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REVIEW ARTICLE

Potato: Breeding and Genomics

Satish K. Luthra[1*], Vinod Kumar[2] and Jagesh K. Tiwari[3]

Abstract

The commonly cultivated potato is a tetraploid and belongs to the species *Solanum tuberosum*, which includes two subspecies viz. ssp. *tuberosum* adapted to long days and ssp. *Andigena* adapted to short days. The conventional potato breeding programmes depend mainly on the identification of promising parental lines for making desired crosses, the creation of genetic variability through the crossing and subsequently the selection of desirable recombinants for further evaluation and vegetative propagation. During the last seven decades, ICAR-CPRI has developed and released as many as 69 improved varieties and one TPS population. These varieties cater to the need of the farmers across the country; and have superior agronomic attributes and resistance to different biotic and abiotic stresses. The somatic hybrids has been produced successfully by utilization of wild solanum species like S. *etuberosum*, S *cardiophyllam* and S *pinnetisectum*. Further, considerable work has been done in potato applying molecular biology and genomics approaches to address biotic and abiotic stress and quality traits.

Keywords: Potato, genepool, breeding, genomics, varieties.

[1]ICAR-Central Potato Research Institute, Regional Station, Modipuram, Meerut-250110, UP, India

[2]ICAR-Central Potato Research Institute, Shimla-171 001, HP, India

[3]ICAR-Indian Institute of Vegetable Research, Varanasi-221 305, UP, India

[*]**Corresponding author;** Email: skluthra@hotmail.com

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Introduction

Potato is the third most food crop in the world, after rice and wheat, in terms of human consumption. Fresh potatoes contain about 78% water, 18.5% carbohydrates, 2.1% protein, 0.1% fat, and 1.7% fibre (Woolfe, 1987). Nutritionally, it is superior food in terms of supply of carbohydrates, proteins, minerals, Vitamin C, several B group vitamins, and high-quality dietary fiber. These nutrients make potatoes second only to eggs in nutritional value as a single food source. Potato is a staple food in European countries and North America and a vegetable in the developing world including India, while a delicacy in some other countries. Per capita consumption of potatoes in India is 24 Kg/annum as compared to 33 Kg in the world. The diversified uses of potatoes cover fresh food, processed products (chips, French fries, flakes, granules, patties), animal food, seeds, and raw material for industries (mainly starch as raw material for alcohol, dextrin, and glucose) (Hawkes, 1990). Potato starch is used in the food industry in the instant pudding, as an additive to some bread and biscuits, and as a thickener in soups. It is also used in the manufacture of adhesives, paper, cosmetics, and pharmaceuticals. They can also be processed into dehydrated and canned products.

The cultivated potato is a primary food crop grown and consumed worldwide, forming a basic food and source of primary income for many societies. It is cultivated in a wide variety of soils and climates in more than 160 countries between 50^0 latitudes on both sides of the equator and from sea level to snow lines up to 4,000 meters altitude. Globally, potatoes are consumed fresh (63.36%), processing (8.25%), seed (7.98%), export (3.97%), and post-harvest losses. Worldwide, potatoes are grown on 16.49 million hectares with a production of 359.07 million tonnes and an average yield of 21.76 t/ha (FAOSTAT, 2022). India is the second largest producer of potatoes in the world after China with a total production of 56.17 Mt in 2020-21 and occupies the third place for the area after China and Russian Federation with an area of 2.20 m ha.

In potato breeding, the objective is to develop varieties with higher yields by overcoming various biotic and abiotic constraints, which limit the yield potential of cultivars. The development of processing varieties has become a meaningful preposition for the growth and development of the processing industry. The varieties should be widely adaptable, resistant to major disease and pests, possess good keeping, and can be used either for table or processing or both. Varieties should produce attractive, medium-sized, shallow-eyed, white, yellow, or red-skinned tubers, with less physical injuries with good keeping and nutritional quality. Low glycoalkaloid content and the ability to withstand cold-induced sweetening are added advantages. Potato varieties with specific quality attributes are required for processing purposes. For the preparation of good quality fried products (chips or French fries) or dehydrated products (flakes, flour, powder, etc.) tubers should have low reducing sugars (< 0.1%), low phenol content (< 0.02 %), and high dry matter content (> 20%). The round-shaped tubers of 45 to 80 mm diameter are preferred for making chips. For French fries, the oblong or long (more than 75 mm in length) tubers are desired.

Genetic resources and diversity

Genetic resources are important for sustainable crop production and their effective protection and use are essential to continue to feed the growing world population. Gene banks play a key role in the conservation and distribution of germplasm for crop improvement and sustainable food production. Genetic resources are the starting point of any plant improvement program. Potato germplasm, including wild and cultivated potatoes, is conserved in gene banks throughout the world. The genetic resources are classified into four categories: (1) wild relatives, (2) native cultivars, (3) modern cultivars of the common potato (*Solanum tuberosum* subsp. *tuberosum*), and (4) other germplasm (e.g., interspecific hybrids, breeding clones, etc.) (Bradshaw *et al*. 2006). Many gene banks around the world are maintaining potato genetic resources including wild types like the International Potato Center (CIP), Peru (7490 accessions), Leibniz Institute of Plant Genetics and Crop Plant Research (IPK), Germany (6124), United States Potato Introduction Project (NRSP-6), Sturgeon-Bay, Wisconsin, USA (5932), Vavilov Institute of Plant Industry, Russia (9000 accessions), Central Potato Research Institute (CPRI), India, (4,669), Commonwealth Potato Collection (CPC), Scottish Crop Research Institute (SCRI now the James Hutton Institute-JHI), Dundee, Scotland (1500); Dutch German Potato Collection (CGN), Wageningen, The Netherlands (1460); Potato Research Institute, Czechoslovakia (2225). In India at ICAR-CPRI, Shimla, the potato germplasm is being maintained in the field gene bank, true seeds, and in vitro conservation. Potato landraces and their wild relatives are diverse sources of genetic variation owing to their great range of ecological adaptation (from deserts to rainforests and even at elevations of 4,700 m above sea level) and wide geographical distribution which could be a source for the development of disease and insect-resistant variety.

Potato breeding and target traits

Presently breeders usually raise seedlings from crosses between pairs of parents with complementary traits to find the best genotype in the best progeny to clonally propagate as a new variety. Present-day cultivars not native to Latin America are an example of progress in utilization since the potato was introduced to Europe over 400 years ago. South American cultivar Daber, Chilean Tuberosum cultivar Rough Purple Chili, and North America's cultivar, Russet Burbank were some of the famous initial varieties, which were used extensively as a parent for the development of many past potato varieties. It was not until the 1930s that modern potato breeding began in China and India, and these countries are now among the leading potato producers in the world. A remarkable achievement of traditional plant breeding outside of South America can be seen in the 2005 edition of the World Catalogue of Potato Varieties, which includes over 4000 cultivars from more than 100 countries. The main route to new cultivars will, no doubt, continue to be traditional breeding involving crosses between pairs of parents with complementary features.

Quality traits

An important aspect kept in mind is the marketability of the produce involving tuber color, size, shape, and defects. Based on dry matter and texture, potatoes can be used for different purposes. A mealy texture is associated with high solids and a waxy texture with low solids. Potatoes containing more than 20% dry matter content with a mealy texture are preferred for fried and dehydrated products, while small-size potatoes containing dry matter between 18-20% with a waxy texture are preferred for salad making and canning. In general, white, yellow, or red skin varieties with shallow or medium eyes are the choice of consumers. Potato varieties with specific quality attributes are required for processing purposes (Luthra *et al*. 2006b). These should possess high dry matter, low reducing sugars, and fewer tuber defects for producing quality processed potato products. Low glycoalkaloid content and the ability to withstand cold-induced sweetening are added advantages. The genetic resources for cold sweetening have been identified (Luthra *et al.* 2009, 2018).

Late blight resistance

Late blight is the most economically important potato disease. This pathogen can infect stems, berries, leaves, and tubers, which leads to complete crop loss. In the nineteenth century, *P. infestans* caused severe destruction of potato crops in Europe, especially in Ireland, where potatoes were the staple food. Intensive research on potato late blight has led to the discovery of dominant resistance genes against *P. infestans* (*Rpi* genes) in potato wild species. The research was initiated to introduce the Rpi genes from *Solanum demissum* into potato cultivars. Potato cultivars carrying resistance genes derived from *S. demissum*, including Pentland Ace (*R3a* and *R3b*), Pentland Dell (*R1*; *R3a*; *R3b*; *Rpi-abpt*), have been registered and cultivated on a large scale in Europe (Paluchowska *et al.*, 2022) . Other cultivars having late blight resistance genes were released throughout the world like the North American cultivar Early Rose (*Rpi-blb2*; *Rpi-vnt1.3*), European cultivar Sarpo Mira (*R3a*; *R3b*; *R4*; *Rpi-Smira1*; *Rpi-Smira2*), Toluca (*Rpi-blb2*), Biogold (*Rpi-abpt*), Craigs Snow White (*R1*), Innovator (*R1*; *R2*-like; *R3a*; *R3b*), Chinese cultivar, Cooperation 88 (*R1*; *R2*; *R3a*; *Rpi-blb1*; *Rpi-blb2*; *Rpi-vnt1*), famous Indian cultivar Kufri Jyoti (*R3*, *R4*, *R7*) and various inouse developed interspecific somatic hyrbids having high resistance to late blight (Luthra *et al.* 2016, 2019; Bhatia *et al.* 2023).

Virus Resistance

Virus infection is mainly responsible for the degeneration of potato seed stocks and probably 54 viruses are identified in the potato which can cause symptoms in foliage and tubers (Jeffries & Lacomme, 2018). Common symptoms in foliage (mosaic, rolling, chlorosis, etc.) and tubers (necrosis and growth cracks) affect yield and tuber quality ultimately affecting marketability. Out of 54 viruses reported in potatoes, some are very common and are found everywhere and some are confined to specific geographical areas. Molecular markers have been applied in virus resistance breeding worldwide (Mangal *et al.* 2021).

Nematode resistance

Nematodes can be found in great numbers in soils. They are small, slender, non-segmented worms that measure between 0.1 and 2.5 mm in length. The most common species are the cyst nematodes (PCN), *Globodera pallida* (pale/white PCN), and *G. rostochiensis* (golden PCN), which are treated as quarantine species in most areas of the world because of their economic impact.

Cold stress

Cold stress sensitivity is a major factor limiting potato production; freezing damage to foliage results in reduced tuber yield and limits cultivation. Although potato is considered to be a cool season crop, freezing damage to the foliage occurs at -3°C, rendering the crop sensitive to episodic frost events both in the spring and fall. The risk of frost damage to the crop by spring and fall frosts limits the effective growing season and therefore the yield potential of the potato crop (Wang-Pruski & Schofield, 2012). In India, potato crop grown in the northern plains (Punjab, Haryana, Rajasthan, and western parts of Uttar Pradesh, Gujarat, and Madhya Pradesh) is prone to frost during the later part (December and January) of the autumn crop season. The genetic resources having frost tolerance have been identified in India (Luthra *et al.*, 2007, 2008; Luthra, 2022).

High temperature stress

High temperatures are also a major limitation on potato production in many developing countries, which prevails during most of the year. The optimum temperature for the growth of haulms is about 25°C, whereas, for rapid tuberization moderate temperatures (about 18–20°C) are beneficial. Optimum temperatures for tuber bulking are between 15–20°C. A progressive reduction in tuberization is encountered with increasing temperatures up to 30°C (Khanna, 1966). Minimum night temperature plays a crucial role during tuberization in potatoes. The tuberization is reduced at night temperatures above 20°C with complete inhibition of tuberization above 25°C. Reductions in leaf area, tuber number, and tuber weight have been reported as symptoms of elevated temperatures during the growing season of potato plants (Luthra *et al.*, 2013).

Water stress

Water stress during tuber initiation has been reported to reduce tuber set. The development of drought-tolerant cultivars is one of the major breeding objectives in hot tropical environments where moisture is insufficient during the growing season (Arvin and Donnelly, 2008). Because of the crop's sensitivity to drought stress, much of the commercial potato crop is grown under irrigation but the cost of the associated irrigation infrastructure and use-based irrigation fees add substantially to the cost of production. In sub-tropics where potato production is only possible with irrigation, short periods of drought often arise because of inadequate irrigation techniques or shortage of water. Taking into account production conditions and the present yield levels, it is estimated that the average potato yield in the world could be increased by at least 50% if the water supply to the crop could be optimized. Therefore, the identification of drought-tolerant genotypes for yield maintenance and breeding purposes is now a priority for improving drought tolerance of potato crops, saving irrigation water, and ensuring yield and food security in the changing scenario of global climate and growing demand for water (Luthra *et al.* 2019, 2020).

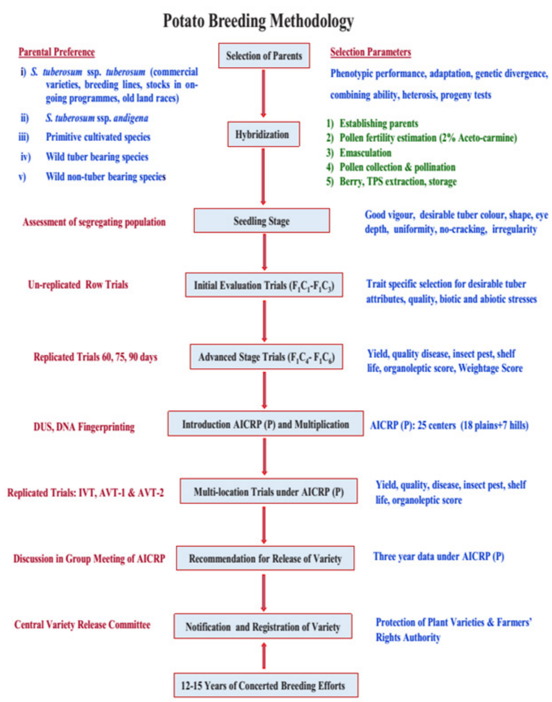

Figure 1: The outline of potato breeding Methodology

Varietal development in India

Based on the diverse soil, climate, agronomic features, and varietal requirements, the potato growing areas in India can be divided into eight zones (Luthra *et al*., 2006). These zones lie in two major potato growing areas i.e. North-Indian hills and North-Indian plains, while southern and north-Bengal and Sikkim hills and plateau are three special problem areas. The outline of the potato breeding methodology is depicted in Figure 1 (Luthra *et al*., 2020). Breeding efforts at the ICAR-Central Potato Research Institute have led to the development of 69 improved potato varieties and a TPS population (92-PT-27) over 72 years, for cultivation in diverse agro-climatic zones of the country (Table 1).

In breeding programs involving resistance to late blight, cyst nematodes, wart, etc. it is possible to discard susceptible genotypes in the seedling stage itself. The breeding population in such cases is subjected both to resistance tests and to rejections based on unacceptable tuber characters.

Screening for late blight resistance

The 4 to 6 weeks old seedlings are screened under controlled conditions against complex races of *Phytophthora infestans* and resistant seedlings are transplanted in the earthen pots in the glass house/field and retained for further evaluation.

Screening for PCN resistance

The selected F_1C_2 stage clones are screened for PCN resistance in the glass house. Five tubers of the selected clone are planted in the pots containing a population of 200 to 250 cysts of both species of Globodera per 100 mL soil. Clones showing 0 to 5 females/ root ball after 60 to 70 days of planting are selected.

Screening for processing

Five tubers of each clone in the F_1C_1 stage are dipped in the brine solution for specific gravity estimation and clones with >1.08 specific gravity are selected. The selected clones in the F_1C_2 generation are tested for chips/ French fries color. Clones showing poor keeping quality due to high shrinkage, rottage, weight loss, and excess sprouting after cold storage are rejected.

Screening for heat tolerance

The seedlings are screened by exposing them at >20°C night temperature and seedlings with the ability to form tubers after 4 to 8 weeks of treatment are selected for further evaluation.

Potato genomics

Potato is the world's most important vegetable crop and the 3rd largest global food crop. The potato genome sequencing: ICAR-Central Potato Research Institute, Shimla had been the partner of the Potato Genome Sequencing Consortium (PGSC) comprising 26 international institutes belonging to 14 countries. Dr. S.K. Chakrabarti was the country leader in the potato genome sequencing project. In India, the project was fully funded by the ICAR, New Delhi, and was executed by ICAR-CPRI, Shimla. The consortium deciphered the complex genome of potato (tetraploid and highly heterozygous) that has been published in the high-impact journal "Nature". This is the first genome of a plant belonging to the Asterid clade of eudicot that represents 25% of flowering plant species. A total of 39,031 protein-coding genes have been predicted in the 840 Mb genome of potatoes. The potato genome data is freely available to the public for research use at *http://solanaceae.plantbiology.msu.edu/pgsc_download.shtml*.

The term functional genomics can be referred to as the "development and application of global (genome-wide or system-wide) experimental approaches to assess gene function by making use of the information and reagents provided by structural genomics" It involves the use of high-throughput methods for the study of large numbers of genes (ideally the entire set) in parallel. Indirect information on cellular or developmental function can be obtained from spatial and temporal expression patterns; for example, the presence of mRNA and/or protein in different cell types, during development, during pathogen infection, or in different environments. The subcellular localization and posttranslational modifications of proteins can be informative as well. The institute has mastered in many functional genomics techniques by standardizing them for potatoes. Since the potato genome sequence is available to the public it can very well be used for functional validation. The techniques used for functional genomics in potatoes by the institute include RNASeq and microarray at the

Table 1: Indigenous potato varieties released by ICAR-CPRI, Shimla

Name	*Year of release*	*Areas of adaptation*	*Salient features*
Kufri Kisan*	1958	North Indian plains	Maturity late; tubers white round, eyes deep and prominent eyebrows and flesh white.
Kufri Kuber*	1958	North Indian plains and plateau region	Maturity medium; tubers white ovoid, tapering towards the crown end, eyes medium deep, flesh white; resistant to PLRV and immune to PVY.
Kufri Kumar*	1958	North Indian hills	Maturity late; tubers white ovoid, tapering towards heel end, eyes fleet, flesh white; immune to wart and resistant to charcoal rot.
Kufri Kundan*	1958	North Indian hills	Maturity medium; tubers white round-ovoid, flattened, eyes medium deep, flesh cram; resistant to charcoal rot.
Kufri Red*	1958	North eastern plains	Maturity medium; tubers red round, eyes medium deep, and flesh yellow.
Kufri Safed*	1958	North Indian plains	Maturity late; tubers white round, eyes medium deep and red-purple, and flesh light yellow.
Kufri Neela*	1963	South Indian hills	Maturity late; tubers white ovoid, eyes medium deep, flesh white; resistant to cyst nematodes.
Kufri Sindhuri	1967	North Indian plains	Maturity late; tubers red round, eyes medium deep, flesh cream; moderately resistant to early blight and tolerant to PLRV.
Kufri Alankar*	1968	North Indian plains	Maturity medium; tubers white ovoid, eyes fleet, flesh white; moderately resistant to late blight.
Kufri Chamatkar*	1968	North Indian plains	Maturity late; tubers white round, eyes medium deep, flesh yellow; resistant to early blight, charcoal rot, and immune to wart.
Kufri Chandramukhi	1968	North Indian plains and plateau region	Maturity early; tubers white ovoid, slightly flattened, eyes fleet and flesh white.
Kufri Jeevan*	1968	North-Indian hills	Maturity late; tubers white ovoid, eyes fleet, flesh white; moderately resistant to late blight.
Kufri Jyoti	1968	Hills, plains and plateau region	Maturity medium; tubers white ovoid, eyes fleet, flesh white; moderately resistant to late blight and immune to wart.
Kufri Khasigaro*	1968	North-eastern hills	Maturity late; tubers white round-ovoid, eyes deep, flesh cream; moderately resistant to late blight and early blight.
Kufri Naveen*	1968	North-eastern hills	Maturity late; tubers white ovoid, eyes fleet, flesh white; moderately resistant to late blight and immune to wart.
Kufri Neelamani*	1968	South Indian hills	Maturity late; tubers white ovoid, flattened, eyes fleet, flesh white; moderately resistant to late blight.
Kufri Sheetman*	1968	North-western plains	Maturity medium; tubers white ovoid, eyes fleet, flesh cream; moderately resistant to charcoal rot and tolerant to frost.
Kufri Muthu*	1971	South Indian hills	Maturity medium; tubers white round-ovoid, eyes medium deep, flesh white; moderately resistant to late blight and immune to wart.
Kufri Lauvkar	1972	Plateau region	Maturity early; tubers white round, eyes fleet, flesh white; tolerant to heat.
Kufri Dewa*	1973	North Indian plains	Maturity late; tubers white round, eyes pink and medium deep, flesh cream; tolerant to frost.
Kufri Badshah	1979	North Indian plains and plateau region	Maturity medium; tubers white ovoid, eyes fleet, flesh white; moderately resistant to late blight, early blight, and PVX.
Kufri Bahar	1980	North Indian plains	Maturity medium; tubers white round-ovoid, eyes fleet, flesh white; immune to wart.
Kufri Lalima	1982	North Indian plains	Maturity medium; tubers red round, eyes medium deep, flesh white; moderately resistant to early blight and resistant to PVX.
Kufri Sherpa*	1983	North Bengal hills	Maturity medium; tubers white round flattened, eyes medium deep, flesh cream; moderately resistant to early blight and late blight, and immune to wart.
Kufri Swarna	1985	South Indian hills	Maturity medium; tubers white round-ovoid, eyes fleet, flesh white; moderately resistant to late blight and early blight, immune to wart, highly resistant to cyst nematodes.

Kufri Megha*	1989	North-eastern hills	Maturity late; tubers white round-ovoid, eyes fleet, flesh white; resistant to late blight.
Kufri Jawahar	1996	North Indian plains and plateau region	Maturity medium; tubers white round-ovoid, eyes fleet, flesh white; moderately resistant to late blight and immune to wart.
Kufri Sutlej	1996	North Indian plains	Maturity medium; tubers white ovoid, eyes fleet, flesh white; moderately resistant to late blight and immune to wart.
Kufri Ashoka	1996	North Indian plains	Maturity early; tubers white ovoid, eyes medium-deep, flesh white.
Kufri Pukhraj	1998	North Indian plains and plateau region	Maturity early; tubers white ovoid, slightly tapered, eyes fleet, flesh yellow; resistant to early blight; moderately resistant to late blight and immune to wart.
Kufri Chipsona-1	1998	North Indian plains	Maturity medium; tubers white ovoid, eyes fleet, flesh white; resistant to late blight; suitable for chips and French fries.
Kufri Chipsona-2	1998	North Indian plains	Maturity medium; tubers white round, eyes fleet, flesh cream; resistant to late blight; tolerant to frost and suitable for chips.
Kufri Giriraj	1998	North Indian hills	Maturity medium; tubers white ovoid, eyes fleet, flesh white; resistant to late blight and immune to wart.
Kufri Anand	1999	North Indian plains	Maturity medium; tubers white ovoid-oblong, eyes fleet, flesh white; moderately resistant to late blight and immune to wart.
Kufri Kanchan	1999	North Bengal hills & Sikkim	Maturity medium; tubers red ovoid-oblong, eyes fleet, flesh cream; moderately resistant to late blight and immune to wart.
Kufri Arun	2005	North Indian plains	Maturity medium; tubers red ovoid, eyes medium deep, flesh cream; moderately resistant to late blight.
Kufri Pushkar	2005	North Indian plains	Maturity medium; tubers white round-ovoid, eyes medium deep, flesh light yellow; resistant to late blight and immune to wart.
Kufri Shailja	2005	North Indian hills	Maturity medium; tubers white, round-ovoid, eyes fleet, flesh white; moderately resistant to late blight.
Kufri Chipsona-3	2006	North Indian plains	Maturity medium; tubers white, round-ovoid, eyes fleet, flesh cream; resistant to late blight; suitable for chips and French fries.
Kufri Surya	2006	North Indian plains and plateau region	Maturity early; tubers yellow oblong, eyes fleet, flesh yellow; immune to wart; resistant to hopper burn and heat tolerant; suitable for early plating.
Kufri Himalini	2006	North Indian hills	Maturity medium; tubers white ovoid-oblong, eyes shallow, flesh cream; moderately resistant to late blight.
92-PT-27**	2007	Eastern plains	Maturity medium; tubers white-cream-yellow round-ovoid-oblong, eyes shallow to medium deep, flesh white-cream-yellow; field resistant to late blight.
Kufri Himsona	2008	North Indian hills	Maturity medium, tubers white round-ovoid, eyes fleet, flesh cream; resistant to late blight and suitable for chips.
Kufri Sadabahar	2008	Uttar Pradesh and adjoining areas	Maturity medium; tubers white oblong, eyes fleet, flesh white; resistant to late blight.
Kufri Girdhari	2008	North Indian hills	Maturity medium; tubers white ovoid-oblong, eyes fleet, flesh pale yellow; resistant to late blight.
Kufri Khyati	2008	North Indian plains	Maturity early; tubers white ovoid, eyes fleet, flesh cream; moderately resistant to late blight.
Kufri Frysona	2009	North Indian plains	Maturity medium; tubers white-cream long-oblong, shallow eyes, flesh white; resistant to late blight; suitable for French fries.
Kufri Neelima	2010	Nilgiri hills	Maturity medium; tubers white ovoid, eyes shallow, flesh white; highly resistant to cyst nematodes; resistant to late blight.
Kufri Garima	2012	Indo-Gangetic plains and plateau	Maturity medium; tubers light yellow ovoid, eyes shallow, flesh light yellow; resistant to late blight.
Kufri Gaurav	2012	North Indian plains	Maturity medium; tubers white-cream ovoid, eyes medium deep, flesh white-cream; nutrient use efficient variety.
Kufri Lalit	2013	Eastern plains	Maturity medium; tubers light red round, eyes medium deep, flesh light yellow; resistant to late blight.

Kufri Mohan	2015	Northern and Eastern plains	Maturity medium; tubers white-cream ovoid, eyes shallow, flesh white; moderately resistant to late blight.
Kufri Lima	2018	North Indian plains	Maturity medium-late; tubers white-cream ovoid, shallow eyes, cream flesh; extreme resistance to PVX and PVY and moderately resistant to root-knot nematode; resistant to hopper burn and heat tolerant; suitable for early plating.
Kufri Ganga	2018	North Indian plains	Maturity medium; tubers white-cream ovoid, shallow eyes, flesh cream; moderately resistant to late blight.
Kufri Neelkanth	2018	North Indian plains	Maturity medium; tubers purple ovoid, eyes shallow, flesh yellow; moderately resistant to late blight; specialty potato, rich in anti-oxidants with excellent flavour.
Kufri Sahyadri	2018	Nilgiri hills	Maturity medium; tubers light yellow ovoid, eyes shallow medium, flesh yellow; resistant to late blight and potato cyst nematode.
Kufri Karan	2018	Hills and Plateau region	Maturity late; tubers white-cream ovoid, eyes shallow, flesh white; resistant to late blight, APCLV, PVX, Y, S, A, M, PLRV; moderately resistant to PCN.
Kufri Manik	2020	Eastern plains	Maturity medium; tubers red round, eyes medium deep, flesh yellow; moderately resistant to late blight; possess anthocyanin and carotenoids
Kufri FryoM	2020	Northern and Central plains	Maturity medium; tubers white oblong, eyes shallow, flesh white; field resistance to late blight and potato virus Y; suitable for French fries
Kufri Chipsona 4	2020	Karnataka, West Bengal, Madhya Pradesh, and Gujarat	Maturity medium; tubers white-cream round, eyes shallow, flesh white; resistant to late blight; suitable for chips.
Kufri Sangam	2020	Northern and Central plains	Maturity medium, tubers white-cream ovoid, eyes shallow, flesh white; moderately resistant to late blight and excellent storability; Very good taste, aroma, mealy texture; suitable for table purposes and processing to chips & French fries.
Kufri Thar-1	2020	Orissa and Uttar Pradesh	Maturity medium, tubers white-cream round-oval, eyes shallows-medium, flesh cream; moderate resistance to late blight; very good storability; suitable for drought prone areas.
Kufri Thar-2	2020	Uttar Pradesh, Rajasthan, Haryana, and Chhatisgarh	Maturity medium, tubers light yellow ovoid, eyes shallow, flesh light yellow; good taste, typical potato flavor, mealy texture, very good keeping quality, long tuber dormancy; suitable for drought prone areas.
Kufri Thar-3	2020	Haryana, Uttar Pradesh and Chhatisgarh	Maturity medium; tubers white round-oval, eyes shallow, flesh cream. Slightly resistant to late blight; High water use efficiency.
Kufri Kiran	2021	North Indian plains and Plateau	Maturity early; tubers white-cream ovoid, eyes shallow, flesh cream; Tolerant to hopper/mite burn and high temperature; suitable for early plating.
Kufri Lohit#	2021	North Indian Plains (Central & eastern plains)	Maturity medium; tubers red, ovoid, eyes shallow, flesh cream, mealy texture; Field resistant to late blight
Kufri Uday#	2021	North Indian plains	Maturity early medium; tubers red, ovoid, eyes shallow, flesh yellow, mealy texture; Field resistant to late blight
Kufri Chipsona-5#	2022	North Indian plains	Maturity medium, tubers White-cream, ovoid, shallow, cream, mealy texture, Field resistant to late blight, suitable for chips
Kufri Bhaskar#	2022	Northern and Central plains	Maturity medium, tubers white-cream, ovoid, shallow, cream, mealy texture, tolerant to hopper and mite, suitable for early plating
Kufri Daksh#	2022	Central and Eastern plains	Maturity medium, tubers light yellow, ovoid, shallow, cream, mealy texture, water use efficient

*Not under seed production at present, **TPS population; #Notification awaited

Plains: Early (70-90 days), Medium (90-100 days), and Late (>100 days);

Hills: Early (100-110 days), Medium (110-120 days), and Late (>120 days)

whole genome level and reverse genetic approaches like gene knockout by RNAi (RNA interference) and VIGS (virus-induced gene silencing) at the gene level (Tiwari, 2023).

Functional genomics for late blight resistance

A typical microarray experiment involves the hybridization of an mRNA molecule to the DNA template from which it originated. Many DNA samples are used to construct an array. The amount of mRNA bound to each site on the array indicates the expression level of the various genes (Tiwari, 2023). This number may run in thousands. All the data is collected and a profile is generated for gene expression in the cell. Microarray analysis for late blight resistant Indian potato cv. Kufri Girdhari revealed up-regulation of 2,344 genes post-inoculation compared to the pre-inoculation stage. It was observed that defence-responsive genes played a key role in the late blight resistance mechanism in potato somatic hybrid clone P-7. MicroRNAs have been shown to play a significant role in local defense, but their association with SAR is unknown. We investigated the role of miR160 in local and SAR responses to *P. infestans* infection in potatoes. MiR160 is associated with local defense and systemic acquired resistance of potatoes against *Phytophthora infestans* infection. The study demonstrates that miR160 plays a crucial role in local defense and SAR responses during the interaction between potatoes and *P. infestans*. In another study, identified genes for late blight resistance in potato somatic hybrids by transcriptome (RNA sequencing) analysis. Potato somatic hybrids (C-13 + *S. pinnatisectum*; C-13 + *S. cardiophyllum*) and parent C-13 were analyzed for late blight resistance by total RNA sequencing. A total of 110 potato genes were found statistically significant ($p < 0.01$) and differentially regulated in various samples for late blight resistance. Identified 17 RB-homologous gene fragments in 11 wild species (*S. chacoense*, *S. pinnatisectum*, *S. polyadenium*, *S. trifidum*, *S. cardiophyllum*, *S. lesteri*, *S. huancabambense*, *S. verrucosum*, *S. jamesii*, *S. polytrichon* and *S. stoloniferum*) of total 44 wild potato species.

Functional genomics for virus resistance

Microarray analysis for differentially regulated genes in response to Apical leaf curl virus resistance. Apical leaf curl disease, caused by tomato leaf curl New Delhi virus-[potato] (ToLCNDV-[potato]), is one of the most important viral diseases of potatoes in India. The genetic resistance source for ToLCNDV in potatoes is not identified so far. Microarray analysis showed that a total of 1111 genes and 2588 genes were differentially regulated in Kufri Bahar (resistant) and Kufri Pukhraj (susceptible), respectively. We identified a total of selected 680 genes in Kufri Bahar, in response to ToLCNDV-potato infection.

Functional genomics for potato tuberization

Identification of genes and pathways affected by high temperature is crucial for developing thermo-tolerant cultivars. Identified heat-tolerant genes in potatoes in response to high night temperature for tuberization. Identified genes controlling potato tuberization in somatic hybrids ['C-13' (+) *S. etuberosum*] by microarray. A total of 468 genes (94 up-regulated and 374 down-regulated) were identified that were statistically significant and differentially expressed in tuber-bearing potato somatic hybrid (E1-3) versus control non-tuberous wild species *S. tuberosum* (Etb). Night temperature beyond 20℃ drastically reduces tuber formation, constraining potato cultivation in the tropics and subtropics (heat tolerant: Kufri Surya *vs.* heat sensitive: Kufri Chandramukhi). Microarray gene expression analysis showed a total of 2500 genes were differentially expressed on 21 days and 4096 genes on 14 days after stress. This study provided useful information on potato tuberization at elevated night temperatures (24℃) and made available a framework for further investigations into heat stress in potatoes.

Functional genomics for improving nitrogen use efficiency in potato

Potato is an N fertilizer responsive crop to produce high tuber yield. The excessive use of N can results in environmental damage and high cost of production, hence improving the NUE of the potato plant is one of the sustainable options to address these issues and increase yield. Potato varieties Kufri Jyoti (N inefficient) and Kufri Gaurav (N efficient) were grown in aeroponics with our solution (patent applied), without N (starvation), low N, and high N. Transcriptomes (total RNA sequencing) were analyzed in leaf, root, and stolon tissues to identify genes and regulatory elements controlling NUE in potatoes. Under the N starvation condition, 233 genes were upregulated, whereas 1188 genes were downregulated in leaf tissues of Kufri Jyoti compared to N sufficient condition. In root tissues of Kufri Jyoti, 645 genes were downregulated and 250 genes were up-regulated under N starvation than N sufficient conditions.

Virus induced gene silencing (VIGS)

VIGS is versatile too for understanding the functionality of biotic and abiotic stress genes in the potato genome. VIGS is a post-transcriptional gene silencing (PTGS) method used by plants as a defense mecha¬nism by targeting the integrity of invading viruses. It involves cloning a short cDNA sequence from a gene of interest into a viral delivery vector and transfecting the plant using Agrobacterium. A double-stranded RNA (dsRNA) is synthesized which is further degraded by plant Dicer-like enzymes into small interfering RNA (siRNA) molecules resulting in activation of PTGS thus leading to the generation of siRNA homologous to the target gene which finally results in the silencing of the endogenous plant gene. In potatoes, PVX (Potato Virus X) and TRV (Tobacco Rattle Virus) vectors have been found suitable for VIGS-based silencing. The main advantages of VIGS include its low cost and rapid performance by identifying a loss of function phenotype for a particular gene within a single generation. Since, its expression is transient in nature; therefore, it does not require laborious transformation procedures for the development of transgenic plants. Therefore, it is extensively used as a powerful tool for decoding the functional relevance of the genes. At the institute, Scientists have applied the VIGS system for functional analysis of genes in Tomato leaf curl New Delhi virus (ToLCNDV) susceptible potato cultivar Kufri Pukhraj by silencing three genes, viz. TMV-induced protein 1-2 gene, peripheral type benzodiazepine receptor, and conserved gene of unknown function. So, VIGS has been proven as a valuable tool in the identification of plant genes involved in infection and resistance to begomoviruses.

Quantitative Real Time-PCR Technology

The technologies are based on the measurement of fluorescence during PCR. The amount of emitted fluorescence is proportional to the amount of PCR product and enables the monitoring of the PCR reaction. The resulting PCR curve is used to define the exponential phase of the reaction, which is a prerequisite for accurate calculation of the initial copy number as well as for expression of the gene at the beginning of the reaction. The simplest and cheapest principle is based on the intercalation of double-stranded DNA-binding dyes. This technology can be easily applied to already established PCR assays and does not need any additional fluorescence-labeled oligonucleotide. However, specific and nonspecific PCR products are both detected. Therefore, these assays require careful optimization of the PCR conditions and a clear differentiation between specific and nonspecific PCR products using melting-curve analysis.

Genome editing

Genome editing is a versatile advanced breeding tool that can be employed for crop improvement programs by removing unwanted sequences and making them a desirable character of interest by gene knockout, knockin, and overexpression studies. Sequence editing either by deleting or modifying the genes individually and then studying the subsequent mutant phenotypes can address the challenges of understanding the function of genes. For precise DNA manipulations, new genome editing systems can induce double-stranded breaks (DSBs) at specific sites in the genome and repair naturally using DNA repair mechanism (non-homologous end-joining or homologous recombination mechanism) thereby, ensuring the gene mutation at the target site. This system is facilitated by protein-guided nucleases, such as zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), or special RNA/DNA-guided nucleases, including RNA-dependent DNA cleavage systems like clustered regularly interspaced short palindromic repeats (CRISPR) – associated protein (Cas) system.

CRISPR is an advanced and improved molecular breeding technique in terms of the creation of mutagenesis for a better improvement program. CRISPR (clustered regularly interspaced short palindromic repeats)/Cas (CRISPR-associated) system, has been developed as easy, specific targeted genome modifications and has emerged as the most powerful method due to ease in designing and construction of gene-specific single guide RNA (sgRNA) vectors. These sgRNA vectors are easily reprogrammable to direct *Streptococcus pyogenes* Cas9 (SpCas9) to generate double-stranded breaks (DSBs) in the target genomes that are then repaired by the cell via the error-prone non-homologous end-joining (NHEJ) pathway or by precise homologous recombination (HR) pathway. Gene editing technologies have been applied for many traits in different crops including potatoes. CRISPR/Cas9 technology has been successfully implemented in potatoes (MSU group USA) for targeted editing to generate mutations (through NHEJ) as well as gene targeting to edit an endogenous gene (by HR). In this bulletin, we describe procedures for designing sgRNAs, protocols to clone sgRNAs for CRISPR/Cas9 constructs to generate knockouts and the design of donor repair templates. Accordingly, CPRI also initiated CRISPR-based targeted editing of potato genome for generating a variety of specific potato seeds and late blight resistance lines.

Future prospective

The future roadmap of potato R&D at CPRI would be primarily focused on enhancing potato productivity to 34.51 t/ha by the year 2050 by producing 125 million tonnes of potatoes from an area of 3.62 million hectares. To meet the targeted demand of potatoes it is important to develop potato varieties with the desired level of productivity and quality. Potato varieties of the future would be of wider adaptability, better nutritional and keeping quality for diverse usage and resistant to major pests and diseases. Special efforts are required to develop varieties of French fries and baby potatoes. An ideal potato variety is not about yield and quality alone but also the production cost, environmental issues (requirement of pesticides), post-harvest losses (susceptibility to mechanical damage or sprouting), and yield of future crops. Conventional breeding may not provide a complete answer to the set objectives. Potato breeders have to use wild species on a large scale to realize national targets. Further to overcome crossability barriers novel techniques like somatic fusions, the use of molecular markers, and the production of transgenics through biotechnological means will be required. The results of all these efforts will be watched with interest.

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सारांश

आमतौर पर उगाई जाने वाली आलू एक टेट्राप्लोइड है और सोलनम ट्यूबरोसम प्रजाति से संबंधित है, जिसमें दो प्रजातियाँ टुबेरोसम (लंबे दिनों) एवं एंडीजीना (छोटे दिनों) वाले शामिल हैं। पारंपरिक आलू प्रजनन कार्यक्रम विधि में संभावित पैतृक वंशक्रमों की पहचान, क्रॉसिंग के माध्यम से प्रोजेनी का विकाश और आगे उनका मूल्यांकन सामिल है। पिछले सात दशकों के दौरान, केंद्रीय आलू अंसन्धान संस्थान, शिमला ने लगभग 70 किस्मों को विकशित किया है। ये किस्में देश भर के किसानों की जरूरतों को पूरा करती हैं। इन क़िस्मों में विभिन्न जैविक और अजैविक तनावों के लिए प्रतिरोधिता व बेहतर कृषि संबंधी गुणो का समावेश हैं। जंगली प्रजातियों का उपयोग करते हुए कायिक संकर का विकाश किया गया है जिन्हें जीन पूल बढ़ाने में मदद हुआ है. इसके अलावा आलू के विकाश में बायोटेक्नोलॉजी एवं जीनोमिक्स का प्रयोग हुआ है।