg kg^{-1} N) compared to phosphorus omission (77.39 kg kg^{-1}). When K was omitted, the PFP of P showed improvement compared to the omission of N (105.61 and 65.40 kg kg^{-1} P_2O_5,). On the other hand, when P was omitted, the PFP of K increased compared to the omission of N (180.59 and 130.80 kg kg^{-1} K_2O, respectively). Singh *et al.* (2020) found that phosphorus positively affected nitrogen uptake. Additionally, K. Girdhari outperformed K. Megha in AEN, AEP, AEK, and PFP. According to Dua *et al.* (2007), the cultivar showed differential responses to AE and PFP for N application.

Economics

Table 2 presents the economics of potato cultivation under different nutrient omission treatments. Cultivation and seed costs remained the same for all treatments except fertilizer. The results showed that nitrogen omission had the highest economic loss compared to P and K nutrient omission, indicating that nitrogen is more crucial for potato yield. Recommended NPK fertilization (T_4) recorded the highest cost of cultivation (₹168566 ha^{-1}), net returns (₹160559 ha^{-1}) and (B:C) ratio (1.95) compared to nutrient omissions and unfertilized control. Unfertilized (-NPK) and N omission (PK) treatments are unprofitable due to lower tuber yield, resulting in losses in net income and Benefit-Cost ratio (0.52 and 0.93 values). The next best profits were obtained by omission of K followed by P. Therefore, nutrient application (NPK) can maximize the economic returns, particularly in nutrient-exhaustive crops like potato.

Table 2. Effect of nutrient omission on the economics of potato cultivation.

Treatments	Economic parameters (Rs/ha)			B:C ratio
	Cost of cultivation	Gross returns	Net returns	
Without N (100% PK)	166722	156960	9761	0.93
Without P (100% NK)	161353	216200	54847	1.34
Without K (100% NP)	166558	253400	86842	1.52
100% RDF of NPK	168566	329125	160559	1.95
Unfertilized control	135000	70600	64400	0.52

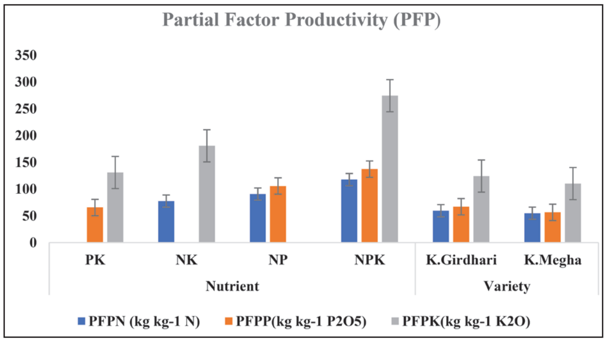

Fig. 7. Partial Factor Productivity (PFP) as influenced by nutrient omission and potato varieties.

CONCLUSION

The current study has adopted an omission technique to determine the importance of nitrogen (N),phosphorous (P) and potassium (K) in potato production in the acidic soil of the Shillong, NEH region, Meghalaya. The results revealed that nitrogen is the most critical nutrient for growth and yield of potato, followed by phosphorus and potassium with average yield reductions of 53%, 34% and 23%, respectively, when these nutrients were omitted. Application of 140 kg N, 120 kg P_2O_5 and 60 kg K_2O ha^{-1} along with farm yard manure significantly improved potato productivity (16.46 t ha^{-1}), higher yield response (12.92 t ha^{-1}) profitability (₹160559 ha^{-1}). This study highlights the importance of integrated nutrient management with organic manures, especially this region was prone to nutrient losses. Farmers should be encouraged to adopt soil test-based fertilizer application to sustain soil health and improving productivity, profitability and nutrient use efficiency of potato. Future research should focus on long-term nutrient studies, the use of precision technologies to optimize fertilizer application and development of location specific nutrient management protocols for hill agriculture. Integrating these approaches can improve the sustainability and profitability of the potato farming system in the North East hilly region and similar agroecological zones.

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AN ASSESSMENT OF POTATO CULTIVATION AND STORAGE FOR IMPROVING POTATO PRODUCTIVITY IN WEST BENGAL

Jamuna Prasad Kundu[1], Manik Chandra Das*[2] and Bijan Sarkar[3]

ABSTRACT: West Bengal generally sells around 40 percent of its total potato production to the other states. It is important to identify the potato cultivation and storage constraints which decrease the potato yield as well as increase the post-harvest losses for improving potato productivity in West Bengal. In view of this, a survey was conducted in the state to assess the knowledge of farmers for identifying the most serious constraints associated with potato storage and cultivation. The survey was carried out during 2024 in 16 blocks of 4 selected potato producing districts of West Bengal to find out the present status of potato storage and cultivation. Focus group discussion and structured questionnaires were used to collect data from potato farmers from each block. The most effective constraints in potato storage and cultivation with risk priority number (RPN) and risk assessment matrix of potato crop failure have been identified. For reduction of the constraints to increase potato productivity in West Bengal, breeding programs, crop protection strategies and other relevant measures need to be properly implemented.

KEYWORDS: Potato; cultivation; storage; constraints; RPN.

INTRODUCTION

The potato is the world's most important nongrain food crop worldwide under Solanaceae family (Gebhardt, 2016). It is grown in more than 125 countries and consumed almost daily by more than a billion of people (Mishra, 2013).

According to the data of Food and Agriculture Organization (FAO) of the United Nations, published in 2023 a total of 360 million tonnes of potatoes were produced worldwide, with China (94 million tonnes) and India (54 million tonnes) the largest potato producing countries in 2021. Globally, potato is used as seed potatoes, ware potatoes and starch potatoes (Kumar *et al.,* 2022). Potato like any other crop is affected by a number of biotic and abiotic stress (Kroschel *et al.,* 2020). These stresses are serious production constraints in potato growing areas. They range from insect attach causing blemishes and therefore the loss of tuber quality to significant reduction in tuber yield (Okonya *et al.,* 2014; Misganaw *et al.,* 2016; Demirel *et al.,* 2020; Demirel, 2023). In order to minimize these stresses, which induce damage to potato during growth, harvesting, post harvesting and storage, good management of the potato crop would help to effectively and efficiently maximize productivity. There may be problems of the potato storage in West Bengal, which, if

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tackled can help improving the post-harvest losses. Despite the rapid growth in potato industry, little researches have been done concerning different economic aspect in the state of West Bengal. Therefore, it has become important to overcome the potato storage constraints to depict their economics in the scenario of the dramatically growing potato industry (Yasmin, 2022).

One of the surest and cheapest ways of increasing the availability of agricultural supply is to minimize the losses by developing appropriate post-harvest technologies (Afzal *et al.*, 2019). These technologies can also add value to the agricultural products. Storage is an important marketing function, which involves holding and preserving goods from time they are produced until the consumption of the same (Duan *at el.*, 2020). While in storage, potatoes suffer losses due to weight loss, sprouting and rotting which are directly affected by storage conditions. Potatoes are more sensitive to quality loss than cereals because conservation using drying techniques cannot be applied and the risk of unacceptable moisture loss, disease spread, mould infections, and insect pests is obvious. In storage, potatoes undergo a gradual weight loss and quality loss which includes moisture loss, respiratory loss and changes in sugar (Scott and Suarez, 2011). Storage is a human activity for sight and safety of commodities from deterioration. Storage function adds time utility to the product (Burek and Nutter, 2020).

MATERIALS AND METHODS

Geographical location of the study area

The survey was conducted in four major potato growing districts of West Bengal lies between 85 degrees 50 minutes and 89 degrees 50 minutes east longitude, and 21 degrees 25 minutes and 27 degrees 13 minutes north latitude shown in Fig.1. Sixteen most potato producing Blocks were selected from these 4 districts. A total number of 400 famers (respondents) were randomly selected from these 16 Blocks. Detail name of the districts, corresponding Blocks and number of farmers selected are given in Table.1.

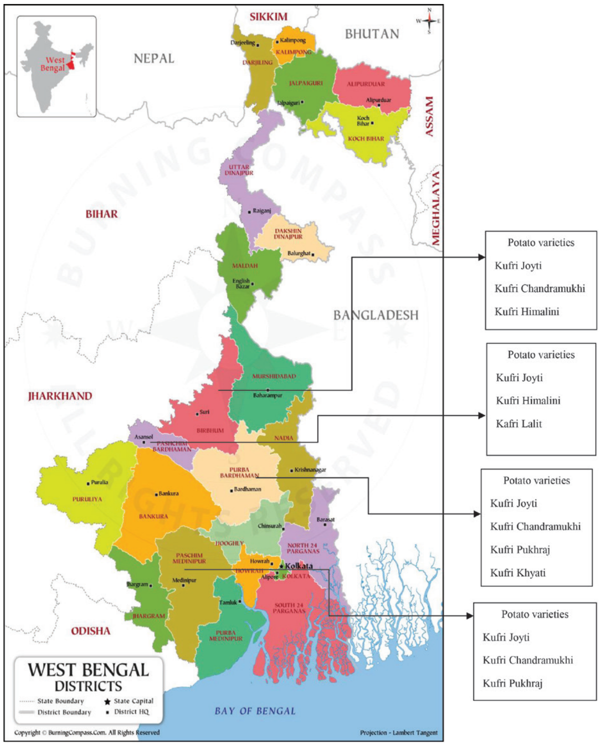


Fig.1. West Bengal district with production of potato varieties

Data collection

Primary data were collected from 400 respondents through partly structured and partly open survey questionnaires, interviews and focus group discussions. The secondary data were collected from publications, research reports, districts agriculture offices, internal and local databases including the international potato centre (CIP), Food and Agriculture organization (FAOSTAT) and Agriculture University.

Table 1. Block wise distribution of farmers (respondents)

Districts	Blocks	Category of Potato	Number of respondents
Hooghly	Tarakeswar	Kufri Joyti, Kufri Chandramukhi, Kufri Khyati, Kufri Pukhraj.	25
	Singure		25
	Khanakul		25
	Pursura		25
Pashchim Midnapore	Chadrakona (1&2)	Kufri Joyti, Kufri Chandramukhi, Kufri Pukhraj.	25
	Garbeta (1&2)		25
	Daspur (1&2)		25
	Kespur		25
Purba Bardhaman	Aushgram (1&2)	Kufri Joyti, Kufri Chadramukhi, Kufri Himalini.	25
	Memari (1&2)		25
	Ketugram (1&2)		25
	Raina (1&2)		25
Bankura	Taldangra	Kufri Joyti, Kufri Himalini, Kufri Lalit.	25
	Kotulpur		25
	Patrasayar		25
	Joypur		25

Data analysis

Completely filled up questionnaires collected from the respondents were stored for processing and data analysis. The descriptive statistics such as percentages, averages, frequencies and rank order were obtained through the statistical package for social science (SPSS) version 22. The analysed primary data have been organized in tables to show the results of the assessment.

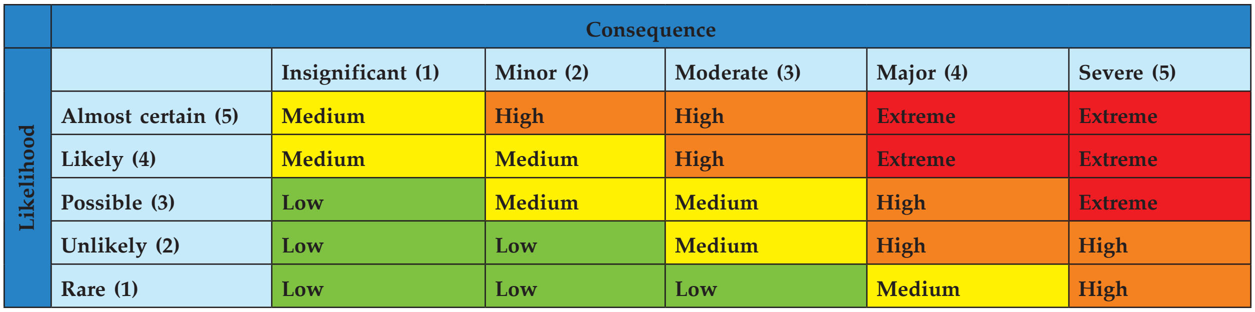
Risk priority number (RPN) and risk assessment matrix

Risk and uncertainty are unavoidable in agriculture and must be carefully managed. Farmers face production risks from weather, crop and livestock performance, pests, diseases, and various institutional, personal, and business factors (Hardaker *et al.,* 2013). A risk priority number (RPN) is a numerical assessment of risk assigned to a failure mode when conducting a Failure Modes and Effects Analysis (FMEA). It involves rating a failure mode's severity, probability of occurrence and likelihood of detection on a numerical scale ranging from 1 to 10. RPN is calculated considering the severity event (S), the probability of occurrence (O) and probability of detection (D) according to the formula (Zandi *et al.*, 2020) mentioned below.

$$RPN = O \times S \times D \quad (1)$$

The RPN value for each failure (Constraint) ranges between 1 and 1000.

A risk assessment matrix is a tool used during the risk assessment stage of project planning. It identifies and captures the likelihood of project risk and evaluates the potential damage or interruption caused by those risks (Liu *et al.*, 2013). A 5×5 risk assessment matrix (shown in Fig. 2) enables business leaders to promote a safety culture that is embedded in their operation. Likelihood is the probability of occurrence of an impact that affects the environment where as consequence is the environmental impact if an event occurs. Risk is calculated as the product of consequence and likelihood.



		Consequence				
		Insignificant (1)	**Minor (2)**	**Moderate (3)**	**Major (4)**	**Severe (5)**
Likelihood	**Almost certain (5)**	**Medium**	**High**	**High**	**Extreme**	**Extreme**
	Likely (4)	**Medium**	**Medium**	**High**	**Extreme**	**Extreme**
	Possible (3)	**Low**	**Medium**	**Medium**	**High**	**Extreme**
	Unlikely (2)	**Low**	**Low**	**Medium**	**High**	**High**
	Rare (1)	**Low**	**Low**	**Low**	**Medium**	**High**

Fig.2. Template of 5×5 risk assessment matrix.

RESULTS AND DISCUSSION

Demographic Characteristics

Complete demographic characteristics such as gender, marital status, age group, and educational level with frequency and percentage of total 400 respondents have been presented in Table 2. The percentage of male respondents involved in potato cultivation is higher (52.50%) than the female respondents. Education plays an important role in decision making process as well as information digestion on potato cultivation (Komba & Muchapondwa, 2017). Educational level such as illiterate, primary, secondary, higher secondary and tertiary with frequency and percentage (%) of the respondents are also shown in the same Table.

Table 2. Demographic characteristics of respondents

Variables	Demographic characteristics	Frequency of the respondents	Percentages (%) of the respondents
Gender	Male	285	71.25
	Female	115	28.75
Age Group	< 18 years	37	9.25
	18 ≥ but < 35 years	201	50.25
	≥ 35 years	162	40.50
Marital Status	Single	121	30.25
	Married	273	68.25
	Divorce	02	0.5
	Widow	04	1.00
Educational Level	Illiterate	12	3.00
	Primary	83	20.75
	Secondary	121	30.25
	Higher Secondary	102	25.50
	Tertiary	82	20.50

Potato seed varieties grown and sources

The farmers in West Bengal cultivate six potato variety (local) namely Kufri joyti, Kufri chandramukhi, Kufri Himalini, Kufri Khyati, Kufri Lalit and Kufri Pukhraj (Table 3). Farmers mention good and bad attributes associated with the cultivated potato varieties. The good attributes are high yield, colour, good marketability, tuber size, shape and resistance to pest (Kolech *et al.*, 2015). They also mention some bad attributes associated with cultivated potato varieties and these are number of tubers (too many), tuber size (small), test and susceptible to disease and pest (Aheisibwe *et al.*, 2014; Ahmed *et al.*, 2017; Byarugada *et al.*, 2013). Percentages (%) of respondents based on the sources of potato seed explored are shown in Table 4. The most important source of seed for potato cultivation in West Bengal is own or recycle seed which is used by 75.25% of the farmers (Table 4). The most of the farmers collect seed from more than one source. An overall 68.75 % farmers collect seed from Traders/ Dealers where as 19.00% of the farmers use local seed. This is a common practice of farmers in most countries like India (Gildemacher *et al.*, 2009). However, the recycled seed tends to lose attributes preferred by farmers such

Table 3. Varieties and attributes of potato seed used by respondents

Potato varieties	Attributes	Frequency of respondents	Percentages (%) of respondents
Kufri Joyti	Tuber is round, ceramist white with shallow eyes	275	68.75
Kufri Chandramukhi	Tuber is white, smooth, large oval flattened, fleet eyes	174	43.5
Kufri Khyati	Light yellow skin, oval shape, medium in size, resistant to disease, marketable	87	21.75
Kufri Himalini	Brown skin, oval shape, high yielding, resistant to pest	76	19.00
Kufri Lalit	Light red skin, round and medium size, pale yellow flesh.	165	41.25
Kufri Pukhraj	Tuber are oval, yellow with deep eyes, low storage quality	197	49.25

Table 4. The potato seed sources and percentages (%) of respondents.

Sources of Potato seeds	Frequency of respondents	Percentages of respondents
Farmers own seed	301	75.25
Neighbours	74	18.5
Other company seed	103	25.75
Local seed producer	76	19.00
Direct from imports	105	26.50
NGO	00	0.00
Traders/ Dealers	275	68.75

as vigour and pest's resistant which leads to low cultivation level. Gap between the actual and potential yield has been minimised by enhancing the seed replacement rate (Kharumnuid, 2021).

Constraints in potato cultivation and storage

Potato farmers in West Bengal face a lot of potato cultivation and storage constraints (Lal *et al.*, 2011). Ten constraints in potato cultivation and five constraints in potato storage have been identified during

Table 5. Constraints in potato cultivation and storage

Types of constraints	Constraints number	Constraint's description	Frequency	(%)
Cultivation	Constraint 1	Accessing quality seeds at affordable prices	345	86.25
	Constraint 2	Low and fluctuating prices at peak harvest period	276	69.00
	Constraint 3	Combating pest and disease	288	72.00
	Constraint 4	The risk of crop failure or yield loss due to moisture stress on rainfall	324	81.00
	Constraint 5	Lack of irrigation facilities	76	19.00
	Constraint 6	Lack of farmers training facilities	78	19.50
	Constraint 7	High price and non-availability in time of pesticides and fertilizers	267	66.75
	Constraint 8	Weed infestation	79	19.75
	Constraint 9	Labour crisis	255	63.75
	Constraint 10	Soil fertility management & technology	154	38.00
Storage	Constraint 11	Lack of modern cold storage facilities	301	75.25
	Constraint 12	High cold storage charge	309	77.25
	Constraint 13	Lack of adequate transportation facilities	177	44.25
	Constraint 14	Pest attack in storage	56	14.00
	Constraint 15	Reliable technology for cold storage maintenance	76	19.00

assessment and the same is presented in Table 5 with description, frequency and percentages of respondents facing these constraints.

Computation of risk priority number (RPN) and risk assessment matrix

As part of Failure Modes and Effects Analysis (FMEA), the RPN in potato cultivation and storage has been calculated using Eq. (1) and the same are shown in Table 6, Table 7 and Fig.3, Fig.4 respectively. The numerical risks assignment of potato cultivation and storage with occurrence and severity value is shown in Table 8. The risk assessment matrix (risk control matrix) in potato cultivation and storage with risks level of all constraints are shown in Fig. 5.

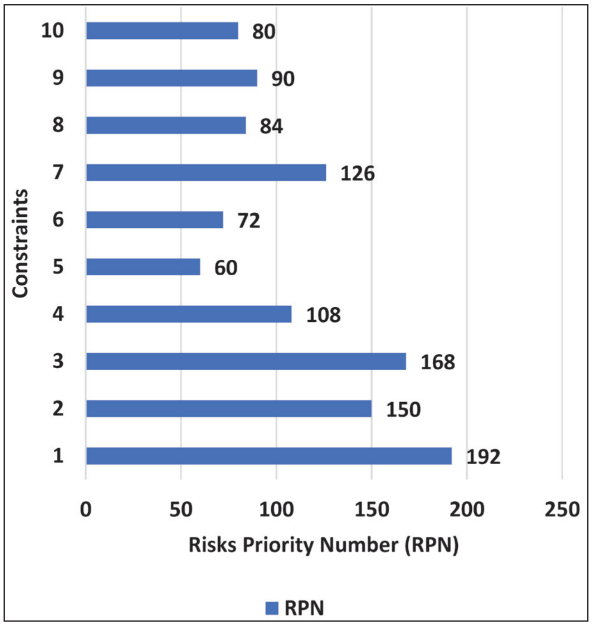


Fig. 3. Risk Priority Number (RPN) in potato cultivation

Table 6. The Risks Priority Number of FMEA in potato cultivation

Aim	Requirement	Failure Mode Or constraint	Effects	Severity (S)	Cause	Control methods			Detection (D)	RPN = O× S× D
						Prevention control	Occurrence (O)	Detection Control		
Improvement of potato productivity in West Bengal	Improvement of potato yield & quality	Quality seed	Low yield & crop failure	8	Unreliable sources	Planting certified seed	6	High yield & healthier plants	4	192
		Low & fluctuating price at peak harvest time	Farmer financial loss	5	Unbalanced supply & demand	Government purchase	6	Farmer profit & low post harvest loss	5	150
		Pest & disease	Crop failure & low yield	7	Climate & seed	Proper use of pesticide	6	High yield & quality	4	168
		Rainfall	Crop failure	9	Climate	Land orientation & Drainage	4	Yield & quality	3	108
		Irrigation	Crop growth	5	Source of water	Government policy	4	Irrigation system	3	60
		Farmer training	Pest & disease control	6	Training strategy	Training camp	4	Farmer knowledge	3	72
		Pesticides & fertilizer	Yield & growth	7	Supply	Proper application	6	Yield & growth	3	126
		Weed infestation	Growth & yield	7	Seed & climate	Weed management	4	Plant growth	3	84
		Labour crisis	Delay time of planting	6	Demand & supply	Use modern technology	5	Harvesting time	3	90
		Soil fertility management & technology	Planting time	5	Modern technology	Research & development	4	Plant growth	4	80

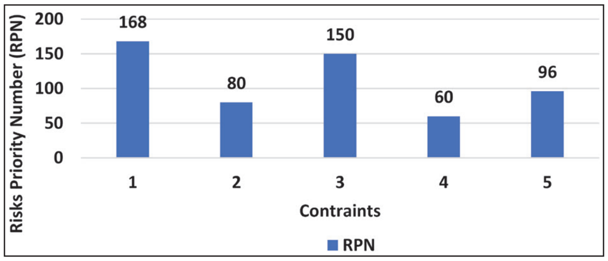


Fig.4. Risk Priority Number (RPN) in potato storage

It is evident from Fig. 5 that, constraints (1,3,4,7,8,11) and (2,5,6,9,10,12,13,14,15) are under high level and medium level risks respectively. The interpretation of the risk assessment has been presented in Table 9 which provides a glimpse on likely remedial actions for lowering of these risks.

Table 7. RPN of Failure Modes and Effects Analysis in potato storage.

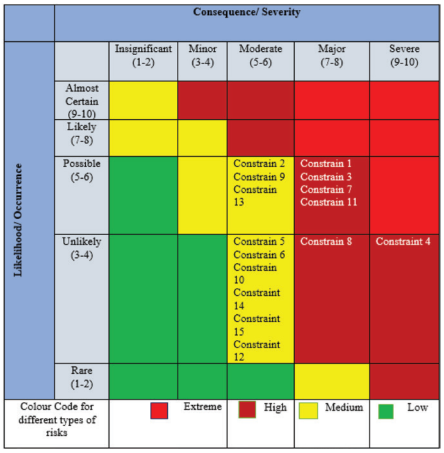
Aim	Requirement	Failure Mode of constraint	Effects	Severity (S)	Cause	Control methods			Detection (D)	RPN = S× O× D
						Prevention Control	Occurrence (O)	Detection Control		
Improvement of potato productivity in West Bengal	Improvement of post-harvest losses	Modern cold storage	Low post harvest loss	7	Modern Technology	Research & Development	6	Post-harvest loss & edible quality	4	168
		Storage charge	Market price	5	Government policy Energy & Labour	Electric energy charge & Labour control	4	Market price	4	80
		Transportation	Improve supply chain	6	Roads & fuel charge	Infrastructure development	5	Carrying charge	3	90
		Pest	Quality & post-harvest loss	5	Pest Management	Pesticides	4	Post-harvest loss	3	60
		Reliable Technology	Maintenance & Material handling	6	Research & Development	Apply modern technology	4	Safety	4	96

Table 8. The risk assessment in potato cultivation and storage

Types of constraints	Constrains	Constrains description	Occurrence	Severity	Risk
Cultivation	Constraint 1	Accessing quality seeds at affordable prices	6	8	High
	Constraint 2	Low and fluctuating prices at peak harvest period	6	5	Medium
	Constraint 3	Combating pest and disease	6	7	High
	Constraint 4	The risk of crop failure or yield loss due to moisture stress on rainfall	4	9	High
	Constraint 5	Lack of irrigation facilities	4	5	Low
	Constraint 6	Lack of farmers training facilities	4	3	Low
	Constraint 7	High price and non-availability in time of pesticides and fertilizers	6	7	High
	Constraint 8	Weed infestation	4	7	High
	Constraint 9	Labour crisis	5	6	Medium
	Constraint 10	Soil fertility management & technology	4	5	Low
Storage	Constraint 11	Lack of modern cold storage facilities	3	7	High
	Constraint 12	High cold storage charge	4	5	Medium
	Constraint 13	Lack of adequate transportation facilities	5	6	Medium
	Constraint 14	Pest attack in storage	4	5	Medium
	Constraint 15	Reliable technology for cold storage maintenance	4	6	Medium

Table 9. Interpretations of the findings of risk assessment of constraints

Level of risk	Constraint No.	Constraint's description	Likely remedial actions
High	1	Accessing quality seeds at affordable prices	Farmers can adopt innovative seed technologies and use certified seed from cooperatives or producer groups.
	3	Combating pest and disease	Farmers should adopt integrated pest management (IPM), use disease-resistant varieties and follow proper crop rotation and sanitation practice.
	4	The risk of crop failure or yield loss due to moisture stress on rainfall	Farmers should adopt precision irrigation, use drought-tolerant varieties and improve soil moisture retention through mulching and organic amendments.
	7	High price and non-availability in time of pesticides and fertilizers	Farmer Producer Organizations (FPOs) can negotiate bulk discounts and ensure timely delivery of inputs. Cooperatives can maintain local warehouses for fertilizers and pesticides, reducing dependency on distant suppliers.
	11	Lack of modern cold storage facilities	Farmers and stakeholders should invest in decentralized storage solutions, adopt energy-efficient technologies, and leverage government and private sector support for infrastructure.
Medium	2	Low and fluctuating prices at peak harvest period	Farmers should adopt staggered marketing, invest in decentralized cold storage and leverage digital platforms and cooperative models to access better markets and price stability.
	5	Lack of irrigation facilities	Farmers should adopt water-efficient technologies like drip irrigation, use mulching and drought-tolerant varieties and tap into government schemes for infrastructure support.
	6	Lack of farmers training facilities	Stakeholders should expand access to agricultural universities, promote mobile-based learning.
	9	Labour crisis	Farmers should adopt mechanization, invest in smart technologies like agricultural robots and streamline operations through cooperative models and training programs.
	10	Soil fertility management & technology	Farmers should adopt precision fertilization, integrate organic and bio-based inputs and use digital tools for nutrient monitoring and soil health mapping.
	12	High cold storage charge	Adopting decentralized mini cold storage units, forming cooperatives for shared storage and leveraging government subsidies and energy-efficient technology.
	14	Pest attack in storage	Maintain strict hygiene, control temperature and humidity precisely, and use safe fumigation or natural repellents.
	15	Reliable technology for cold storage maintenance	Cold storage owners and operators should adopt smart monitoring systems, energy-efficient designs and predictive automation technologies.



		Consequence/ Severity				
Likelihood/ Occurrence		Insignificant (1-2)	Minor (3-4)	Moderate (5-6)	Major (7-8)	Severe (9-10)
	Almost Certain (9-10)					
	Likely (7-8)					
	Possible (5-6)			Constrain 2 Constrain 9 Constrain 13	Constrain 1 Constrain 3 Constrain 7 Constrain 11	
	Unlikely (3-4)			Constrain 5 Constrain 6 Constrain 10 Constraint 14 Constraint 15 Constraint 12	Constrain 8	Constraint 4
	Rare (1-2)					
Colour Code for different types of risks		🟥 Extreme		🟥 High	🟨 Medium	🟩 Low

Fig.5. Risk assessment matrix in potato cultivation and storage

CONCLUSION

Present research has been conducted to assess the current scenario and the major constraints in potato cultivation and storage along with the associated risks in the state of west Bengal. The study provides risk information through risk assessment matrix based on farmers' knowledge regarding potato cultivation and storage. The application of such control measures and knowledge acquired through training and community agriculture information sources could be keys to improving potato productivity in the state of West Bengal. Data Showes that major growers of potato are male and the Kufri Joyti is the most popular potato variety among them. Majority of the framers used their own seed for potato cultivation. Non-availability of quality seed and high price are the major constraints of potato cultivation for the farmers. The quality seed as well as other input need to be available to the potato growers in time at reasonable price. This research will be helpful to the planners and policy makers in contriving micro and macro level policy for the enlargement of potato production in West Bengal.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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GENETIC DIVERSITY AND MULTIVARIATE ANALYSIS OF YIELD PERFORMANCE TRAITS IN POTATO

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ABSTRACT: The present study investigated the genetic diversity and yield performance traits in 332 potato accessions evaluated in 2020 and 366 accessions in 2021 at ICAR-Central Potato Research Institute, Regional Station, Modipuram. An augmented design, was used to assess the marketable tuber yield (MTY), non-marketable tuber yield (NMTY), total tuber yield (TTY), specific gravity (SG), and plant maturity (PM). Significant genetic variation was observed, with heritability values exceeding 90% for key traits like TTY and MTY. Principal component analysis (PCA) identified marketable and total tuber yield as primary contributors to variability, which explained 63.2% of the total variance. The formation of four distinct clusters (red, blue, green, and black) in the present investigation highlights the presence of subgroups with shared traits. Hierarchical clustering highlighted the potential of combining the yield related traits of Tuberosum accessions, the genetic diversity of Andigena accessions (*Solanum tuberosum* Andigena group), and the regional adaptability of Indian varieties to develop superior potato cultivars with improved yield. Key accessions, including JEX/A-459 and Kufri Pushkar, exhibited superior yield performance, which can be a promising candidate for breeding programs.

KEYWORDS: Genetic diversity, marketable tuber yield, specific gravity, principal component analysis, hierarchical clustering.

Abbreviations: PM – Plant maturity, MT – Marketable tuber number, NMT – Non-Marketable tuber number, MTY – Marketable tuber yield, NMTY – Non-Marketable tuber yield, TTY – Total tuber yield, SG – Specific gravity.

INTRODUCTION

Potato (*Solanum tuberosum* L., 2n = 4x = 48) originated from the Titicaca Lake basin in the Peruvian and Bolivian Andes, is the world's most important non-grain food crop after rice and wheat (Sood *et al.,* 2024). This crop contributed vital role in food security and serves as a significant source of carbohydrates, vitamins, and minerals for millions of people worldwide (Mangal *et al.,* 2022).

Along with its important role in food security, potato have unique genetic traits and a rich cultural history, which makes this crop valuable for both agricultural and genetic research (Datta *et al.,* 2015). In India, potato cultivation holds a crucial role in agriculture, which contributes significantly to both domestic consumption and the agricultural economy. The growing demand for high

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yielding varieties with improved tuber quality traits, and challenges such as climate change, pests and diseases, highlights the need for superior potato varieties through continuous breeding efforts.

Genetic variability is backbone for breeding potato varieties with improved disease resistance, better environmental adaptability and high yield (Mangal *et al.,* 2024). It provides new alleles for complex traits and strengthen the genetic base for sustainable crop development (Deperi *et al.,* 2018). For achieving this all our breeding activities mainly depends on the genetic diversity within available germplasm, which needs comprehensive evaluation of their phenotypic and genotypic diversity (Esnault *et al.*, 2014). Phenotypic diversity present among the cultivated potato varieties or germplasm is essential for breeding and adaptation to diverse environments (Abebe *et al.,* 2013). Evaluating phenotypic variation among potato accessions based on agro-morphological traits and yield attributes is essential for identifying valuable genetic traits and enhancing strategies for adaptation (Ahmadizadeh and Felenji 2011). Despite a wide genetic diversity available in the potato germplasm, most cultivated varieties have a narrow genetic base, due to prolonged selective breeding focus on few traits only (Bhardwaj *et al.,* 2023). Breeding programs aim to improve potato yield and quality by selecting accessions with desirable agronomic traits, such as high marketable or total tuber yield, diseases resistance, and adaptability to diverse environmental conditions. The genetic improvement of potatoes is complex due to its heterozygous and tetraploid nature, which complicates the inheritance patterns of key yield contributing traits. However, the extensive genetic diversity within potato populations offers significant opportunities and challenges for breeders seeking to integrate multiple desirable traits into new varieties.

To tackle all these challenges, a comprehensive evaluation of a large number of genotypes is essential. In the augmented design, check varieties are replicated across blocks, which enable the evaluation of a large number of accessions with reduced resources and useful in preliminary breeding trials to identify promising accessions for further testing. Principal component analysis (PCA) is utilized to explore the relationships among the studied traits and to identify variability in the dataset. Additionally, hierarchical clustering is employed to assess the genetic and phenotypic diversity among the accessions, which enable the identification of distinct clusters that could serve for future breeding efforts.

The present study provides valuable insights into the genetic diversity and yield potential of a diverse collection of potato accessions, which provides critical information for breeding programs focusing on developing high yielding new varieties. The use of statistical methods, such as PCA and hierarchical clustering, facilitates a deeper understanding of the complex relationships among traits and help in the identification high-yielding potato accession to enhance food security.

MATERIAL AND METHODS

Experimental site

The experiment was carried out at the ICAR-Central Potato Research Institute (CPRI), Regional Station, Modipuram, Meerut, during the rabi seasons (October to February) of 2020 and 2021. The geographical location of the station is 29.033°N latitude, 77.683°E longitude, with an elevation of approximately 237 meters above sea level. The region experiences a subtropical climate, characterized by hot summers and cool winters, which is suitable for potato cultivation.

An augmented design was used to evaluate a large number of accessions efficiently: 332 accessions in year 2020, 366 in year 2021, with 319 accessions common during both the years (Table 1). In the year 2020 studies, blocks 1 to 7 each comprised of 42 test accessions along with 4 replicated check varieties, whereas block 8 included 34 accessions and 4 checks. In the year 2021 experiment, blocks 1, 2, 4, 5 and 6 comprised of 46 test accessions and 4 checks, block 3 contained 45 test accessions and 4 checks, block 7 included 43 test accessions and 4 checks, and block 8 comprised 44 test accessions and 4 checks. All accessions used were obtained from the ICAR-Central Potato Research Institute (ICAR-CPRI), where they are conserved in the *in-vitro* form. A total of four check varieties were used, Kufri Jyoti, Kufri Chipsona-1, Kufri Himalini, and Kufri Girdhari. The accessions used in this study belonged to three groups: CP (*Solanum tuberosum*, Tuberosum group) for high-yielding cultivated lines, JEX-A (*Solanum tuberosum*, Andigena group) for genetic diversity and stress tolerance, and Kufri (Indian varieties) bred for regional adaptability. Standard agronomic practices recommended for potato cultivation in the region were followed

Table 1. List of potato accessions used in the study.

S. No.	Accession	S. No.	Accession	S. No.	Accession	S. No.	Accession	S. No.	Accession	S. No.	Accession	S. No.	Accession	S. No.	Accession
1	CP1012	26	CP1347	51	CP1462	76	CP1642	101	CP1753	126	CP1982	151	CP2224	176	CP3079
2	CP1038	27	CP1348	52	CP1468	77	CP1646	102	CP1764	127	CP1988	152	CP2235	177	CP3081
3	CP1137	28	CP1367	53	CP1470	78	CP1653	103	CP1767	128	CP1989	153	CP2284	178	CP3096
4	CP1140	29	CP1368	54	CP1479	79	CP1659	104	CP1784	129	CP1990	154	CP2285	179	CP3098
5	CP1143	30	CP1379	55	CP1480	80	CP1662	105	CP1800	130	CP2010	155	CP2321	180	CP3102
6	CP1151	31	CP1390	56	CP1486	81	CP1664	106	CP1802	131	CP2011	156	CP2324	181	CP3103
7	CP1157	32	CP1395	57	CP1491	82	CP1667	107	CP1806	132	CP2029	157	CP2335	182	CP3106
8	CP1159	33	CP1399	58	CP1529	83	CP1668	108	CP1824	133	CP2030	158	CP2338	183	CP3116
9	CP1175	34	CP1402	59	CP1533	84	CP1669	109	CP1827	134	CP2049	159	CP2339	184	CP3124
10	CP1177	35	CP1405	60	CP1538	85	CP1672	110	CP1835	135	CP2059	160	CP2346	185	CP3145
11	CP1187	36	CP1411	61	CP1544	86	CP1673	111	CP1846	136	CP2061	161	CP2347	186	CP3153
12	CP1215	37	CP1414	62	CP 1545	87	CP1674	112	CP1854	137	CP2065	162	CP2348	187	CP3171
13	CP1218	38	CP1418	63	CP1553	88	CP1685	113	CP1864	138	CP2071	163	CP2350	188	CP3173
14	CP1225	39	CP1420	64	CP1555	89	CP1687	114	CP1868	139	CP2086	164	CP2364	189	CP3180
15	CP1235	40	CP1426	65	CP1559	90	CP1688	115	CP1869	140	CP2089	165	CP2368	190	CP3182
16	CP1246	41	CP1427	66	CP1564	91	CP1693	116	CP1871	141	CP2090	166	CP2370	191	CP3183
17	CP1263	42	CP1428	67	CP1571	92	CP1700	117	CP1873	142	CP2110	167	CP2385	192	CP3189
18	CP1291	43	CP1431	68	CP1581	93	CP1706	118	CP1881	143	CP2118	168	CP2390	193	CP3192
19	CP1302	44	CP1433	69	CP1584	94	CP1710	119	CP1884	144	CP2134	169	CP2412	194	CP3201
20	CP1304	45	CP1435	70	CP1588	95	CP1711	120	CP1889	145	CP2142	170	CP2418	195	CP3203
21	CP1319	46	CP1440	71	CP1597	96	CP1730	121	CP1918	146	CP2149	171	CP2927	196	CP3211
22	CP1325	47	CP1447	72	CP1602	97	CP1735	122	CP1922	147	CP2165	172	CP3036	197	CP3222
23	CP1326	48	CP1450	73	CP1616	98	CP1736	123	CP1926	148	CP2171	173	CP3044	198	CP3246
24	CP1330	49	CP1453	74	CP1619	99	CP1747	124	CP1971	149	CP2183	174	CP3068	199	CP3247

S. No.	Accession	S. No.	Accession	S. No.	Accession	S. No.	Accession	S. No.	Accession	S. No.	Accession	S. No.	Accession	S. No.	Accession
25	CP1335	50	CP1454	75	CP1633	100	CP1749	125	CP1974	150	CP2189	175	CP3072	200	CP3256
201	CP3261	226	CP3549	251	CP3792	276	CP4214	301	JEX/A-202	326	JEX/A-468	351	JEX/A-93	376	K. Sadabahar
202	CP3274	227	CP3575	252	CP3795	277	CP4224	302	JEX/A-21	327	JEX/A-498	352	JEX/A-947	377	Kufri Sindhuri
203	CP3295	228	CP3577	253	CP3796	278	CP4242	303	JEX/A-215	328	JEX/A-506	353	JEX/A-99	378	K. Surya
204	CP3296	229	CP3585	254	CP3797	279	CP4254	304	JEX/A-22	329	JEX/A-513	354	KCM	379	K. Swarna
205	CP3318	230	CP3587	255	CP 3799	280	CP4256	305	JEX/A-232	330	JEX/A-539	355	Kufri Anand		
206	CP3328	231	CP3588	256	CP3809	281	CP4311	306	JEX/A-26	331	JEX/A-58	356	Kufri Arun		
207	CP3329	232	CP3600	257	CP3816	282	CP4316	307	JEX/A-267	332	JEX/A-597	357	Kufri Ashoka		
208	CP3334	233	CP3625	258	CP3853	283	CP4398	308	JEX/A-275	333	JEX/A-612	358	Kufri Badshah		
209	CP3352	234	CP3632	259	CP3867	284	CP4593	309	JEX/A-288	334	JEX/A-638	359	Kufri Bahar		
210	CP3362	235	CP3634	260	CP3871	285	CP4594	310	JEX/A-296	335	JEX/A-668	360	K. Chipsona-1		
211	CP3363	236	CP3636	261	CP3880	286	CP4596	311	JEX/A-298	336	JEX/A-683	361	K. Chipsona-3		
212	CP3412	237	CP3639	262	CP3881	287	CP655	312	JEX/A-299	337	JEX/A-705	362	Kufri Dewa		
213	CP3414	238	CP3641	263	CP3885	288	CP658	313	JEX/A-30	338	JEX/A-707	363	Kufri Frysona		
214	CP3442	239	CP3646	264	CP3891	289	CP659	314	JEX/A-316	339	JEX/A-708	364	Kufri Garima		
215	CP3443	240	CP3651	265	CP3893	290	JEX/A-10	315	JEX/A-317	340	JEX/A-763	365	Kufri Gaurav		
216	CP3475	241	CP3652	266	CP3894	291	JEX/A-1016	316	JEX/A-32	341	JEX/A-79	366	Kufri Girdhari		
217	CP3486	242	CP3679	267	CP3898	292	JEX/A-1038	317	JEX/A-329	342	JEX/A-801	367	Kufri Himalini		
218	CP3491	243	CP3681	268	CP3901	293	JEX/A-1046	318	JEX/A-361	343	JEX/A-804	368	Kufri Jyoti		
219	CP3502	244	CP3690	269	CP3903	294	JEX/A-1081	319	JEX/A-379	344	JEX/A-827	369	Kufri Kanchan		
220	CP3505	245	CP3696	270	CP3917	295	JEX/A-1092	320	JEX/A-380	345	JEX/A-865	370	Kufri Karan		
221	CP3506	246	CP3718	271	CP3939	296	JEX/A-1152	321	JEX/A-390	346	JEX/A-877	371	Kufri Khyati		
222	CP3511	247	CP3738	272	CP4052	297	JEX/A-15	322	JEX/A-42	347	JEX/A-907	372	Kufri Lauvkar		
223	CP3525	248	CP3761	273	CP4096	298	JEX/A-164	323	JEX/A-45	348	JEX/A-912	373	Kufri Megha		
224	CP3527	249	CP3763	274	CP4149	299	JEX/A-19	324	JEX/A-457	349	JEX/A-918	374	Kufri Pukhraj		
225	CP3529	250	CP3768	275	CP4179	300	JEX/A-197	325	JEX/A-459	350	JEX/A-920	375	Kufri Pushkar		

throughout the growing seasons. Each accession was grown in a single-row plot of 3m length, with a row-to-row spacing of 60 cm and plant-to-plant spacing of 20 cm, which accommodate 15 plants per plot. The replicated check varieties were distributed across the blocks for statistical adjustments.

Crop management: The crop was raised in the winter season (October - February). Fields were ploughed and levelled before planting. The farmyard manure @ 10-15 t/ha and N:P:K fertilizer was applied @180:80:100 kg/ha during both the years. Full FYM, full P and K while half N fertilizer were applied at the time of field preparation. Rest half of the nitrogen was applied at the time of earthing up, 30-40 days after planting. Well sprouted tubers of size 40-60 g were planted manually across the locations. Pre-emergence herbicide, metribuzin @ 0.7-1.0 g/l was applied for weed control followed by one manual weeding within a month after planting. Pre-sowing irrigation was given for uniform germination followed by four irrigations at 10-15 days interval as per the need and soil type. The crop was sprayed with insecticides and fungicides to manage the insect pests and late blight disease at 15-20 days interval thrice after earthing up. The dehaulming and harvesting were done at 90 and 105 days after planting, respectively.

Data collection and observations

1. **Marketable tuber (MT) number:** Tubers were harvested at maturity, sorted based on market standards (typically size), and counted to determine the number of marketable tubers (MT).
2. **Marketable Tuber Yield (MTY):** MT were then weighed to measure the yield, which was recorded in kg per plot basis and converted to tons per hectare.
3. **Non-Marketable tuber (NMT, no./plant):** Tubers at the time of harvesting which did not meet proper size and weight were classified as non-marketable.
4. **Non-Marketable Tuber Yield (NMTY):** NMT tubers were counted, weighed, and the yield was recorded in kg per plot basis and extrapolated to tons per hectare.
5. **Total Tuber Yield (TTY):** The total tuber yield was determined by summing the marketable and non-marketable tuber yields, recorded in kg per plot basis and converted to tons per hectare.
6. **Specific Gravity (SG):** This trait was measured using the standard water displacement method, wherein tuber samples were immersed in water, and the volume of displaced water was measured. The formula used for specific gravity was:

   Specific gravity = Weight of tubers in air)/(Weight of tubers in air-weight of tubers in water)
7. **Plant Maturity (PM):** Physiological maturity was determined by observing the natural senescence of the foliage at 90 days after planting. Maturity was recorded as a numerical percentage, which represent the proportion of foliage that had senesced.

Data Analysis

The analysis was performed using various R packages essential for multivariate data analysis and visualization. The *FactoMineR* package (Husson *et al.,* 2016) was used for PCA and *factoextra* (Kassambara & Mundt, 2017) helped to visualize the results. Package *ggplot2* (Wickham & Wickham, 2016) was used to generate quality graphs, and *corrplot* (Wei *et al.,* 2013) was used for visualizing correlation matrices. Data manipulation and cleaning were done with *tidyverse* (Wickham *et al.,* 2016) and *dplyr* (Wickham & Wickham, 2020) package in R.

RESULTS

The use of an augmented design in this experiment facilitated the evaluation of a large number of potato accessions with minimum resources and also maintained statistical robustness. The incorporation of replicated check varieties among the blocks enabled accurate variance estimation and adjustment for block effects. The results also revealed significant differences among test genotypes and checks, which demonstrated the effectiveness of this design in distinguishing superior accessions. The ANOVA demonstrated significant variation among treatments, which indicates substantial phenotypic differences in the evaluated accessions (Table 2). Significant block effects indicated environmental heterogeneity across blocks, which was effectively adjusted for result accuracy. The checks vs. accessions comparison showed the presence of superior accessions compared to standard checks (Kufri Jyoti, Kufri Chipsona-1, Kufri Himalini and Kufri Girdhari).

The genetic parameters for yield and its contributing traits in 2020 and 2021 revealed significant variability for key traits. In 2020, total tuber yield (TTY) exhibited a high genotypic coefficient of variation (GCV) of 36.03%, phenotypic coefficient of variation (PCV) of 36.58%, and a low environmental coefficient of variation (ECV) of 6.36%, with heritability (H^2) of 96.98% and genetic advance as a percentage of mean (GAM) of 73.19%, which indicate strong genetic influence and improvement potential (Table 4). The highest TTY was recorded in the accession JEX/A-459 (24.23 t/ha) and the lowest in JEX/A-21 (1.73 t/ha) (Table 3). Other accessions which exhibited high yield were CP2086 (24.15 t/ha) followed by CP3898 (23.95 t/ha), CP2142 (23.81 t/ha) and CP1330 (23.4 t/ha). Similarly, marketable tuber yield (MTY) showed a GCV of 40.6%, PCV of 41.12%, ECV of 6.52%, with H^2 = 97.49% and

Table 2. Analysis of variance (ANOVA) for agronomic traits across two years (2020 and 2021).

Source	Df		MT		MTY		NMT		NMTY		SG		TTY		PM
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2021
Treatment (ignoring Blocks)	331	365	2561.79**	3238.97ns	22.81**	15.9**	4236.58**	11141.83**	0.64**	0.9**	8.2e-05ns	8.1e-05**	22.76**	15.9**	17.54**
Treatment: Check	3	3	640.2*	4462.95ns	8.25**	5.57*	1849.08**	3220.83ns	0.38ns	0.18ns	0.0014**	0.00074**	9.21**	5.25*	27.08**
Treatment: Test vs. Check	1	1	56.91ns	40164.02**	211.08**	324.26**	1742.9**	42931.69**	2.53**	1.11ns	3.9e-05ns	0.00019**	259.84**	287.41**	137.82**
Treatment: Test	327	361	2587.08**	3126.51ns	22.37**	15.13**	4266.11**	11119.59**	0.64**	0.91**	6.9e-05ns	7.6e-05**	22.16**	15.23**	17.12**
Block (eliminating Treatments)	7	7	340.71ns	2547.17ns	0.38ns	6.19**	1284.21**	1526.79ns	0.64**	0.3ns	5e-05ns	9.9e-06ns	1.58ns	5.26**	5.36ns
Residuals	21	21	174.75	2533.42	0.56	1.4	209.65	1126.19	0.16	0.26	7.20e-05	2.10e-05	0.67	1.27	3.27

GAM = 82.69%. Accession CP 2142 exhibited highest MTY (22.94 t/ha), whereas andigena accession JEX/A-865 recorded the lowest (0.32 t/ha) MTY. The non-marketable tuber yield (NMTY) exhibited GCV = 50.72%, PCV = 58.3%, and ECV = 28.76%, with moderate heritability (75.67%) and GAM = 91.01%.

In 2021, a slight reduction in genetic control was observed. TTY had a GCV of 33.0%, PCV of 34.46%, and ECV of 9.94%, with H^2 of 91.69% and GAM = 65.19%. Indian variety Kufri Pushkar recorded the highest TTY (23.98 t/ha) and the andigena accession JEX/A-708 the lowest (2.08 t/ha). Likewise, other accessions which showed high yield were CP1989 (22.91 t/ha), CP3641 (22.28 t/ha) and Kufri Khyati (19.68 t/ha). MTY demonstrated a GCV of 38.92%, PCV of 40.86%, and ECV of 12.43%, with H^2 = 90.75% and GAM = 76.49%. Kufri Pushkar showed the highest MTY (22.0 t/ha), while CP 2011 exhibited the lowest (1.3 t/ha) MTY. The NMTY exhibited a GCV of 44.63%, PCV of 52.75%, and ECV of 28.12%, with H^2 = 71.59% and GAM = 77.91%.

Marketable tuber (MT) number in 2020 recorded GCV of 32.43% and PCV of 33.59%, with high heritability (H^2 = 93.25%) and GAM = 64.61%, while in 2021, environmental influence increased, with H^2 = 18.97%. For non-marketable tuber number (NMT), the GCV and PCV remained high across both years (68.43% and 70.18% in 2020, 61.37% and 64.73% in 2021), reflecting strong genetic control (H^2 = 95.09% in 2020, 89.87% in 2021). The specific

Table 3. Summary of yield and quality traits in potato accessions during 2020 and 2021.

Traits	Mean		Min		Max		Std. Error		Std. Deviation		CV	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
PM	NA	72.24	NA	63.12	NA	89.38	NA	0.21	NA	4.09	NA	2.5
MT	151.44	174.33	11.59	0	282.84	424.47	2.81	3.11	51.21	59.58	8.72	28.44
NMT	93.07	162.9	0	23.75	609.87	781.25	3.61	5.41	65.72	103.5	15.31	20.96
MTY	11.5	9.52	0.32	1.3	22.94	22	0.26	0.2	4.73	3.91	6.4	12.11
NMTY	1.37	1.8	0	0.21	4.56	6.71	0.05	0.05	0.84	0.96	28.14	28.37
TTY	12.87	11.33	1.73	2.08	24.23	23.98	0.26	0.2	4.71	3.89	6.24	9.74
SG	1.06	1.06	1.04	1.04	1.09	1.1	0.00049	0.00046	0.01	0.01	0.79	0.43

NA - This parameter was not measured in the year 2020

Table 4. Genetic variability, heritability, and genetic advance estimates for studied traits in potato accessions during 2020 and 2021.

	GCV		PCV		ECV		H^2 (BS)		GA		GAM	
Trait	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
PM		5.15		5.73		2.5		80.88		6.91		9.56
MT	32.43	13.97	33.59	32.07	8.73	28.87	93.25	18.97	97.84	21.88	64.61	12.55
NMT	68.43	61.37	70.18	64.73	15.56	20.6	95.09	89.87	128.12	195.51	137.66	120.02
MTY	40.6	38.92	41.12	40.86	6.52	12.43	97.49	90.75	9.51	7.28	82.69	76.49
NMTY	50.72	44.63	58.3	52.75	28.76	28.12	75.67	71.59	1.25	1.41	91.01	77.91
TTY	36.03	33	36.58	34.46	6.36	9.94	96.98	91.69	9.42	7.38	73.19	65.19
SG	NA	0.69	0.78	0.82	0.79	0.43	NA	72.23	NA	0.01	NA	1.22

GCV: Genotypic Coefficient of Variation, PCV: Phenotypic Coefficient of Variation, ECV: Environmental Coefficient of Variation, H^2 (BS): Broad Sense Heritability, GA: Genetic Advance, GAM: Genetic Advance as Percentage of Mean.

gravity (SG) remained stable with minimal variability, showing H^2 = 72.23% in 2021.

The year-wise adjusted mean values for the studied traits across the years 2020 and 2021 are presented in Fig. 1 The median values for marketable tuber (MT) number were slightly higher in 2021 compared to 2020, which indicate a higher marketable tuber number in the second year. For non-marketable tuber number (NMT), the median is higher in 2021, and the variability was higher in comparison to 2020. There were several outliers in both years for MT (except 2020) and NMT, which indicate few accessions had very high or few tuber numbers (Fig. 1a). The adjusted mean boxplot for plant maturity (PM) indicated that the majority of the observations fall within a narrow range, with a median value of approximately 73 (Fig. 1b). The median value for specific gravity (SG) during both the years was nearly identical, around 1.07, which indicate consistency in specific gravity values across the years (Fig. 1c). The overall variation for SG was low, with values mostly clustering around 1.06 to 1.07. The year-wise adjusted mean boxplots for tuber yield indicated that marketable tuber yield (MTY) and total tuber yield (TTY) were slightly higher in 2020 compared to 2021, with more variability observed in 2020. Non-marketable tuber yield (NMTY) was consistently low across the years, with minimal impact on overall yield (Fig. 1d).

The bar chart (Fig. 2) illustrates the contribution of different variables to the first two principal components (Dim-1-2). It shows how much each variable contributes to the variation captured by these principal components (PCs), with MTY and TTY contributed the most (each 20-22%), followed by NMT, NMTY and MT. The other traits

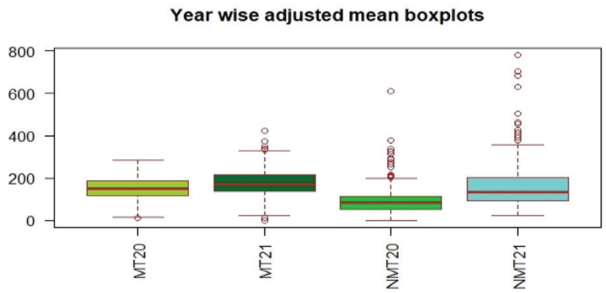

Fig. 1a. Year-wise adjusted mean boxplots for marketable tuber count (MT) and non-marketable tuber count (NMT) in 2020 (MT20, NMT20) and 2021 (MT21, NMT21). The Y-axis represents the number of tubers per plot.

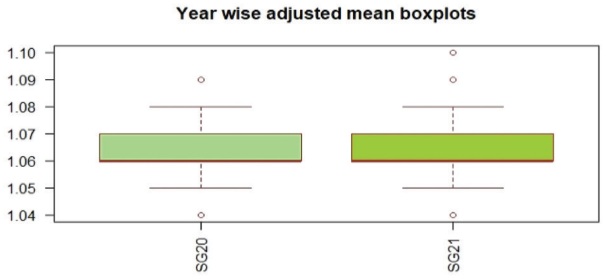

Fig. 1c. Year-wise adjusted mean boxplots for specific gravity (SG) in 2020 (SG20) and 2021 (SG21). The Y-axis represents specific gravity.

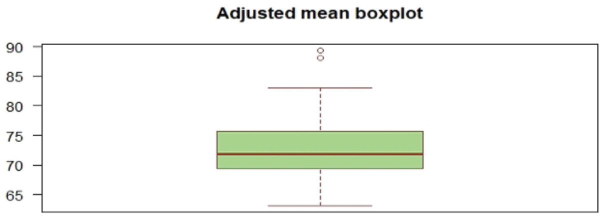

Fig. 1b. Boxplot showing the adjusted mean values for plant maturity (PM) across evaluated potato accessions. The Y-axis represents the number of days to maturity.

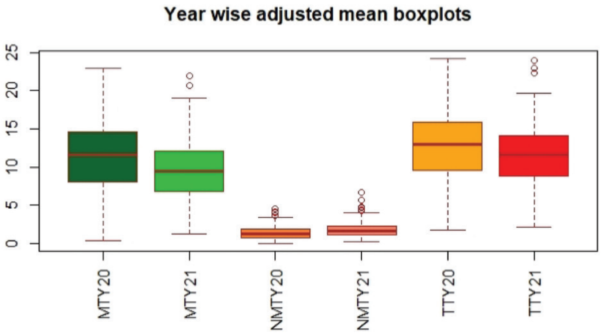

Fig. 1d. Year-wise adjusted mean boxplots for marketable tuber yield (MTY), non-marketable tuber yield (NMTY), and total tuber yield (TTY) in 2020 (suffix '20') and 2021 (suffix '21'). The Y-axis represents yield in tons per hectare (t/ha).

viz., SG and PM showed relatively lower contributions, that suggest these variables have less influence in the first two dimensions of the PCA. Complementing this, the second plot (Fig. 3) presents a correlation matrix between the PCs (Dim 1 to Dim 5) and the original variables (PM, MT, MTY, NMT, NMTY, SG, TTY). The size and colour intensity of the circles indicates the strength and direction of the correlation between each variable and principal component. Dim 1 appears to be heavily influenced by yield-related variables like MTY and TTY. Dimension 4 (Dim 4) showed strong associations with variables like SG and PM, that indicate these components capture variance related to these specific traits.

The correlation matrices for the year 2020 and 2021 in the figure 4 and figure 5 revealed the relationships between yield-related traits in potato. In both the years, a strong positive correlation was observed between MT, MTY and TTY, that showed increase in the number of marketable tubers is strongly associated with higher yields (both MTY and TTY), with MTY playing a crucial role in contributing to the total tuber yield. Similarly, NMT and NMTY were strongly positively correlated with each other in both years, but they exhibited weak negative correlations with MT, MTY, and TTY. In 2021, PM showed a strong negative correlation with MTY and TTY, indicating that increased maturity may lead to reduced yields, a relationship not prominently seen in 2020.

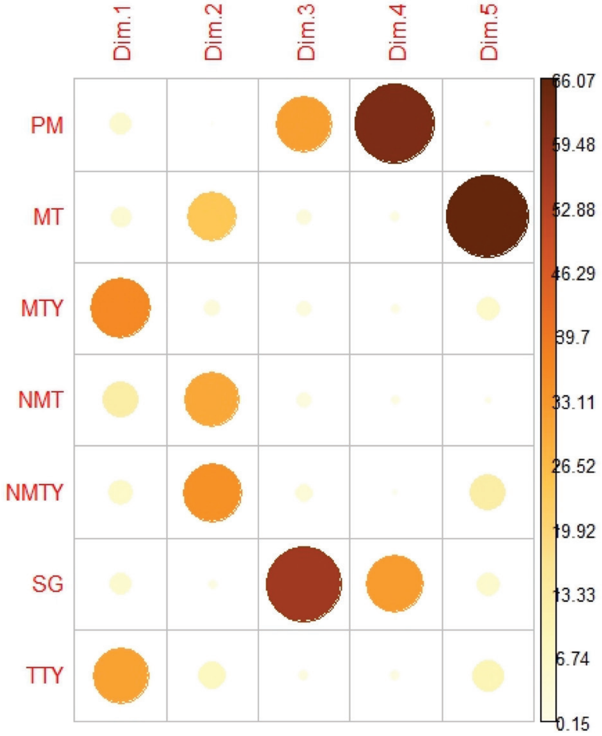

Fig. 3. Correlation between principal components and yield related traits

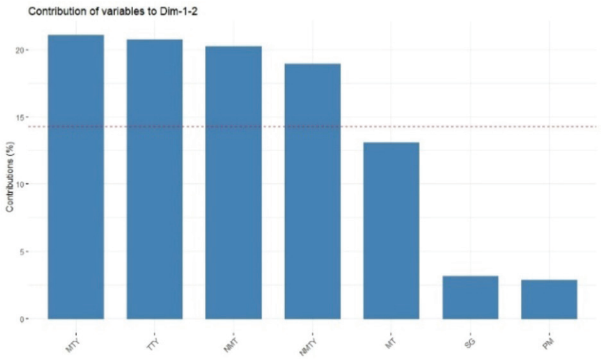

Fig. 2. Contribution of yield and its contributing traits to principal components 1 and 2

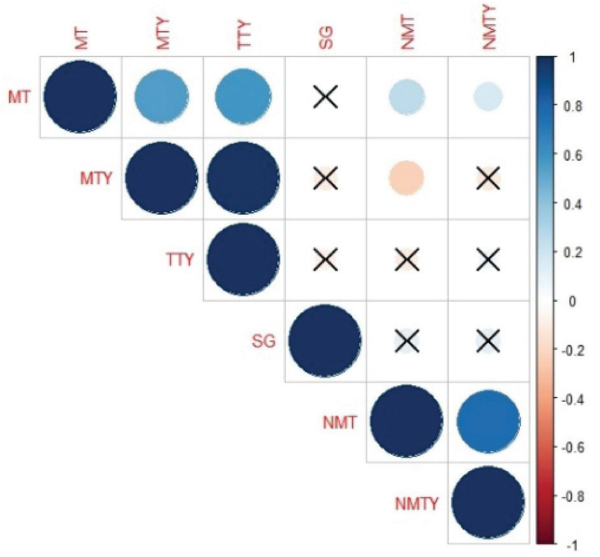

Fig. 4. Pairwise correlation matrix among studied traits (Year 2020)

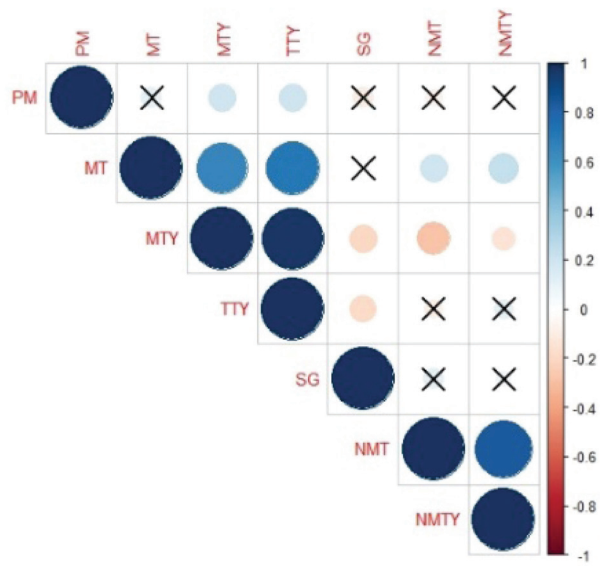

Fig. 5. Correlation matrix of yield and quality traits in potato accessions evaluated in 2021. Traits include plant maturity (PM), marketable tuber number (MT), marketable tuber yield (MTY), total tuber yield (TTY), specific gravity (SG), non-marketable tuber number (NMT), and non-marketable tuber yield (NMTY).

Table 5. Correlation coefficients of variables across principal components (Dim 1 to Dim 5).

Variable	Dim.1	Dim.2	Dim.3	Dim.4	Dim.5
PM	0.35	0.05	-0.55	0.76	0.05
MT	0.32	0.69	0.15	0.11	-0.62
MTY	0.94	0.23	0.15	-0.10	0.18
NMT	-0.55	0.77	-0.15	-0.10	0.06
NMTY	-0.39	0.83	-0.18	-0.07	0.27
SG	-0.35	0.15	0.73	0.55	0.17
TTY	0.88	0.39	0.12	-0.11	0.23
% of variance	34.94	28.32	13.49	13.1	8.27
Cumulative % of variance	34.94	63.26	76.75	89.85	98.12

The first five PCs accounted for almost the entire variability in the data, with the first component explained approximately 34.94% of the total variance, the second component 28.32%, and the third 13.49%. Collectively, the first three PCs captured around 76.75% of the total variance, and by the fifth component, 98.12% of the variance was explained, which showed these components provide a comprehensive representation of the data (Table 5). First PC was heavily influenced by MTY and TTY, contributing 35.98% and 31.31% respectively. These variables were the primary drivers of the variance in this dimension, or in the overall yield performance. Second PC was significantly influenced by NMTY and NMT, with contributions of 34.58% and 29.90%, respectively. This indicates that Dim-2 captured the variability related to non-marketable tuber yield. Dim-3 was dominated by specific gravity, which contributes 56.36%, suggesting that this component was primarily related to the quality aspects of the tubers. The similar things were also represented by PCA biplot in our study (Fig. 6).

Hierarchical clustering of genetic accessions in a circular dendrogram:

The circular dendrogram represented the hierarchical clustering of different accessions based on their genetic or phenotypic similarity, derived from pooled data of two year (Fig. 7). The color-coded clusters in the diagram indicated the distinct groups of similar samples, with red (131 accessions), blue (96), green (44) and black (48) labels which represent the main clusters. The clustering analysis in the current investigation exhibited distinct genetic groupings of the potato accessions, with each cluster provides valuable insights for breeding and genetic improvement programs. The red cluster, comprised of 113 accessions of Tuberosum lines, 15 Andigena, and 3 Indian varieties (Kufri Megha, Kufri Lauvkar, and Kufri Bahar), which exhibited superior performance in TTY and MTY, which provides yield related traits to potato breeding programs. The blue cluster, includes 73 Tuberosum, 18 Indian varieties, and 5 Andigena, showed moderate and stable performance among studied traits, indicating suitability of these

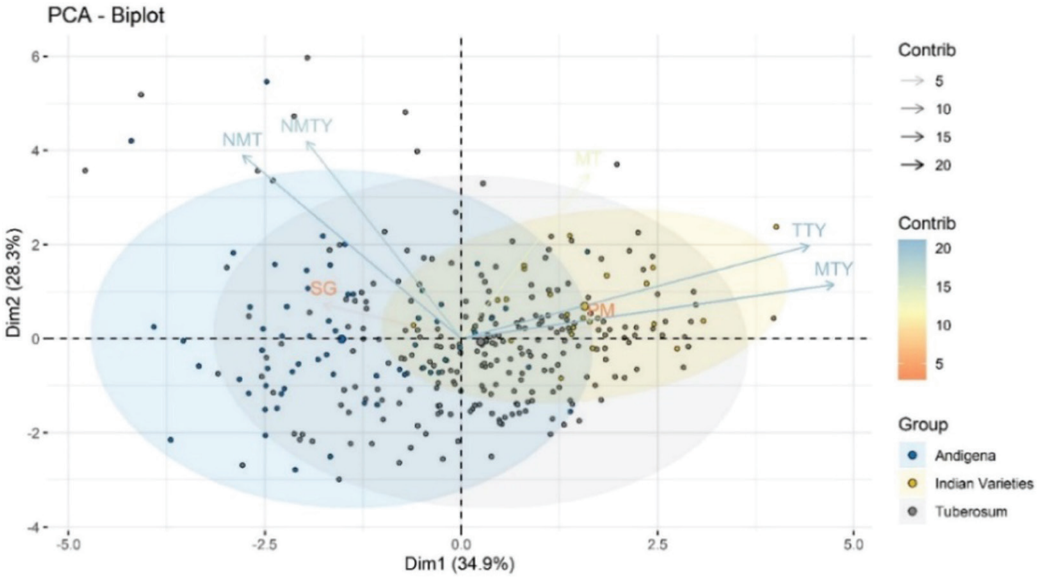

Fig. 6. PCA biplot illustrating the contribution of studied traits across potato accessions

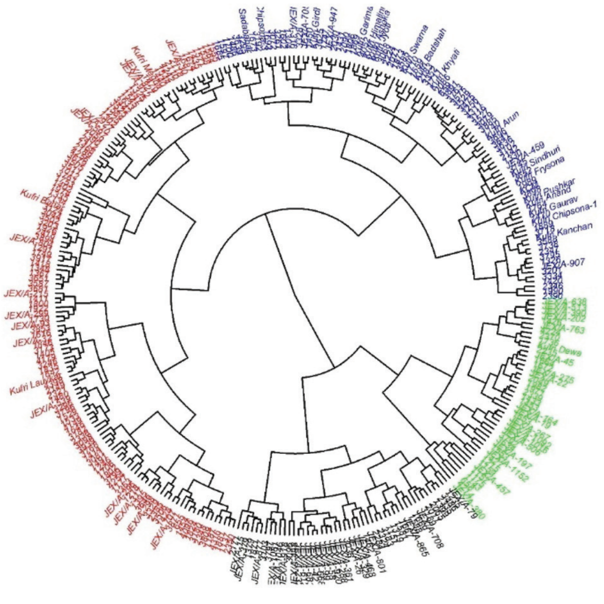

Fig. 7. Phylogenetic clustering of potato accessions based on genetic similarity

accessions for improving adaptability in potato cultivars. The green cluster, comprises of 25 Tuberosum, 18 Andigena, and one Indian variety, demonstrated significant diversity, particularly in traits like specific gravity and plant maturity. These traits are valuable for breeding programs which targets tuber quality and maturity traits. The fourth cluster (black), comprised of 24 Andigena and 24 Tuberosum lines, demonstrated higher variability in non-marketable tuber number and yield. This clustering analysis provides an understanding the genetic or phenotypic diversity within the dataset and identifying closely related groups of samples.

DISCUSSION

The augmented design allowed for the evaluation of a large breeding material through repeated checks among blocks. This is beneficial for genetic diversity studies where a large number of unreplicated test entries need to be assessed under similar field conditions. The findings from this study provide important insights into the genetic diversity, trait variability, and stability of key potato yield and quality traits across different accessions evaluated over two years (2020 and 2021). The integration of PCA and hierarchical clustering enabled a comprehensive understanding of the underlying patterns and relationships among the studied traits.

Year-wise stability and variability in yield traits

The year-wise comparison of yield traits revealed slight variations between the year 2020 and 2021, particularly in yield related traits (MTY and TTY), with higher variability and slightly better performance observed in the year 2020. This variation could be attributed to environmental factors that may have influenced the growth and yield of the potato plants. The stability observed in specific gravity across both the years suggests that this trait is less sensitive to environmental variations and strongly influenced by genetic factors. The consistently low values of NMTY across both years indicated that most of the accessions evaluated had low non-marketable tuber yield, which is a desirable trait for potato improvement. From the current investigation it is clear that MTY and TTY are the key traits with high genetic control (H^2) and genetic advance (GAM), which makes them superior traits for selection in potato breeding programs. Superior accessions such as JEX/A-459, CP 2142, and Kufri Pushkar demonstrated excellent performance, which underscores their potential as parental lines for yield improvement.

Trait variability and principal component analysis

The PCA revealed that majority of the variability in the dataset is captured by the first two PCs, which together accounted for 63.2% of the total variance. The high contribution of yield related traits (MTY and TTY) to Dim1 (PC1) suggested that these traits are the primary contributors of yield performance across the evaluated accessions. These findings align with the previous studies by other researchers which highlighted the importance of marketable yield in their breeding programs. Seid *et al.* (2021) reported that the first six PCs accounted for 88.20% of the total variation among 24 potato accessions, with the first PC alone contributed 34.30%, which underscores key traits for processing quality in potatoes. Tessema *et al.* (2022) used PCA to identify key traits contributing to yield variability among Ethiopian potato varieties, with the first few PCs captured the majority of phenotypic variation. Khan *et al.* (2020) in their study demonstrated that the first two PCs captured around 48.29% of the total variability, which showed complexity and breadth of phenotypic trait variation. Another PCA study showed that the first PC accounted for 33.72% of the variation, followed by the second and third which contributes 16.16% and 10.70%, respectively (Verma and Singh 2016). Ahmadizadeh and Felenji (2011) reported that the first PC accounted for 38.3% of the total variation among potato cultivars, governed by key yield-related traits.

The separation of NMTY and NMT along Dim2 indicates that these traits capture those aspect of variability which were related to factors that reduces marketable tuber yield. The minimal contribution of specific gravity and plant maturity to the first two dimensions suggested that these traits, may have less influence on the overall variability. The correlation matrix allows for an understanding of how each variable correlates with the different principal components. The correlation strength in our study varied across dimensions, which reflects multidimensional nature of the data and the distinct role of each variable in contributing to different aspects of the variance.

The PCA biplot effectively demonstrates how different potato genotypes (Andigena, Indian varieties, Tuberosum) relate to key agricultural traits (MT, MTY, TTY, NMT, NMTY, SG, PM) (Fig. 6). The Indian varieties and the tubersoum genotypes were found to be good for TTY, MTY and MT, while most of the Andigena genotypes had more of NMT and NMTY. This trait distinction clearly revealed that the tuberosum types had good tuber size and yield and must be utilized in breeding programmes.

Genotypic diversity and clustering analysis

The hierarchical clustering analysis revealed valuable insights into the genetic and phenotypic diversity among the evaluated accessions. The formation of four distinct clusters (red, blue, green, and black) in the present investigation highlights the presence of subgroups with shared traits. The distribution of potato accessions across the four identified clusters underscores the genetic diversity within the population, which is crucial for the success of breeding programs for improve specific traits. Abebe *et al.* (2013) revealed three distinct groups among Ethiopian potato varieties in their study, which underscores significant phenotypic diversity that can be leveraged for targeted breeding programs. Through SSR markers and phenotypic traits, Dalamu *et al.* (2024) identified four major genetic clusters in native potato accessions, which highlights genetic diversity valuable for breeding programs to improve resilience and adaptability. Similarly, Datta *et al.* (2015) observed substantial genetic diversity across yield and quality traits, with distinct clusters formed based on tuber weight, tuber count, and dry matter content. Esnault *et al.* (2014) identified distinct genetic clusters within a diverse potato collection, including Chilosé Island landraces and global cultivars, which demonstrated substantial genetic diversity. Ahmadizadeh and Felenji (2011), Khan *et al.* (2013), Iqbal *et al.* (2018), Panigrahsi *et al.* (2014) categorized potato cultivars into two, five, two and seven distinct clusters respectively, based on morphological traits, which showed the effectiveness of phenotypic diversity in targeted breeding. Ghebreslassie *et al.* (2015) used single linkage clustering to classify potato accessions into three main clusters: Group I (average yield traits), Group II (high yield potential), and Group III (lower yield but distinct morphology). This finding highlights the substantial phenotypic diversity within cultivated potatoes. Samiha *et al.* (2024) reported that hierarchical clustering of 62 accessions grouped high-yielding and robust accessions into distinct clusters, which revealed differences in tuber weight, plant height, and dry matter content across clusters. Cluster analysis by Seid *et al.* (2021) categorized 24 potato accessions into six clusters, with accessions in cluster II and VI showed superior traits, such as higher tuber yield, specific gravity, and dry matter content, which were promising candidates for processing breeding programs.

The clustering of accessions with similar yield performance or quality traits suggested that these subgroups may be valuable for targeted breeding efforts. For example, accessions in the red cluster in our study, demonstrated high marketable yield, which could be prioritized for breeding programs on this trait. Conversely, accessions in the green cluster, which showed distinct characteristics from red cluster, might be explored for their unique attributes that could contribute to broader genetic diversity in breeding populations. The dominance of Tuberosum accessions across clusters, particularly in the red and blue clusters, underscores their significance as the primary cultivated group, valued for their high yield potential, tuber uniformity, and other quality. These accessions serve as the backbone for commercial potato production and provide stable performance in diverse agroecological conditions. In contrast, the presence of Andigena accessions in all clusters, particularly in the green and black clusters, emphasizes their importance as a reservoir of genetic diversity. As a landrace species from South America, Andigena contributes traits such as stress tolerance, disease resistance, and adaptability to marginal environments.

These accessions are vital for the introduction of novel alleles into breeding populations and broadening the genetic base of potato cultivars. The inclusion of Indian varieties is significant due to their regional adaptability, market acceptability, and resistance to biotic and abiotic stresses. These varieties demonstrated the importance of integrating locally adapted germplasm into breeding programs to address the specific challenges of Indian agroecological zones. The clustering patterns revealed the potential of combining the productivity traits of Tuberosum, the genetic diversity of Andigena, and the regional adaptability of Indian varieties to develop superior potato cultivars with enhanced yield, quality and resilience. The grouping of most Indian varieties into a single cluster highlights their shared genetic background and adaptation to similar agroecological conditions, which showed their development for consistent performance in specific environments and suitability for targeted breeding programs. Certain Andigena accessions, like JEX/A-707, JEX/A-298, JEX/A-317, JEX/A-539 and JEX/A-32, may have been improved through geneflow or adapted to similar environmental and cultivation conditions as Tuberosum, which also results into comparable agronomic performance and their categorization in the red cluster.

CONCLUSION

The current investigation provides a detailed analysis of potato accessions using PCA and hierarchical clustering. The findings of this study emphasize the importance of marketable yield as an important trait of variability, the stability of specific gravity, and the potential for focused breeding efforts based on identified genotype clusters. These finding are valuable for future potato breeding programs focused on improving yield and quality traits. This study also demonstrated the utility of the augmented design for evaluation of genetic diversity and yield performance traits in a large panel of potato accessions. The identification of traits which govern yield variability, combined with the clustering of accessions based on similar traits, provides valuable information for selection of parental lines in the breeding programs. Future studies could explore the environmental factors that contributed to the year-to-year variability observed in this study. Additionally, further genetic analysis of the identified clusters could provide insights into the underlying genetic mechanisms controlling the key traits identified in this study.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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TRAINING NEEDS OF POTATO GROWERS TOWARDS IMPROVED PRODUCTION TECHNOLOGY IN UTTAR PRADESH

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ABSTRACT: The present study was carried out during the year 2024-25 in Uttar Pradesh to know the training needs of the potato growers their preference time, duration, place of training and training of methodology, for this study the data was collected from 192 Potato growers through personal interview schedule. After analyses of data, it was found that agronomical training needs shows higher priorities of improved varieties reported by 59.37% respondents, with mean score of 2.51, after this fertilizer based on soil testing recommendation needs reported by 47.91% of the respondents with mean score of 2.40 and regarding needs of Potato processing reported by 33.85% respondents with mean score of 2.18. These needs were place Ist, IInd and IIIrd respectively. Regarding time of training 46.35% respondents preferred one to two weeks before cropping season start, 64.58% respondents preferred one to three days training, 44.27%, respondents preferred place of training at village level and 47.92% respondents preferred lecture cum demonstration cum tour programme training methodology.

KEYWORDS: Potato growers, priorities of package & practices and preference time of training

INTRODUCTION

Training is essential to induce motivation, create confidence and inculcate efficiency in an individual. Training is also inevitable for imparting new knowledge and updating the skills of the farmers. Training of farmers had assumed further importance and urgency in the context of the high yielding varieties and improved practices in agriculture and allied fields. (Kumar *et al.*, 2017). Thus, training plays a very important role for human resource development. Potato is an integral part of daily diet in all walks of society. They are cheaper and are better source of protective foods. Daily consumption of sufficient potato (vegetables) could help to prevent major diseases such as cardio- vascular diseases and certain cancers. The present production could be increased considerably of the available technology is effectively transferred to the farmers. Training has become a critical input especially in view of the growing sophistication in agricultural technology as well as its cost intensive nature.

However, no training programme would bring desirable changes in the knowledge, skill, attitudes, and other behavioral components unless it is a need-based programme. Our training programmes need to focus more on transferring of new technologies from the confines of laboratories and research institutes to the farmers and make them result oriented (Lynton R.P. Pareek, U. 2011) Its profitability

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needs to be enhanced further, but still profitability of potato growing is beset with many constraints faced by the potato growers due to production and marketing. So, therefore the potato grower's needs to be properly trained in the latest improved cultivation practices for realizing more productivity and production of crop. (Verma. S.L. and Ansari, M.N. (2013).

Research methodology

The present study was conducted in Uttar Pradesh, the Uttar Pradesh consists of 18 divisions out of which three divisions were selected purposively i.e. Agra, Aligarh and Meerut for the investigation. From each division one district was selected for the investigation from each district two blocks were selected purposively for the investigation. Thus, the total 06 blocks were selected for the investigation from each block two villages were selected randomly. A list of potato growers from selected villages were made and those farmers were selected who were growing potato not only for their personal consumption but for commercial purpose. From prepared list 16 potato growers were selected by stratified random sampling from each village to make a sample size of 192 respondents for investigation. The data was collected through personal interview and collected data was coded, then analyzed using relevant statistical tools & techniques to find out frequency, percentage, arithmetic mean, standard deviation and coefficient of correlation and the results were then interpreted.

RESULTS AND DISCUSSION

The data presented in (Table 1) revealed that among soil and land preparation practices, soil selection had the highest mean score of 1.48. very few respondents preferred most needed making within this category, while other activities like ploughing and field leveling were least needed. In agronomic practices, improved varieties had high preference with a mean score of 2.51, the respondents 59.37% reported most needed. followed by seed treatment (2.30) and seed rate (2.21), highlighting the growers strong demand for training on seed quality and management (Gupta, S. (2020). Within fertilizer practices, fertilizer application based on soil test recommendations scored highest (2.40), 47.79% respondents were reported most needed emphasizing the importance of soil-specific nutrient management, followed by optimum fertilizer doses (2.15) was found IInd place in this category (Meena, R.K. and Chauhan, M.S. (2002). For irrigation management, rainwater storage (2.04) and drip irrigation (1.75) received the highest mean scores, reflecting growing interest in water conservation techniques. In plant protection, insect identification and control measure had a mean score of 1.89 in this category 42.18% respondent were reported less need priorities, closely followed by disease management (1.81), showing concern for pest and disease control. Regarding weed control, inter-culture operation scored highest (1.94), indicating the priority of mechanical weed management, while knowledge of herbicides and spray preparation scored slightly lower. Finally, in the harvesting and post-harvest category, processing mean score was found highest (2.18) and marketing/storage (2.04) were the most needed areas for training, suggesting a desire to improve value addition and market linkages. The lowest mean scores generally corresponded to routine or well-understood practices, reflecting farmers' focus on areas they perceive as directly impacting productivity and income (Das, Rajib and Jha, K.K. (2017).

The data presented in (Table 2) revealed that majority of farmers 46.35% preferred receiving training 1–2 weeks before the cropping season start, indicating their inclination toward timely and actionable knowledge. Short-duration training of 1–3 days was favored by 64.58% of respondents,

Table 1. Distribution of respondents according to practices wise training need preference as perceived by potato growers.

S. No.	Area of Training	Most needed		Needed		Least needed		Mean score	Rank
		F	%	F	%	F	%		
A.	Soil and land preparation								
	a. Soil Selection	4	2.08	85	44.27	103	53.64	1.48	I
	b. Field leveling	2	1.04	20	10.41	170	88.54	1.12	III
	c. Ploughing	1	0.52	19	09.89	172	89.58	1.10	IV
	d. Application of FYM/Compost	3	1.56	39	20.31	150	78.12	1.23	II
B.	Agronomic Practices								
	a. Improved varieties	114	59.37	62	32.29	16	08.33	2.51	I
	b. Seed rate	60	31.25	113	58.85	19	09.89	2.21	III
	c. Sowing time	12	06.25	62	32.29	118	61.45	1.44	V
	d. Method of sowing	21	10.93	85	44.27	86	44.79	1.66	IV
	e. Seed treatment	98	51.04	55	28.64	39	20.31	2.30	II
	f. Spacing	00	0.00	66	34.37	126	65.62	1.34	VI
C.	Fertilizer practices								
	a. Identification of important fertilizer	37	19.27	101	52.60	54	28.12	1.91	III
	b. Optimum dose of fertilizer	65	33.85	92	47.91	35	18.22	2.15	II
	c. Application of fertilizer at Basal, Top dressing and spraying.	20	10.41	77	40.10	95	49.47	1.60	IV
	d. Fertilizer based on Soil Test recommendation.	92	47.91	86	44.79	14	07.29	2.40	I
D.	Irrigation Management practices								
	a. Storage of Rain Water for future use	55	28.64	91	47.39	46	23.95	2.04	I
	b. Flood Irrigation in Potato Crops	16	08.33	38	19.79	138	71.87	1.36	III
	c. Furrow irrigation in potato crops	05	02.60	09	04.68	178	92.70	1.09	IV
	d. Drip Irrigation	39	20.31	67	34.89	86	44.79	1.75	II
E.	Plant protection Practices								
	a. Identification of disease and control measures	42	21.87	72	37.05	78	40.62	1.81	II
	b. Identification of insects and control measures	45	23.43	81	42.18	66	34.37	1.89	I
	c. Preparation of spray solutions and application	30	15.62	59	30.72	103	53.64	1.61	III
F.	Weed Control								
	a. Identification of weeds	10	05.20	28	14.58	154	80.20	1.25	IV
	b. Knowledge of herbicide	33	17.18	82	42.70	77	40.10	1.77	II
	c. Preparation of spray solution and application	41	21.35	65	33.85	86	44.79	1.76	III
	d. Inter-culture operation	47	24.47	88	45.83	57	29.68	1.94	I
G.	Harvesting and post harvesting technology								
	a. Time and method of harvesting	8	4.16	12	06.25	172	89.58	1.14	IV
	b. Processing	65	33.85	97	50.52	30	15.62	2.18	I
	c. Marketing of storage	54	28.12	92	47.91	46	23.95	2.04	II
	d. Seed production	44	22.91	76	39.58	72	37.05	1.85	III

Table 2. Distribution of respondents according to time, duration, place and training methodology preferred.

S. No.	Particulars	No. of respondents (F)	Percentage (%)
	Time of Training		
1.	1-2 week before cropping season start	89	46.35
2.	2-3 week before cropping season start	65	33.85
3.	3-4 week before cropping season start	38	19.80
	Duration of Training		
1.	1 to 3 days	124	64.58
2.	3 to 5 days	57	29.69
3.	5 to 7 days	11	05.73
	Place of Training		
1.	At krishi vigyan kendra	62	32.29
2.	At village level	85	44.27
3.	At block level	27	14.06
4.	At district level	18	09.38
	Training Methodology		
1.	Lecture cum discussion	05	2.60
2.	Lecture cum demonstration	65	33.85
3.	Lecture cum demonstration cum tour	92	47.92
4.	Lecture cum skill training	30	15.63

highlighting the importance of concise and time-efficient learning sessions given the growers' busy schedules (Rai, D.P. and Singh, K. 2008). In terms of location, 44.27% preferred training at the village level, followed by 32.29% at Krishi Vigyan Kendra, suggesting that accessibility and minimal travel are important considerations for participation. Regarding the training methodology, nearly half 47.92% of the farmers preferred a "lecture cum demonstration cum tour" approach, emphasizing their interest in experiential learning and field exposure (Bajpai *et al*. (2007). This was followed by 33.85% who favored lecture cum demonstration sessions. the least preferred training needs were also notable (Dangi, R. and Bairthi, R. (2006). Only 19.80% of respondents favored training 3–4 weeks before the cropping season start, suggesting reduced relevance or recall of information if provided too early. Long-duration training 5–7 days was the least preferred in terms of time commitment with only 5.73% supported, likely due to constraints on farmers' availability. Training conducted at the district level (9.38%) and block level (14.06%) also saw low preference, indicating challenges related to distance, travel, and time. Among training methodologies, the least favored was the "lecture cum discussion" by only 2.60% of respondents Notably, theoretical or discussion-based methods were the least preferred. Overall, the findings underscore the need for training programs that are brief, well-timed, locally accessible, and practically oriented to effectively engage potato growers and enhance the adoption of improved production technologies (Dangi, R. 2004).

CONCLUSION

It may be concluded that training should be based on the needs and interest of the farmers and their priority areas. The most priority area was reported by the farmers as like improved varieties, fertilizer based on soil test recommendation, optimum dose of fertilizer and post-harvest processing and the training programme organized well in advance before the cropping season start. The training programme should be organized at village level, this was the requirement of most of trainees, one to three days duration of training and lecture cum demonstration cum tour programme methodology of training should be followed so the farmers knowledge, skills, understanding and confidence can be enhanced.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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BIOFORTIFICATION IN POTATOES: A SYSTEMATIC REVIEW

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ABSTRACT: Crop biofortification has emerged as a powerful tool to combat micronutrient malnutrition. It is vital to address the issue of hidden hunger in light of the expanding global population. Across the world, biofortification is a workable, economical, and sustainable way to meet the nutritional needs of the weaker segments of society. Malnutrition, specifically hidden hunger, is an international phenomenon. Individuals with mineral deficits who are unable to afford a diversified diet or dietary supplements may benefit from biofortified variants. To satisfy the nutritional requirements, an integrated approach incorporating breeding, biotechnology, and agronomy would be implemented. Unlike dietary diversification, nutritional supplementation, and fortification, biofortification requires a one-time investment for the development of biofortified varieties, with recurring costs comparable to those of any crop variety now in use. The potato crop responds well to agronomic techniques, but maximising the benefits of these techniques requires knowledge and understanding. Potato biofortification can also be facilitated by knowledge of the genetic basis of the micronutrient concentrations in potato tubers. Potato germplasm has a broad range of genetic variability for mineral concentration, which can be used in crop breeding to create potato cultivars that are high in nutrients. Though conventional breeding takes a lot of time, more precise breeding strategies can be designed to improve the nutritional components of potatoes with the use of the latest tools like DNA free gene editing.

KEYWORDS: Potatoes, Nutrition, Biofortification, Breeding Approaches, Nutrition security

With a net productivity of 25.79 tonnes per hectare and a total production of around 60.14 million tonnes from a planted area of 2.33 million hectares, India ranks as the second largest potato producer in the world (2022-23) (Sources: https://agriwelfare.gov.in; Department of Agriculture & Farmers Welfare, 2022-23 Final). The latest (2022) global annual production of potatoes is 375 million tonnes, with an average productivity of 21.1 t/ha (2022; FAOSTAT), and thus average productivity of potatoes in India is higher than that of the world's average potato productivity. India alone produces nearly 14% potatoes of the total world potato production. It is anticipated that the medium and long-term observed changes in Indian socioeconomics will increase per capita fresh potato consumption from 19.78 (2010) to 48.47 kg by 2050 and corresponding national food demand for fresh potatoes will be 38.2 and 78.5 million tonnes during 2025 and 2050, respectively (Vision 2025). As a result, biofortified potatoes may be able to

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meet a large portion of the general public's nutrient needs.

Nutritional components of potatoes

Potato tubers contain on an average of 80% water and the rest of the proximate composition is constituted by starch, protein, fibres, free sugars, fat, vitamins, minerals and phytonutrients (Table 1). Though potato is a starchy crop under high-GI category food and is viewed as a less healthy dietary option; however, there are many aspects to consider about the value of potato in the human diet (Sagili *et al.*, 2022). Post-harvest processing can have a major effect on the GI/ GL values of potatoes and is a good source of instant energy for the undernourished people. The potato proteins have a very high biological value (BV) of 90 (Egg protein has a biological value of 100 and is considered the reference protein) and are comparable/ better to soybean with a BV of 84 and beans with a BV of 73 (McGill *et al.*, 2013). Better protein quality can be very useful, especially to malnourished populations. Potato is one of the rich sources of Vitamin C, Potassium and Folate (Raigond *et al.,* 2023). Therefore, despite having carbohydrate rich potato has several nutraceutical components to make it one of the options to fight hunger and malnutrition.

However, potato tuber contains many more phytochemicals, which have nutraceutical properties. Phenolics and flavonoids, including carotenoids, anthocyanins, and flavonols, are the primary phytochemical components found in potatoes and there are genotypic differences in the content of these phytochemicals and usually colored skin/ fleshed potatoes are richer in anti-oxidant compounds as compared to white skin/ fleshed ones (Ezekiel *et al.*, 2013). It has been demonstrated that potato genotypes with pigmentation-primarily purple and red cultivars-contain noticeably larger quantities of antioxidants than those with white or yellow flesh (Kulen *et al.,* 2013; Stushnoff *et al.*, 2008). These chemicals can counteract oxidative cell damage and provide protective or disease-preventive qualities. Thus, they may aid in the prevention of age-related neuronal degeneration, cancer, and chronic illnesses. Phenolics, which are among these phytochemicals, are known to provide both health advantages and organoleptic qualities. Chlorogenic acid accounts for around 80% of the total phenolic content in potatoes (Brown, 2005). Following apples and oranges, potatoes rank as the third most significant source of phenols, with about half of the phenols concentrated in the peel and adjacent tissues (Freidmen, 1997). Anthocyanins, which are also critical antioxidants, are found in coloured potatoes. A subset of flavonoids is responsible for the red, blue, and purple hues of potato flesh and skin. The presence of acylated glycosides of pelargonidin results in the red hue, while acylated glucosides of malvidin, petunidin, peonidin, and delphinidin impart a purple hue (Brown, 2005). These substances enhance the overall appearance and promote the health and well-being of consumers by inhibiting the oxidation of LDL-cholesterol and safeguarding human cells from the damage caused by free radicals. Potatoes also contain carotenoids, in white-fleshed potatoes the values are 5–10 mg kg^{-1} FW,

Table 1. Nutrient content of potato per 100-gram fresh weight

Nutrient (unit)	Content	Nutrient (unit)	Content
Carbohydrates (g)	17	Phosphorus (mg)	57
Fat (g)	0.09	Zinc (mg)	0.29
Protein (g)	2.0	Copper (mg)	0.11
Fiber (g)	2.2	Manganese (mg)	0.15
Calcium (mg)	12	Vitamin C (mg)	19.7
Iron (mg)	0.78	Vitamin B complex (B1, B2, B3, B5, B6) (mg)	0.03-1.05
Potassium (mg)	421	Vitamin B9 (µg)	16
Magnesium (mg)	23	Vitamin A (IU)	2

while yellow-fleshed potatoes have 10–35 mg kg^{-1} FW. Lutein, zeaxanthin, violaxanthin and neoxanthin are the major carotenoids present in potatoes, whereas β-carotene is present in trace amounts (Tatarowaska *et al*., 2019). Cultivars differ in these carotenoids' ratios. Despite not being precursors to vitamin A, all xanthophylls are powerful antioxidants. Zeaxanthin and lutein are responsible for the orange and yellow colours of the tuber flesh, respectively. In addition to providing possible protection against chronic illnesses and some types of cancer, lutein/zeaxanthin has been implicated in preventing age-related macular degeneration and shielding the retina from blue light damage (Ezekiel *et al*., 2013).

Potato-A perfect crop for biofortification

A crop with great versatility, potatoes are grown in over 150 nations from Chile to Greenland, right from temperate to sub-tropical and tropical climates, from sea level to 4,700 metres above sea level. Potatoes are more efficient than cereals in productivity per unit of area and water used (Kanter and Elin, 2019). Potatoes are much-admired for their role in alleviating hunger and reducing malnutrition and are marketed as a nutritious food because they contain antioxidants and other health beneficial compounds. Potato is the only noncereal staple food ranked fourth after grain crops. The bioavailability of iron (Fe), zinc (Zn), potassium, vitamin C, vitamin B6, and folates is higher than that of cereal crops due to lower phytic acid content and higher ascorbic acid content (Rashid *et al*., 2024). Potatoes are ideally suited for biofortification since potato cultivars have high ascorbic acid to phytate ratio, which may be considered appropriate for mineral fortification for targeted mineral delivery since phytate inhibits mineral absorption while ascorbic acid promotes their absorption in the gut (Joshi *et al*., 2021). With its maximum variation among the agronomic and quality traits, the potato has great potential especially for micronutrient biofortification (Rashid *et al*., 2024). Potato is also a good source of resistant starch. In several ways, natural resistant starch supports a healthy colon (Leeman *et al*., 2006). One approach to this shift is biofortification, which is based on the idea of improving nutrient composition through breeding techniques.

Health benefits of biofortified potatoes

The use of food-based strategies to avoid chronic diseases is becoming more and more popular (McGill *et al*., 2013). Additionally, potatoes are becoming more and more well-known as a source of minerals and bioactive phytochemicals (Brown *et al*., 2003; Thompson *et al*., 2009). In addition to their antioxidant properties, phenolic compounds may have other health-promoting properties. Numerous research investigations examined the anticancer, antiproliferative, and antioxidant properties of potato polyphenols (Singh *et al*., 2008, Kaspar *et al*., 2010, Madiwale *et al*., 2012). Of all the phenolic compounds, phenolic acids have sparked the most interest due to their possible health advantages (Mattila *et al*., 2007). Potato tubers with higher concentrations of chlorogenic acid have been shown to enhance insulin sensitivity, reduce intestinal glucose absorption, and inhibit gluconeogenesis (Andre *et al*., 2014; Ong *et al*., 2013). In a six-week study, Kaspar *et al.* (2010) examined the impact of eating potatoes with pigment on inflammatory damage and oxidative stress in men. The findings demonstrated that eating potatoes with yellow and purple flesh decreased DNA damage and inflammation. Increased consumption of potatoes, which are rich in anthocyanins, was correlated with lower plasma concentrations of C-reactive protein, a biomarker for the course of disease (Kaspar *et al*., 2010). Some of the hepatic antioxidant enzymes expressed more and antioxidant potential in the serum and liver increased in rats, when purple potato flakes were fed to them (Han *et al.*, 2007). Additionally, rats' hepatic superoxide dismutase mRNA was increased by red potato flakes, enhancing the antioxidant system (Han *et al.*, 2007).

Potato polyphenols also have certain other positive health effects that may not be related to antioxidants (Andre *et al.*, 2008). For example, potato extracts reduced the proliferation of breast (Leo *et al.*, 2008) and colon (Madiwale *et al.*, 2012) cancer cells, with the latter case also demonstrating pro-apoptotic characteristics (Roleira *et al.*, 2015). Potato anthocyanin compounds inhibited the growth of benzopyrene-induced stomach cancer in rats (Madiwale *et al.*, 2012, Hayashi *et al.*, 2006). Higher phenolic content extracts showed stronger cytotoxic and antioxidant properties (Roleira *et al.*, 2015). Given that potatoes are widely consumed worldwide, they may therefore be a perfect source of phytochemicals that promote health.

Factor affecting the nutritional quality of potatoes

The stability and concentration of phytochemicals in the human diet are subject to various influences, including genotype, agronomic conditions, post-harvest storage, cooking and processing (Ezekiel *et al.*, 2013).

Variety: From variety to variety, the nutritional content may differ slightly (Luthra *et al.*, 2018a). The amount of protein in 100 grams of potatoes can range from 1 to 4.2 grams on a fresh weight (FW) basis, depending on the variety (McGill *et al.*, 2013). Antioxidants such as flavonoids, anthocyanins, polyphenols, and β-carotene are abundant in coloured potatoes (Soare *et al.*, 2020) and phenolic content may vary upto fifteen times (Navarre *et al.*, 2009). Andre *et al.*, (2007) documented that the concentration of total carotenoids in 74 Andean landraces varied from 3 to 36 μg/g DW. Brown *et al.* (2007) conducted a study on 38 native South American potato cultivars, selected for coloration of skin and flesh combined with high dry matter, and assessed the antioxidant values and total anthocyanins. The results revealed that the concentrations of total anthocyanin varied from undetectable to 23 mg cyanidin equivalents/100 g FW, total carotenoid levels varied from 38 to 2020 μg zeaxanthin equivalents/100 g FW, hydrophilic oxygen radical absorbance capacity (ORAC) values ranged from 333 to 1408 μM Trolox equivalents/100 g FW and lipophilic ORAC values ranged from 4.7 to 30 nM-tocopherol. Total anthocyanins and total carotenoids have been reported to be negatively correlated (Li *et al.*, 2022). Recently, Dalamu *et al.* (2023) found substantial diversity for anthocyanins (1.81–17.20 mg/100 g FW), ascorbic acid (14.50–85.00 mg/100 g FW), carotenoids (4.75–27.75 μg/g FW), and total phenolics (19.22–73.54 mg GAE/100 g FW), tuber dry matter content (14–26 percent), iron (30.49–56.29 ppm), and zinc (10.62–27.58 ppm based upon the nutritional investigation of 71 potato genotypes. According to the study's findings, two genotypes-the indigenous Kala Aloo line and the Andigena line JEX/A-122 may be utilised as parents to develop potato varieties with better nutraceutical values. There is large variability in the potato germplasm concerning tuber size, shape, flesh colour, skin colour, pigment distribution, skin type, nutrient concentrations, and resistance to biotic and abiotic stresses (de Haan *et al.*, 2019; Singh *et al.*, 2020b). A diversified gene pool for potatoes must therefore contain undiscovered genes that could potentially be employed in potato biofortification initiatives. The ability to increase the diversity of existing potato cultivars will be facilitated by the identification of genes regulating tuber mineral concentration in various potato populations (Bradshaw *et al.*, 2006; Subramanian *et al.*, 2017). Furthermore, the potato genome sequence is publicly accessible, which provides the genomic resources to accelerate the biofortification process.

Luthra *et al.* (2018a) found that there was a positive correlation between tuber dry matter content and soluble protein (0.76), ascorbic acid (0.51), and total free amino acid (0.83), and a negative correlation between tuber yield and total protein (-0.75) and ascorbic acid (-0.59). According to Dalamu *et al.* (2023), there was a negative association between tuber yield for anthocyanin (r = -0.46; -0.43), total carotenoids (r = -0.47; -0.38), ascorbic acid (r = -0.27; -0.24), and tuber dry matter (r = -0.21, -0.24). Thus, there always a need to strike a balance between yield and biofortification.

***Environment*:** The impact of environmental conditions on crop quality and yield is a major challenge to breed for the enhancement of a specific trait (Nzaramba *et al*., 2013). The productivity and quality of crops are impacted by environmental circumstances, which encompass phytonutrient levels (Payyavula *et al*., 2012) and potato tuber specific gravity (Davenport, 2000; Sterrett *et al*., 2003). The strategies employed in breeding to enhance the micronutrient content of potato tubers are contingent upon the soil composition and environmental circumstances. Foliar application of micronutrient fertilizers has been used to fortify raw potatoes for the contents of iron and zinc (Ierna *et al.,* 2020). Genotype × environment interactions (GEI) exert a substantial influence on the nutritional quality of the tuber (Mohammed 2017; Haynes *et al*., 2019). Burgos *et al*. (2007) showed significant discrepancies in the contents of Fe and Zn in tubers cultivated at two distinct locations as a result of GEI. To limit the impact of GEI and select potential parents for potato breeding programmes multi-environmental experiments are necessary (Kelly *et al*., 2007).

Storage: Besides the genotype, environment and cultural practices; maintenance of nutritional composition during storage is also one of the desirable characteristics of biofortified potatoes. Since potatoes are around 80% water and 20% dry matter, they are a semi-perishable commodity and must be kept in a regulated environment to be consumed for an extended period for round the year supply for fresh market as well as processing industry consumption. In India, nearly 90% of potatoes are produced in winter and stored during long hot summer. Potatoes used for seed, table and processing are kept under refrigerated conditions., The nutritional content of stored potatoes is affected by the storage temperature and conditions used. According to the findings of Rosenthal and Jansky (2008), the antioxidant activity of preserved tubers was greater than that of fresh tubers. Total phenols increased during storage, with the rise being greatest at 4°C and 16°C, according to Ezekiel and Singh (2007), who examined the effects of storing four cultivars at 4, 8, 12, 16 and 20°C for 180 days. It has been found that irradiated potatoes contain a greater quantity of total phenols following storage at 10, 20, and 30°C (Thomas, 1982) and 5 and 20°C (Mondy and Gosselin, 1989). After analysing the anthocyanin content of tubers from 14 genotypes both immediately after harvest and after 135 days of storage at 4°C and 86 percent relative humidity, Jansen and Flamme (2006) did not see a statistically significant alteration in the tuber anthocyanin content. A five-month storage study of potatoes in Sweden demonstrated that the amount of vitamin C decreased by 60% and the amount of vitamin B6 increased by 20%. The levels of potassium, thiamine and other vitamins and minerals were unchanged (Ohrvik *et al*., 2010). After seven months of cold storage at 4°C, all potato cultivars had a mean decline in vitamin C concentration up to 52%, while two coloured varieties had a modest rise in total polyphenol content (Kulen *et al*., 2013).

From various studies, it may be deduced that the storage temperature and storage environment including relative humidity, gaseous composition etc. impacts potato nutrition content. Therefore, biofortification improvement programmes should aim at developing potato varieties with minimum losses of nutrients upon long term storage under prevailing storage practices of the region.

Processing: The potato processing industry in India is currently expanding at a rapid rate as a result of the growing urban working population, the universal acceptance of potato processed products, and the availability of specialised varieties for processing (Gupta *et al.*, 2020). Currently, processing accounts for about 8.9% of all potato yield; by 2025, that percentage is expected to rise to 10.76 percent (CPRI Vision, 2050). Tubers should have a high dry matter content (> 20 percent) and low reducing sugars (ideally < 0.1 percent on a fresh weight basis) to be used for high-quality dehydrated products (flakes, flour, powder, etc.) or fried products (chips or French fries) (Kumar and Ezekiel, 2006). Dehydrated chips, cubes, and other items are also easily made at the small-scale industrial level, which can give employment to rural youth and village women (Luthra and Gupta, 2019). In addition, potatoes are used in the production of other processed foods including tikkis, Alu Bhujia, dried chips, and samosas.

To produce the final product with additional value, potatoes must go through multiple processing steps. Depending on the operation involved, nutrient losses are known to occur to varied degrees. Traditional potato processing methods like chuno lead to a nutritional loss in potatoes (Woolfe, 1987). One of the main concerns when processing potatoes into different products is the loss of nutrients, which must be kept to a minimum. When potatoes are dehydrated into products like potato flour, flakes, granules, and dice, nutritional value is lost in the process. Changes in phytochemicals and the activation of certain enzymes that alter the concentration of phenolic compounds can result from processes such as handling, washing, and slicing (Tudela *et al.*, 2002). It has been demonstrated that cutting fresh potatoes can alter their phenolic component and antioxidant content (Reyes *et al.*, 2007). According to Reyes and Cisneros (2003), the wounding reaction is genotypically specific and raises the phenolic content and antioxidant capacity of purple-flesh potatoes while decreasing total soluble phenolics and antioxidant capacity in white-flesh potatoes by 15% and 51%, respectively (Reyes *et al.*, 2007). A potato can accumulate polyphenols during the process of slicing. Vahteristo *et al.* (1997) noted a folate content that was 35 to 52 percent lower in French fries compared to the folate content reported by Konings *et al.* (2001) for fried and raw potatoes. Temperature, pH, and the presence of proteins, enzymes, and metallic ions all impact the stability of anthocyanins throughout the processing stage (Rein, 2005).

The breakdown of anthocyanin was reportedly induced by thermal processing (Patras *et al.*, 2010). The anthocyanins undergo enzymatic degradation when exposed to polyphenol oxidase, which can be rendered inactive with gentle heating or blanching (Enaru *et al.,* 2021). Due to their high oxidation susceptibility, anthocyanins and other phenolic compounds become sensitive to oxidative destruction at numerous processing stages (Patras *et al.,* 2010). In comparison to raw potatoes, the hydrogen oxygen radical absorbance capacity (HORAC) and total anthocyanin content of chips and French fries were notably diminished (Brown *et al.*, 2008). In general, potato processing diminishes the antioxidant content. The anthocyanin concentration is diminished more significantly by boiling than by microwave cooking or frying. Potatoes that have been cooked without peeling may retain more minerals, and other nutrients and have higher dietary fibres as compared to peeled potatoes (Singh *et al.*, 2020a; Singh *et al.*, 2020b; Sampaio *et al.*, 2020). Anthocyanin and other nutritional components persist in substantial quantities even after cooking (Ercoli *et al.*, 2021). Anthocyanins and carotenoids retain their antioxidant activity even after being subjected to standard cooking methods (Brown, 2005). The impact of cooking on total anthocyanins and HORAC was investigated by Brown *et al.* (2008) in four genotypes whose flesh contained different concentrations of anthocyanins. Total anthocyanins were retained throughout boiling and microwaving but were reduced during baking and frying. According to Navarre *et al.* (2010), efforts to enhance the phytonutrient content of potatoes will be ineffective if the desired phytonutrients are not cooked to a suitable degree. Since potato peels are known to contain a lot of phenolics, boiling and baking potatoes in their skins is thought to be a beneficial cooking technique since it helps to maintain the majority of the nutrients. According to a study by Mattila and Hellstrom (2007), peeled and cooked potatoes had a reduced phenolic concentration in comparison to raw potatoes. In their study, Barba *et al.* (2008) observed substantial reductions in the phenolic content of peeled and unpeeled potatoes, as well as boiled and baked potatoes. A variation in phenolic concentration was documented by Takenaka *et al.* (2006) during the processing stage. This variation was attributed to several factors, including phenolic loss by leaching into water, degradation caused by heat, oxidation by polyphenol oxidase, and isomerization. Baking at 170 °C was shown to greatly reduce total phenolic levels, whereas boiling for 30 minutes and microwave cooking exhibited the least reductions (Stushnoff *et al.*, 2008). The phytonutrient losses resulting from baking, boiling, frying, and microwaving were compared by Blessington *et al.* (2010). Boiling potatoes were shown to have a lower carotenoid level than raw potatoes; other cooking techniques did not significantly differ from one another. There was a noticeable drop in quercetin content after baking, boiling, frying, and microwaving (Blessington *et al.*, 2010). Tudela *et al.* (2002) reported a comparable drop in quercetin derivatives.

According to Jongstra *et al.* (2020), potatoes have a significantly higher iron bioavailability than cereals. By employing an in vitro gastrointestinal digestion assay and a $CaCO_2$ line-based model of the human gut, Andre *et al.* (2015) demonstrated that around 70% of the iron that was liberated from the potatoes remained accessible at the intestinal level. Due to the presence of large amounts of organic molecules that facilitate zinc absorption in potatoes and low concentrations of chemicals that inhibit zinc absorption, zinc bioavailability in potato tubers is high. Consequently, potatoes provide a substantial portion of the recommended daily intake (RDA) for zinc and iron. Vergara *et al.* (2019) effectively enhanced the zinc bioavailability in potato tubers through the implementation of a zinc solution priming technique.

According to Singh *et al.* (2022), the higher nutrient concentrations in entire tubers as opposed to tuber flesh indicate that these nutrients are mostly found in the tuber's peripheral layers, where peeling the tubers off causes nutrient loss. Peeling off the tubers caused the greatest loss in Fe (35.63%), which was followed by Cu (22.80%), Mn (21.69%), Ca (21.27%), Mg (12.89%), K (12.75%), Zn (10.13%), and Mo. (9.87%).

The losses can be mitigated somewhat by boiling the potatoes with their skins, rather than peeling them (Robertson *et al*., 2018). The cooking methods that do not involve water, preserve more of the water-soluble vitamin and mineral content (Finglas *et al*., 1984). Han *et al*, (2007) reported lower vitamin C losses when potatoes were baked (<51%), microwaved (<33%), and sautéed (<67%) than boiled (<88%). It's interesting to note that the vitamin C loss was somewhat decreased to 61-79 percent when salt was added to the boiling water.

Biofortification in potatoes

Nutrient deficiencies resulting from unbalanced dietary practices, and limited access to balanced food options, particularly among impoverished populations, constitute a significant public health concern in both developed and developing nations. Diverse methods of nutrition supplementation each have advantages and disadvantages (Agrawal *et al*., 2024). Biofortification, which operates on the idea of increasing the nutrient density of food crops through means of plant breeding, biotechnological interventions, or physical application of mineral micronutrient fertilisers to the crop canopy or soil, is one such method. Scientific evidence supports the viability, usefulness, and economics of crop biofortification as a strategy to mitigate nutritional deficiencies. Potato varieties cultivated and consumed throughout Europe and South America are far more diverse, yellow fleshed and are generally regarded as having a more natural flavour (Walker, 1996). The objective of the potato biofortification breeding effort in India is to increase the concentrations of iron and zinc, as well as antioxidants (carotenoids and anthocyanins), in future potato varieties (Luthra *et al*., 2020a).

Biofortification is an economically viable method of enhancing the nutritional content of food items that are frequently deficient or insufficient in essential elements. This approach primarily addresses the nutritional needs of marginalised communities residing in distant areas, where the execution of alternative nutrient supplementation initiatives is predominantly impeded by inadequate infrastructure. For biofortification programmes to be successful, it is crucial to have a nutrient-dense variety that is well-adapted, popular among farmers and consumers and leads to a marked improvement in the population's health. When the programme is coupled with initiatives to raise community awareness of nutrition and dietary practises, it becomes more successful. Biofortification concentrates on two strategies i.e.: i) biofortification of staple crops to capitalise on the large amounts of food staples that are consistently consumed daily by all members of the family, including women and children who are most vulnerable to micronutrient malnutrition; and (ii) targeting the impoverished mass with low income.

Biofortification is a complementary approach to dietary diversity and other interventions that target micronutrient shortages, like supplementation and fortification, rather than the exclusive means of enhancing micronutrient intakes. Biofortification is a successful strategy to reduce malnutrition in several studies on efficacy (biological impact under controlled conditions similar to clinical trials) and effectiveness (biological influence in real life) (Bouis and Saltzman, 2017).

Breeding for nutritional improvement

Potato is an optimal food for the enrichment of phytonutrients, given that its phytonutrient content can be inherited *via* breeding approaches (Nzaramba *et al*., 2007). Global breeding programmes are currently raising the amounts of phenolics and/or carotenoids to increase the antioxidant content of potatoes (Andre *et al.*, 2007; Reddivari *et al.*, 2007). Thus far, the primary emphasis of Indian potato breeding endeavours has been on enhancing both productivity and resistance to diseases and pests. With the introduction of nutrient content as a criterion for cultivar promotion and the development of specialty potatoes, greater emphasis should be placed on breeding potatoes that are rich in nutrients. Exploring the current biodiversity is therefore the initial stage in the development of nutrient-dense potatoes.

Genetics of coloured potatoes

Due to their antioxidant properties, carotenoids and anthocyanins are good for human health. Potato skin or flesh colour varies due to the presence of anthocyanins. The presence or lack of these pigments is regulated by many genes. Chromosome 2 contains the genes that regulate the production of red pigment, whereas chromosomes 11 and 4 have the genes that produce blue and purple pigment, respectively (Brown, 2005). Potato skin and flesh colour distribution is governed by intricate genetic regulation. A single gene determines whether anthocyanin is present or absent, but the distribution pattern is multigenic (Brown *et al.,* 2003). The primary regulatory allele governing the yellow and white flesh colour of potato tubers is the Y locus on chromosome 3, which controls the monogenic inheritance of carotenoids in tubers (Bonierbale *et al*., 1988). An *Or* allele at the Y locus, which is dominant over Y and y, which control yellow and white flesh, respectively, is responsible for the orange flesh (high zeaxanthin). Modifying genes has been linked to regulating the amount of total carotenoids (Brown *et al*., 2006). According to Wolters *et al*. (2010), the dominant allele of beta-carotene hydroxylase (Chy2 allele3) is responsible for the yellow flesh phenotype. The primary element influencing the functional quality of potatoes is genotypic variation (Toledo and Burlingame, 2006). Parra-Galindo *et al*. (2019) identified seven quantitative trait loci (QTLs) regulating anthocyanin concentration in potato tubers on chromosomes 1, 2, 10, and 11. Zhang *et al.* (2009) identified QTLs determining the extent of flesh pigmentation on chromosomes 5, 8, and 9. Yellow-flesh factor (Y/y), which is found on chromosome 3, is the monogenically inherited component that causes the cream, white, yellow, or orange tuber flesh colour due to variable carotenoid content. For marker aided breeding, candidate genes linked to QTLs must be identified. Kloosterman *et al*. (2010) identified the β-carotene hydroxylase (bch) gene linked to the flesh colour of yellow tubers by mapping the gene underlying a significant QTL for flesh colour on chromosome 3. Potato tubers with orange flesh are produced when the homozygous recessive Zep allele coexists with the dominant Bch or Chy2 allele (Wolters *et al*., 2010). Humans need trace amounts of iron and zinc, which are essential for many metabolic activities. Due to their high anthocyanin content, coloured potatoes have the potential to be used as a natural colouring alternative for food products, as they are considered to provide health benefits over banned dyes (Hejtmankova *et al*., 2009).

Multigenic inheritance is observed for mineral characteristics. All 12 chromosomes have minor QTLs for zinc and iron, indicating that breeding to increase these qualities genetically necessitates combining a variety of genes that contribute to the traits (Pandey *et al*., 2023). Studying the processes behind plant mineral uptake, homeostasis, and gene identification related to mineral accumulation is necessary for mineral biofortification. Tuber mineral concentrations are also influenced by some physiological processes. For example, the slow mobility of tuber zinc in the phloem limits the amount of this element in the tuber (Pandey *et al*., 2023).

Targeted nutrients for biofortification of potatoes

Carotenoids, anthocyanins and micronutrients like iron and zinc are the nutrients that are the focus of the Indian potato biofortification initiative. Carotenoids are mostly found in higher content in yellow fleshed potatoes, whereas antioxidants such as anthocyanins are found in larger levels in purple and red potatoes. Antioxidants have been linked to several significant health-promoting activities, including provitamin A activity, immune system augmentation, decreased risk of cancer or cardiovascular disease, and assistance in preventing atherosclerosis (Fakhri and Farzaei, 2022). Anaemia, or iron deficiency, is a major public health issue in India that affects 50-70% of the population, including infants and young children, adolescent boys and girls, women of childbearing age, and pregnant women. It is common in both urban and rural areas. Deficiency of zinc results in pneumonia, respiratory tract infections, and diarrhoea. A severe zinc shortage results in anorexia, cognitive impairment, skin diseases, hypogonadism, and compromised immunological function. Zinc deficiency accounts for around 4.4% of child mortality in developing countries under the age of five (5.3 percent in Africa and 3.7 percent in Asia. One of the main dietary issues in underdeveloped nations is vitamin A deficiency. Clinical and subclinical vitamin A deficiencies are quite prevalent (62 percent) in India, resulting in 330,000 fatalities annually (Akhtar *et al*., 2013).

Strategy for potato biofortification

In India, majority of potato is consumed as vegetable and the potatoes with white skin and white or yellow flesh are consumed by majority of population. In some parts of Bihar and Uttar Pradesh, red skinned potatoes are preferred. Biofortification can be accomplished through genetic (conventional breeding), agronomic, and biotechnological methods.

(i) Breeding approach: In general, conventional breeding programmes for potatoes are mainly concerned with increasing crop productivity and disease resistance. There is less genetic variability for nutraceuticals traits in modern potato cultivars since they are bred using a limited number of germplasm (Barrell *et al*., 2013; Luthra *et al*., 2020a). So far, the majority of breeding efforts have been concentrated on creating potato types with white/yellow flesh that are resistant to biotic and abiotic stressors. The availability of different germplasm enables us to boost potato breeding to generate biofortified varieties, as the *Solanum* germplasm is a rich source of numerous features.

Some of the possible approaches for developing biofortified potato varieties with improved nutritional value have been listed below:

Characterization of potato germplasm including wild species: Germplasm evaluation serves as the preliminary stage in determining the existing variability in populations, which will serve as the foundation for subsequent enhancements. Significant variations can be observed in the shape and colour of tubers (skin/flesh) among potatoes (Fig. 1). There are around 5,000 identified potato cultivars, all of which are members of the genus *Solanum* and species *tubersoum*. Furthermore, eight other *Solanum* species, namely *S. ajanhuiri*, *S. juzpeczukii*, *S. curtilobum*, *S. chaucha*, *S. stenotomum*, *S. phureja*, *S. hygrothermicum*, and *S. goniocalyx*, which serve as a gene pool for the specified nutrients.

All coloured potatoes contain carotenoids (Fig. 2). While the carotenoids in white and yellow skinned potatoes are identical,

Fig.1. Variation for tuber shape and colour of skin/flesh in potatoes

Fig.2. The contrasting intense tuber and flesh colour, yellow colour for carotenoid contents and red/purple colour for anthocyanins

the yellow colour is caused by a larger concentration of xanthophylls. The main type of carotenoids found in potato flesh are called xanthophylls. The carotenoid concentration of the tubers of a hybrid population of diploid potatoes (*S. Phureja* and *S. stenotonum*) was as high as 1435 µg 100 g^{1} FW, the main carotenoids were lutein-5,6-epoxide, violaxanthin, and lutein, followed by neoxanthin, zeaxanthin, and an unknown carotenoid. On the other hand, in the tetraploid clones, violaxanthin is the most abundant carotenoid, accounting for 40% of the total, followed by lutein, lutein-5, 6-epoxide, neoxanthin and zeaxanthin (Lu *et al.*, 2001). All potato cultivars have carotenoids in their flesh, although depending on the colour of the flesh, the concentration might differ between cultivars, ranging from 50 to 2000 µg per 100 g FW (Hejtmankova *et al.*, 2013). Brown *et al.* (2008) reported a range of 50-100 µg/100g FW in white fleshed varieties, 100-350 µg/100g FW in moderately yellow fleshed varieties and above 1,000 µg/100g FW in intense yellow varieties. Dalamu *et al.* (2017) reported a mean carotenoid content of 98.23 µg/100g FW with a range of 59.71-227.28 µg/100g FW in an investigation on 32 genotypes grown under Indian climatic conditions. Luthra *et al.* (2018b) investigated 64 progenies of cross between Bareilly Red and CP3770 and identified advanced clones like MSP/15-26 and MSP/15-44 (yellow flesh with red vascular ring), MSP/15-56 (yellow flesh with red vascular ring/medulla, multi-coloured chips) MSP/15-51 (red purple flesh), and MSP/15-64 (purple red scattered flesh) having superiority for nutritional components and were considered potential clones for use as elite germplasm for developing superior genotypes under speciality potato sector in India. The mean carotenoid content in flesh was 1060 µg/100g FW, and it ranged from 551 (MSP/15-56) to 1550 (MSP/15-64) in comparison to the parents Bareilly Red (1450) and CP3770 (1500 µg/100g FW).

The Yellow Potato (Papa Amarilla) of the short-day South American Andes has high levels of zeaxanthin (carotenoids) ranging from 800 to 2,000 µg per 100 g FW. The coloured potatoes have also been associated with greater iron levels (Andre *et al.,* 2007; Brown 2008). The bio-accessibility of iron in potatoes is 63 to 79%, which is significantly higher than wheat, common bean, and pearl millet (<30%) (Andre *et al.,* 2015). Burgos *et al.* 2023 found that the absorbed iron from the iron biofortified potato meal was higher as compared to non-biofortified potato meal. Thus, the selection of yellow tuber fleshed germplasm with high iron content is the selection yardstick for breeding iron rich genotypes along with yield advantage, agronomic superiority and wider adaptability.

Presently, the ICAR-Central Potato Research Institute, Shimla in India maintains a modest collection of around 5000 accessions. More than 1000 lines have been screened for ascorbic acid and nearly 300 germplasm lines have been screened for other components like anthocyanin, carotenoids, iron and zinc etc. Around 100 germplasm accessions have been shortlisted from indigenous/exotic sources in the germplasm repository of the institute with one or more nutritional components.

Hybridization to develop biofortified progenies and evaluation of generated progenies: The breeding scheme for the development of nutrient rich potatoes has been described by Luthra *et al*. 2020a. The technique of hybridization entails mating selected nutrient-rich germplasm with variants of improved agronomic traits and wider adaptability to produce a variety of segregating progenies with higher nutritional values (Fig. 3). In single hill seedling generation, the segregating progenies produced are assessed, and clones with acceptable tuber characteristics are chosen. Seedlings and initial clonal generations are cultivated in a zone with low aphid populations, which are vectors for viruses. Cross-breeding diploid and tetraploid varieties can be used to introduce desirable traits, including higher levels of micronutrients

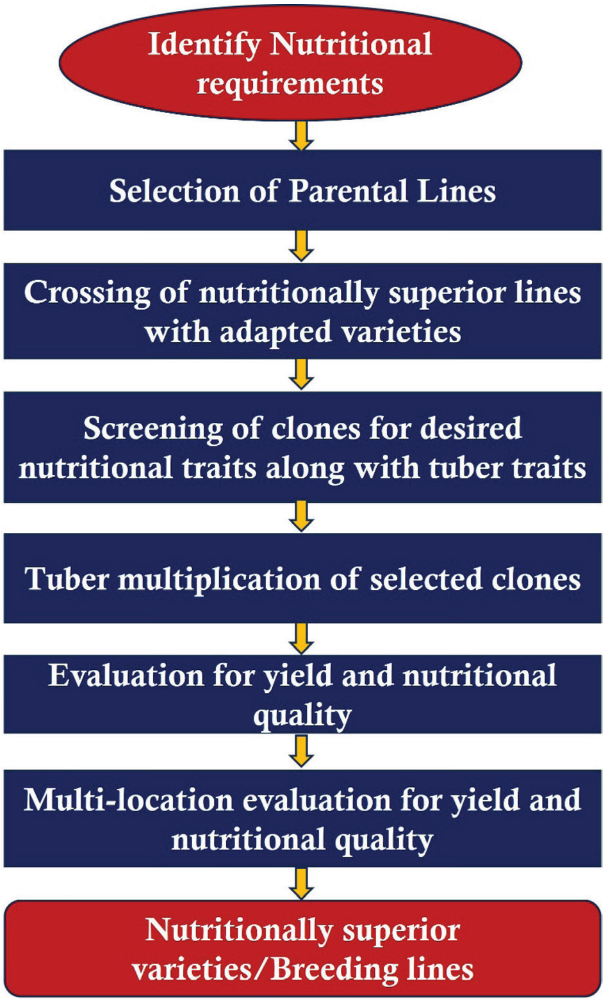

Fig. 3. Breeding Scheme for Development of Nutritionally Superior Varieties

like iron and zinc (Agarwal *et al.,* 2024). The selected tetraploid clones are evaluated in initial clonal stages (F_1C_1, F_1C_2), where the selection of clones is based on shape, colour of skin and flesh, tuber size/uniformity, bulking capacity and targeted nutritional/ mineral components etc. In the F_1C_3 stage, the selection is based on yield advantage (10% better over best control) along with nutritional components. In advanced stage trials, the selection is done based on desirable tuber attributes and nutritional components.

The traditional method of potato biofortification has several drawbacks, including poor heritability of the trait, linkage drag associated with the trait, limited genetic variability accessible for a given nutrient, and a lengthy (10-12 year) period between initial hybridization and variety release.

(ii) Biotechnological approaches: Approaches for genetic modification are especially useful when the desired characteristic is absent from the current germplasm or there is a need to develop genotypes in a relatively shorter time with minimum undesirable traits. Sustainability is provided by the transgenic method of micronutrient biofortification since the seeds produced by the transgenics are self-fertile (Blancquaert *et al*., 2015). This strategy can be used to lower the amount of anti-nutrients (Perez Massot *et al.*, 2013) and is an effective and economical way to leverage a wide variety of genes linked to various micronutrients from even completely unrelated species (Xu *et al.*, 2017). Through gene modification, the "golden potato" was created, resulting in increased levels of lutein (30-times), β-xanthophylls (nine-fold), α-carotene, and β-carotene (>3000 fold over the wild type) (Chitchumroonchokchai *et al.*, 2017). Researchers have demonstrated the use of transgenic manipulations for crop improvement to enhance beta-carotene's value through RNAi-based silencing of the beta-carotene hydroxylase gene (bch); overexpression of the strawberry GalUR gene to produce anthocyanins and ascorbic acid; coexpression of cystathionine γ-synthase genes to produce essential amino acids like methionine; expression of Amaranth albumin (ama1) genes to increase protein and methionine content in tubers; and role of microRNA (miR828) in purple/red potatoes, among other transgenic manipulations. Under the control of the CaMV35S promoter, the overexpression of the *Arabidopsis thaliana* PDXII gene in potatoes increased vitamin B6 accumulation and improved resistance to abiotic stress (Bagri *et al*., 2018). In a similar study, Muniz Garcna *et al*. (2018) found that adding Arabidopsis ABF4 to potatoes increased tuber yield, quality and resistance to abiotic stress. However, transgenic crops come with some drawbacks, such as strict biosafety regulations and low public acceptance, among others. Future developments in genome editing technology, however, might resolve these problems. To increase beta-carotene level, the potent pro-vitamin A metabolite, the beta-carotene hydroxylase (*BCH*) gene can be targeted. In one of the studies, silencing of *BCH* by using RNAi lead to tubers with more than 300 µg of beta-carotene per 100 g fresh weight (Tuncel and Qi, 2022). Vitamin C contents in tubers were increased up to three-fold when polyubiquitin promoter was used to express GDP-L-galactose phosphorylase (*GGP* or *VTC2A*) gene that is responsible for catalyzing the first committed step of ascorbate biosynthesis in plants (Bulley *et al*., 2012).

Due to the potato genome's high heterozygosity and polyploidy, the investigation of favourable genetic variations and their introgression into present potato cultivars is extremely difficult (PGSC-Potato Genome Sequencing Consortium, 2011). Efficient methods for identifying the beneficial genes and genomic loci linked to traits of interest include genome-wide association studies (GWAS) and genomic selection (GS) (Rojas *et al*., 2019). These have been effectively implemented in potatoes to determine the relationships between traits and markers, including tuber bruising (Urbany *et al*., 2011), starch content (Schonhals *et al*., 2016) and glycoalkaloid content (Vos *et al*., 2016). Nonetheless, the genetic underpinnings of the micronutrient composition of potatoes remain obscure, necessitating additional research into genetic polymorphisms for various nutritional traits (Haynes *et al*., 2012).

(iii) Agronomic approaches: To increase the micronutrient concentrations in the edible part of food crops, agronomical biofortification entails priming seed tubers and applying mineral fertilisers (Cakmak and Kutman 2018). It directs the physical addition of nutrients to the soil or foliage, which will improve the food crops' nutritional makeup and, eventually, the nutritional condition of the humans who eat those crops, albeit only momentarily. The mineral fertilisers containing micronutrients can be applied in the soil or foliar to plants. The foliar application of micronutrient fertilisers is a more effective method of increasing the mineral content of a crop's edible portions.

Potato plants that were sprayed with micronutrients had higher tuber yields and dry matter contents in addition to higher micronutrient concentrations in the tubers (Zhang *et al*., 2019). Numerous variables, including soil composition, pH, mineral mobility, mineral accumulation, weather circumstances, and plant growth stage at the time of fertilizer application; affect agronomic biofortification (Garg *et al*., 2018). Sharma *et al*. 2022 reported that the bioavailability of Zn from potatoes is high, therefore, the soil application of Zn fertilizers during the initial crop growth stage can be adopted as a simple strategy to increase its content in tubers for addressing Zn-related malnutrition issues.

Furthermore, adding soil microorganisms such as *Rhizobium*, *Bacillus*, *Azotobacte*r, and *Pseudomonas* increases the phyto-availability of mineral elements from the soil to plant edible sections and thus improves the nutritional status of the plants. There exist certain instances of potato biofortification using agronomic interventions, such as foliar zinc treatments that raise the concentration of zinc in entire potato tubers. Even though agronomic biofortification is a straightforward, efficient method, there are strict safety considerations that must be taken about the source of nutrients and how they are applied to prevent toxicity. Affordability and accessibility of fertilisers for farmers with limited resources are further challenges.

Food Security to nutritional security in India

Potatoes have become a staple in the country's households ever since their introduction in the early 17th century, more than four centuries ago, most likely by Portuguese traders. Presently, potatoes are cultivated across all states of India, thriving in a variety of agroclimatic conditions that span from temperate highlands to subtropical plains. In India, the utilization of indigenous and exotic genetic resources has resulted in the development and release of 73 indigenous potato varieties suitable for different agro-ecologies and 46 elite genetic stocks have been registered with ICAR-NBPGR (Luthra and Kumar, 2024). Traditionally, white, cream or yellow skin potatoes are normally favoured in India; however, consumers also exhibit a preference for red skin potatoes in the eastern regions of the country and Jammu and Kashmir. A stronger antioxidant capacity of coloured potatoes may be more desirable for human consumption. Further, they offer diversification of potato dishes in Indian food.

So far three nutrient dense (biofortified) potato varieties namely Kufri Manik (Kumar *et al*., 2023) and Kufri Neelkanth (Luthra *et al*., 2020b) and Kufri Jamunia (Recommended for release by the 41st Group Meeting of AICRP (Potato) held during October 16-18, 2023 at CCS HAU, Hisar, Haryana) have been released in India (Fig. 4). Kufri Manik produces attractive, deep red, round shaped tubers with medium eyes and yellow flesh. Kufri Manik is a nutrient dense variety by virtue of high anthocyanin (68 µg/100g FW), Zinc (33 ppm), and Iron (30 ppm). Kufri Neelkanth has excellent storage qualities and yields visually appealing ovoid tubers that are purple, have shallow eyes, and have flesh that is pale yellow. It is well-known that potatoes, with their purple skin and yellow flesh, contain more anti-oxidants, such as carotenoids and anthocyanins, which help humans fight off a variety of diseases (Luthra *et al*., 2019; Luthra *et al.*, 2020b). Kufri Neelkanth possesses higher carotenoids (351 ug/100 g fresh tuber weight, FTW) in the edible part (flesh) and higher anthocyanins in whole tuber (flesh+peel) (84.81 mg/100g FTW). Kufri Jamunia with a total tuber yield of 32-35 t/ha produces attractive purple oblong tubers with shallow eyes and purple flesh. It has 17-19% tuber dry matter, medium tuber dormancy and very good keeping quality (Unpublished). Kufri Jamunia possessed high ascorbic acid content (51.52 mg/100 g fresh tuber weight in flesh) as compared to nutritional superior potato varieties Kufri Manik (37.99) and Kufri Neelkanth (29.04). The purple flesh colour is known to indicate superiority of genotypes for high anthocyanin content and Kufri Jamunia with purple flesh colour possessed higher anthocyanin content (32.36 mg/100 g fresh tuber weight in flesh) than Kufri Manik (26.66) and Kufri Neelkanth (1.12). Kufri Jamunia possessed high carotenoid content (163.04 ug/100 g fresh tuber weight in flesh) as compared to Kufri Manik (99.20) and Kufri Neelkanth (107.52). Kufri Jamunia also possessed at par zinc (22.77 ppm) and iron (32.23 ppm) content on a dry weight basis with Kufri Manik and Kufri Neelkanth. It is suitable for table potatoes and due to its purple colour will add novelty in the preparation of various dishes.

Beside three elite potato genetic stocks namely MSP/16-26 (INGR22062, high carotenoids in flesh (823ug/ 100g FW), **y**ellow flesh colour with red vascular ring); MSP/16-51 (INGR22063, High ascorbic acid in flesh (68 mg/100gFW), distinct red purple flesh) and MS/8-1148 (INGR23120, High vitamin C content (77.7 mg/100g FTW)) has been registered by NBPGR, New Delhi.

Incorporation of nutrient dense traits in breeding population has led to identification of nutrient dense advanced potato clones namely MSP/15-60 (coloured baby potatoes, high anthocyanins:35 mg/100g FW-whole tuber, carotenoids:435 ug/100g FW-flesh, ascorbic

Fig. 4. Biofortified potato varieties released by the ICAR-CPRI, Shimla

acid:44 mg/100g FW-flesh); MSP/16-216 (Multi-coloured chips, high anthocyanins:31 mg/100g FW-whole tuber, carotenoids:176 ug/100g FW-flesh, ascorbic acid:37 mg/100g FW-flesh, and flavouring compounds-AMP+GMP: 4.34 ug/g); MSP17-300 (Purple skin/flesh colour, high anthocyanins:87 mg/100g FW-whole tuber, carotenoids:339 ug/100g FW-flesh, ascorbic acid:32 mg/100g FW-flesh and flavouring compounds-AMP+GMP:4.43 ug/g); MSP/17-375 (purple skin/flesh, high anthocyanins:204 mg/100g FW-whole tuber, carotenoids:370 ug/100g FW-flesh, ascorbic acid:43 mg/100g FW-flesh and flavouring compounds: AMP+GMP-4.75 ug/g); MS/17-739 (high yield, high vitamin C: 45 mg/100g FW, high Fe: 37/44 ppm-flesh/ whole tuber); MS/17-848 (multi-coloured flesh, high anthocyanins: 152mg/100g FW on whole tuber, vitamin C: 45 mg/100g FW) in flesh, high zinc:25/28ppm and iron: 38/46 ppm on a flesh/whole tuber).

In India, the breeding programme aiming to develop biofortified potatoes is progressing well and around 1000 nutritionally superior clones are available in various stages of the breeding programme. Recently, screening for lower glycemic index and higher resistant starch has been started and in years to come, we may be able to provide potato varieties having these desirable attributes.

FUTURE THRUSTS

The potatoes are healthful food that, when consumed in sufficient amounts, meets all dietary requirements for nutrients. Any dish made with potatoes has varying nutritional value depending on how it is cooked and what else is included. The development of nutrient-dense potato cultivars is imperative, particularly in light of the growing per capita consumption of potatoes in India (Vision 2050). In this context, initiatives have been launched, and populations up to advanced generations have been created and will soon be distributed as "Nutrient Rich Potatoes" (CPRI Annual report 2018-19). However, for the commercial and economic viability of these nutrient rich potatoes yield advantage, better keeping quality, culinary properties as well as disease and pest resistance are to be taken care of. Further fine mapping of QTLs for nutrient compounds, identification of candidate genes and a better understanding of biosynthesis pathways of these nutrient elements is required for the deployment of functional markers.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors.

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