CROP IMPROVEMENT BY RADIATION-INDUCED MUTATION BREEDING

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Abstract:

Atomic energy has peaceful applications in agriculture for crop improvement, crop production and crop protection. Crop improvement is basically dependant on wide genetic variability for economic characters towards achieving higher productivity for food security. In nature, occurrence of genetic change (mutation) is evolutionarily slow and gradual process. The frequency of such mutations can be increased through atomic radiations. These radiations bring genetic changes at chromosomal, gene or DNA level, which are manifested into desirable characters in crop plants. India's economy is immensely reliant on continued developments and accomplishments in agriculture amid rising concerns due to climate change, growing population and dwindling agricultural land. Mutation breeding being one of the important breeding method contributed significantly for crop improvement by bringing unique genetic variability, evolving superior varieties and rectifying popular varieties in various crops. Since 1950s, BARC has been involved in radiation-based mutation breeding by using beta particles, X rays, gamma rays and recently electron beam. BARC has successfully developed 62 improved Trombay varieties in cereals, pulses and oilseeds and were released and notified for farmer cultivation across the country in collaboration with ICAR research institutes and State Agricultural Universities. Several of Trombay varieties have been cultivated extensively by the farmers in most of the states and have immensely benefitted them by enhancing their farm income.

Keywords: *Agriculture, Crop improvement, Induced mutation, Mutation breeding, Gamma rays, Oilseeds, Pulses, Cereals*

Introduction:

Agriculture along with its allied sectors, is the principal source of livelihoods in our country. It forms the backbone of Indian economy as it engages 54% of the workforce and contributes about 21% Gross value added (GVA) to the country. Of the India's total geographical area of 328.7 million ha, 139.90 million ha were reported to be net sown area and 211 million ha were gross cropped area. In 2021-22, total food grain production was estimated at 285 million tonnes. India is the world's highest producer of pulses, onion, milk, buffalo, goat and ranks second for the production of rice, wheat, sugarcane, groundnut, cotton, tobacco, jute, tea, potato, vegetables, fruits, egg, cattle and sheep. By 2030, India's population is likely to reach 1.5 billion and therefore our motto is to produce more food from shrinking arable land, reducing irrigation water amid increasing biotic and abiotic stresses. Implications due to climate change, such as extreme temperature, drought, water logging, flooding and increased soil salinity are also affecting food production. These challenges need to be addressed through innovative agricultural research along with appropriate policies, effective delivery and market systems. Synergistic blend of conventional and innovative methodologies in crop improvement, crop production and crop protection would contribute significantly towards achieving country's nutritional and food security. Bhabha Atomic Research Centre (BARC), Mumbai has been engaged in the field of nuclear agriculture by using atomic radiations to develop newer crop varieties through mutation breeding; to control insect pests; to trace the pesticide residues and uptake of fertilizers and other nutrients.

Crop breeding:

Crops have progressed over a time with complicated genetic systems, which allow them to acclimatize to environmental changes towards completing their life cycle. Since the environment differs as per season and location, performance of variety also varies from season to season and place to place. Persistent plant breeding endeavours based on Mendelian genetic principles have played critical role for improving crop varieties. Crop breeding is an art and science of improving characters in crops to make more desirable agronomically and economically for the benefit of humankind. Crop breeders have put forward consistent efforts to make our food, fiber, forage and industrial crops more productive and nutritious by improving traits like yield, nutritional value, taste, color, maturity, plant type, adaptation to environmental stresses (heat, drought, frost, salinity), resistance to pests and diseases etc., For crop improvement, breeders employ various breeding methods viz., recombination breeding to pool together desirable genes from various parents; mutation breeding to create new alleles; heterosis breeding to exploit hybrid vigour; molecular marker-assisted selection; genetic engineering to incorporate genes from distant species and gene editing to modify specific genes. These developments have fetched huge societal gains, larger food and nutritional security, better food choices and safer foods.

Induced mutations:

Mutation is a heritable change in the genetic material of an organism not caused by recombination or segregation. It has been the main driver for crop evolution, hence their speciation and domestication. Mutagenesis is the process of bringing changes in the genetic information in a stable manner. It can be a) **Induced mutagenesis,** wherein mutation is induced by treating the seeds with radiations or chemical mutagens; b) **Insertion mutagenesis,** wherein mutation is obtained due to DNA insertions from genetic transformation or transposon activation and c) **Site-directed mutagenesis** by creating a mutation at a targeted DNA site by genetic transformation followed by homologous recombination between the T-DNA fragment and native DNA molecules. Induced mutants occur at random whose genes mostly are recessive in nature occasionally with pleiotropic effects and are influenced by genetic background and environmental effects. Induced mutagenesis dates back to early 20th century following the discovery of X- rays and their application to induce mutations in barley seedlings and sterility in maize tassels as shown by Stadler in 1928.

Mutagen:

A mutagen is an agent that brings genetic mutations in DNA. These agents include physical, chemical and biological agents. Physical mutagens, generally ionizing radiations have been employed for bringing mutations in plants. Globally, >85% mutant varieties were developed through radiations. Radiation is an energy travels through a distance either in the form of particles (corpuscular radiation) or waves (electromagnetic radiation). Further, radiations are ionizing or non-ionizing based on their capacity to produce ions. When ionizing radiation pass through a plant tissue, it dislodges an electron from its orbit around the nucleus, thus producing an ion (ionization) and free radicals. Radiations bring changes in base sequence of DNA molecule either by base substitution (transition or transversion) or by base addition or deletion. Majority ionizing radiations are released from naturally decaying isotopes and also can be produced artificially in reactors and later modified through accelerators (Table 1). The most commonly used chemical mutagens for crop improvement include alkylating agents (Eg.: Ethyl methanesulphonate, nitrosoethyl urea, N-methyl N-nitrosourea, colchicine) and sodium azide.

Table 1: Ionising radiations applied for induced mutagenesis in crop plants

Types of radiation	Source	Plant tissue penetration
X-rays	X-ray machine	A few mm to many cm
Gamma rays	Nuclear reactor, Radioisotopes	Whole part
Neutron (Slow, Fast, Thermal)	Nuclear reactors, accelerators	Many cm
Beta particles, fast electrons	Radioactive isotopes or accelerators	Several cm
Alpha particles	Radioisotopes	Fraction of a mm
Protons	Nuclear reactors or accelerators	Up to many cm
Ion beams	Particle accelerators	A fraction of mm to few cm

In some situations, physical mutagens are better and more effective in comparison to chemical mutagens. In vegetatively propagated crops, large sized plant material in greater number needs to be treated with the mutagen to have larger M_2 population. Physical mutagens have deeper penetrability in tissues of these crops than chemical mutagens. In order to introduce beneficial gene from distant species or genera through inter-specific or inter-generic crosses, physical mutagens facilitate better chromosomal translocations from such species than chemical mutagens. In genetically conserved plant species, physical mutagens are better placed to bring gross genetic changes. Transposons get activated comparatively more in the genome through physical mutagens. Such activation of transposons in turn bring mutations in the genes. Physical mutagens would influence DNA methylation or demethylation towards altering gene expression.

Mutation breeding:

Crop improvement is a continuous process of development of suitable improved varieties for which greater genetic variability of target traits is extremely crucial. In nature, new variability arises spontaneously due to effect of natural radiations and other factors at extremely low frequency (one in a million). Using radiations and/or other chemical mutagens, mutation frequency can be enhanced to several folds (one in thousands). The resulting phenotypic diversity from induced genetic variation is used to develop new traits during plant breeding. Induction, isolation and stabilization of mutants for crop improvement is termed as **mutation breeding**.

Fig. 1 Seed irradiation with gamma rays: a. BRIT gamma irradiator 2000; b. Time setting for gamma irradiation based on dose rate; c. Positioning of seed samples for irradiation

Successful mutation breeding starts with well-defined objectives to generate new genetic variability for nuclear and/or cytoplasmic traits; to improve one or few traits in popular and well adapted variety; to break the tight linkages between the traits; to enhance chromosomal translocations in inter-specific crosses and to improve vegetatively propagated crops (eg: banana, sugarcane, potato, turmeric etc.). In mutation breeding, the main goal is to develop suitable varieties with enhanced seed yield and nutrients, earliness, desired seed size and dormancy, tolerance to diseases, insects, drought, salinity, heat, etc. For physical mutagenesis, existing popular cultivars, varieties, mutants, selections, hybrids or advanced lines of target crop are selected. To begin with, effective dose ideal for mutant induction has to be standardized for the selected genotype in each crop by treating seeds with series of doses of radiations like gamma rays (Fig. 1). Later, values on seed germination and seedling growth are subjected to Probit analysis to derive the dose close to LD_{50} (50% lethal dose) and GR_{50} (50% growth reduction). For large scale induced mutagenesis, seeds are treated with 2-3 doses of gamma rays around LD_{50} or GR_{50} values (M_1 generation). These treated M_1 seeds are sown in the agricultural fields to raise M_1 plants. Seeds (M_2) from the M_1 plants are sown to raise M_2 generation. Usually genetic variants (mutants) are identified from M_2 generation onwards. In the subsequent generations, breeding behavior of the induced mutants is studied and is followed till the

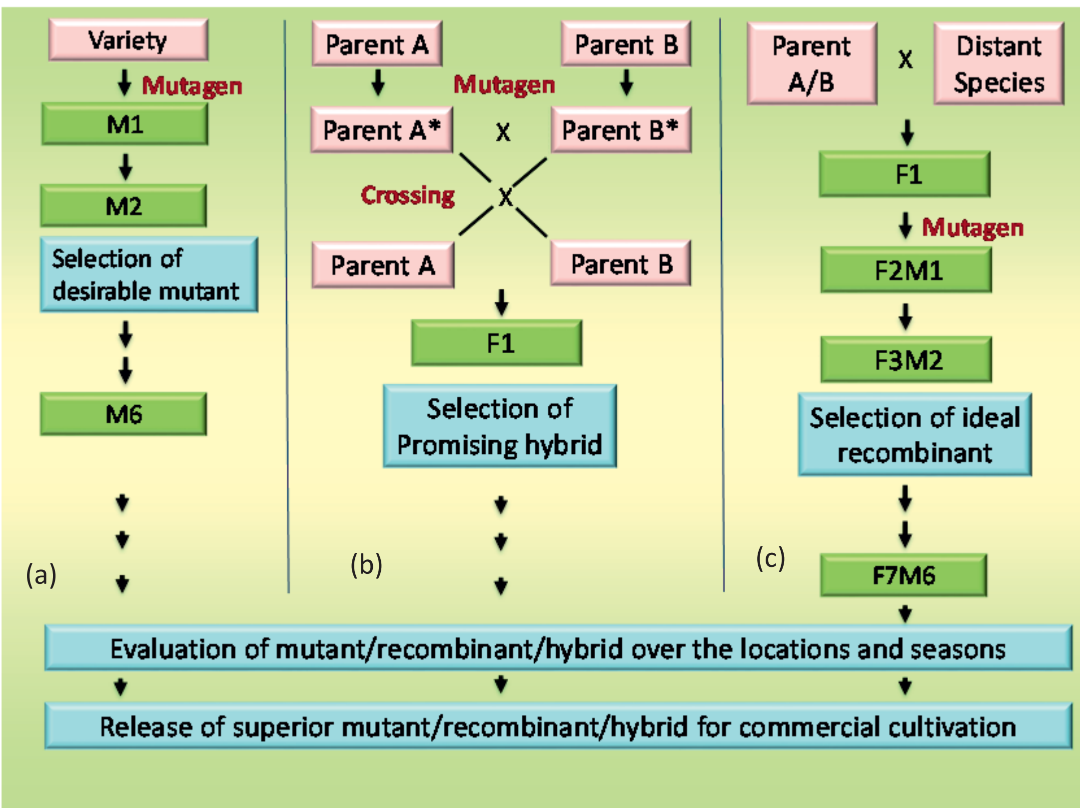

Fig. 2 Scheme of mutation breeding: a) for self-pollinated crops, b) for cross-pollinated crops, c) to introgress genes from distant species

induced mutant becomes genetically stable (attaining homozygosity). These stabilized mutants are evaluated with the existing varieties over the locations and seasons to find their yield superiority, suitability and adaptability in the trials conducted by Indian Council of Agricultural Research (ICAR) through their coordinating units and the State Agriculture Universities (SAUs). Based on the superiority of new mutant, varietal identification committee of ICAR/SAU recommends the suitable mutant for release. Further, Department of Agriculture and Cooperation, Ministry of Agriculture & Farmers Welfare, Government of India releases and notifies new mutant for commercial cultivation (Table 2). Sometimes, such mutants are crossed with other mutant, variety or distant species to integrate the beneficial traits from both the parents (Recombination or cross breeding) (Fig.2).

Crop improvement at BARC:

In the early fifties, experiments were undertaken at the BARC to study radiosensitivity, mutation frequency, cytological aberrations, morphological, biochemical and physiological traits by treating seeds of over 50 varieties of different crop plants with X rays, neutrons and gamma rays[1-5]. With basic understandings from these experiments, BARC had initiated radiation-based mutation breeding in cereal, oilseed and pulse crops in line with the national breeding programs. Using radiation induced mutagenesis, hundreds of mutants with several desirable agronomic traits were developed in these crops. Such mutants were directly utilized or judiciously blended to develop 62 improved varieties. These varieties have been released and notified for commercial cultivation across different states in the country during 1973-2023 in synergistic research collaboration with the ICAR and SAUs (Table 2, 3, 4, 5). Some of the desirable traits in these crops are enhanced seed yield and nutrients, earliness, greater seed size, seed dormancy and resistance to diseases and moisture stress. These characters not only boosted the crop productivity and protection but also facilitated for the development of new or alternate cropping systems, regained lost cropped area, which in turn generated additional farm income. BARC/SAUs undertake breeder seed production of new mutant varieties followed by foundation and certified seed production by the national and state seed corporations, seed companies and other seed agencies to reach the farmers with the seeds of new mutant variety.

Table 2: Different stages for the development, release and notification of Trombay mutant and mutant derived crop varieties

Stages	Institution involved	Time required (Year)	Activity
Induction	BARC	1	Treatment of seeds with radiation or crossing of mutants with other desired parent.
Identification	BARC	1-2	Detection of desired mutant or recombinant from large population.
Stabilization	BARC	4-6	Attaining true breeding nature of selected mutants or recombinants for desired trait for 4-5 generations.

Assessment	BARC	2	Testing of selected mutants or recombinants along with existing varieties over the seasons and isolation of the ones with greater yield and other improved traits.
Evaluation in all India coordinated trials	Indian Council of Agricultural Research (ICAR)	3-4	1. Evaluation of new mutants or recombinants along with such new lines developed by other research institutes in comparison with existing local, zonal and national check varieties in initial (IVT) and advanced (AVT) varietal trials over the locations and seasons of the zone. 2. Identification of superior line(s) for a given zone and season. 3. Recommendation of superior line for release by the identification committee for a given zone and season.
Evaluation in state university trials	State Agricultural Universities (SAU)	4-5	1. Evaluation of new mutant or recombinants along with such new lines developed by the SAU in comparison with existing local, zonal and national check varieties in station trials (ST), multi-location trials (MLT) and farm/adaptive trials over the seasons. 2. Identification of superior line(s) for a given region and season of the state. 3. Recommendation of superior line for release by the university scientific committees for a given region and season of the state.
Central Release	Dept. of Agriculture & Cooperation	1	Approval for the release of new mutant or recombinant from ICAR trial for a given zone and season for national trials.
State Release	State Variety Release Committee	1-2	Approval for the release of new mutant or recombinant from the state trials.
Notification	Ministry of Agriculture & Farmers Welfare	1	Gazette notification of the new mutant or recombinant developed in ICAR or state trials for commercial cultivation in a given zone and state, respectively.

***Improvement of Groundnut*:**

Groundnut or peanut (*Arachis hypogaea* L.) is an important oilseed, food and feed crop and grown on 5.75 million ha with 10.11 million tonnes production. It occupies 19% of the oilseed area and contributes 27% of the oilseed production in India. Groundnut mutation studies were started with X-ray irradiation in 1957 at BARC and with gamma rays and electron beam in subsequent years. The effective dose was 200-300 Gy for gamma rays and 150-250 Gy for electron beam. Periodical induced mutagenesis in groundnut had generated gene pool having many divergent mutants. Succeeding breeding efforts using these mutants in recombination breeding has developed and released 16 Trombay groundnut (TG) varieties for cultivation in different states[6]. These TG varieties were with semi-dwarf height, compact plant type, large seed, early maturity, fresh seed dormancy, drought tolerance, high oleic acid, which were valuable traits to fit into different cropping systems.

BARC had developed first mutant variety in 1973, TG 1 with large seed from X-ray mutagenesis of Spanish Improved (Table 3). Subsequently, another X-ray mutant, TG 3 was commercialised for Kerala. Inter-mutant crosses resulted in the development of TG 17 variety for Maharashtra. Crosses involving both TG 1 and TG 17 had developed a mutant derivative, TKG 19A having large seed for Maharashtra. Further, these TG mutants and their derivatives were genetically diversified by other varieties, M 13 and Robut 33-1 to develop TGS-1 (Somnath) and TG 22 for Gujarat and Bihar, respectively. Recombination breeding involving these mutants and M 13 has resulted in the development of four varieties, TAG 24 and TLG 45 for Maharashtra; TG 39 for Karnataka and Rajasthan and RARST-1 (TG 47) for Andhra Pradesh. Genetic diversification of these mutants was continued by involving more parents for incorporation of newer characters, which has evolved five varieties, TG 26, TG 37A, TG 38, TPG 41 and TG 51 for different states. Recently, TG 73, another gamma ray mutant, has been released as TAG 73 for Maharashtra and GG 37 (Sorath Gaurav) for Gujarat (Fig. 3).

Fig. 3 Plant, seed and pods of groundnut variety, TAG 73 released for Maharashtra

These TG varieties have also contributed as parents in various state university breeding programmes by evolving another 14 varieties (JCG 88, TPT 25, TCGS 894 for Andhra Pradesh; JL 501, GG 34, GG 35, GG 41 for Gujarat; GPBD 5 for Jharkhand, Manipur; Dh

40, R 9251, Dh 232 for Karnataka; JL 501, PDKVG 335 for Maharashtra; GG 21, RG 559-3 for Punjab; GG 21, JL 501, RG 559-3 for Rajasthan; TCGS 894 for Tamil Nadu, Telangana; RG 559-3 for Uttar Pradesh). To realize the yield potential of TG varieties by the farmers, BARC and other universities have supplied more than 2500 tonnes breeder seed of TG varieties to various public and private agencies for multiplication of foundation and certified seeds, which were sown by the farmers. Most of these TG varieties have considerably benefited thousands of farmers, traders and exporters. Commercially, several crores worth of TG varieties were traded in many groundnut markets.

***Improvement of mustard*:**

In India, rapeseed-mustard (*Brassica* spp.) is the key edible oilseed crop grown on 8.06 million ha with 11.75 million tonnes production, accounting for 27% of total oilseed area and 31% of total oilseed production, respectively. Indian mustard (*Brassica juncea*) is the most commonly cultivated in our country. Induced mutagenesis in Indian mustard at BARC had isolated mutations for morphological, physiological, biochemical, yield and yield contributing characters [7]. Sustained breeding efforts with these mutants has evolved eight varieties, which are released for different states (Table 3). In mustard, yellow seed coat mutant has more oil, more protein, thinner seed coat and lower fiber compared to brown seed coat parents. First yellow seed coat mutant in India, Trombay Mustard 1 (TM 1) was developed by BARC by treating Rai 5 variety with beta rays from Phosphorus-32 radioisotope. Recurrent selection in the same mutant has resulted in high yielding variety, TPM 1 with reduced erucic acid (25%) for Maharashtra. Earlier years, a direct mutant TM 2 and a mutant derivative TM 4 have been released for Assam. TPM 1and TM 4 are with yellow seed coat. Further, TM 2 was diversified using IC264133 to develop two varieties: Trombay Him Palam Mustard 1 (THPM-1) for Himachal Pradesh; Birsa Bhabha Mustard-1 (BBM-1) for Jharkhand. Similarly, TM 102 was successively recombined with other breeding lines to evolve TAM 108-1 for Maharashtra; TBM-143 (Fig. 4a, b) and TBM-204 for West Bengal.

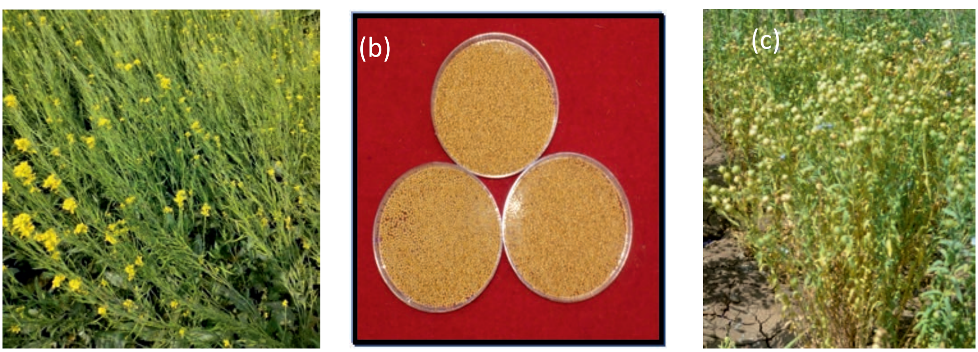

Fig. 4 Plant (a), seed (b) of mustard variety, TBM-143 and plant (c) of linseed variety, TL 99

***Improvement of other oilseed crops*:**

Soybean (*Glycine max* (L.) Merr.) is the most premier Indian oilseed crop with the largest area of 12.7 million ha and the highest production of 12.9 million tonnes. Radiation induced mutagenesis in soybean at BARC has generated diverse genetic variability for important agronomic and economical traits. BARC has developed two soybean varieties viz., TAMS 38, a gamma ray mutant of JS 80-21 and TAMS 98-21, a cross derivative with superior seed yield, non-pod shattering, resistance to diseases and pests [8]. Both the varieties were cultivated widely by the farmers in Vidarbha region of Maharashtra.

Linseed (*Linum usitatissimum*) is the winter oilseed crops of the country and its seeds are used for oil, manufacture of linoleum, paints, printing ink, varnish and feed. Its oil contains mainly unsaturated fatty acids viz., linolenic acid (36–50 %), linoleic acid (18–24 %) and oleic acid (16–24 %). Its oil during storage develops off-flavours, hence is non-edible. Varieties having reduced linolenic acid will enable linseed oil to use as edible oil. BARC has developed a high yielding variety, TL 99 with 2-5% linolenic acid which was released for commercial cultivation in Assam, Bihar, Jharkhand, Nagaland, Uttar Pradesh and West Bengal[8]. TL 99 is the first edible oil Indian variety (Fig. 4c). In sunflower (*Helianthus annuus* L.), gamma ray mutagenesis of zebra stripped seed coat variety, Surya has resulted in high yielding black seed coat variety, TAS 82 with 2-7 % more oil than its parent. TAS 82 was commercially released for Maharashtra[7].

Table 3: Trombay varieties in oilseed crops released for cultivation in India

Variety	Year of release	States	Varietal features
Groundnut			
TG 1	1973	Maharashtra, Gujarat	50 days seed dormancy, more branches, large seed (85g/100 seeds), 130-135 days maturity.
TG 17	1985	Maharashtra	25-30 days seed dormancy, No secondary branches, high harvest index (40%).
TG 3	1987	Kerala	High yield, suitable for rice fallows.
Somnath (TGS 1)	1991	Gujarat	Semi-runner type with main stem & sequential flowering, Large seed (60-70 g/100 seeds), Maturity of 120-125 days.
TAG 24	1992	Karnataka, Maharashtra, Odisha, Rajasthan West Bengal	Small dark green thick leaves, Semi-dwarf, high harvest index, high partitioning %, Earliness (95-100 days), wider adaptability, salinity & drought tolerance.
TG 22	1994	Bihar	50 days seed dormancy. Medium large seed (55-60g/100 seeds), Maturity of 110-120 days.
TKG 19A	1996	Maharashtra	30 days seed dormancy, Large seed (70-75g/100 seeds), Maturity of 115-120 days

TG 26	1996	Gujarat, Maharashtra, Madhya Pradesh	20 days seed dormancy, Earliness (95-100 days), high harvest index, Smooth pods, Iron chlorosis tolerance, Salinity tolerance
TG 37A	2004	Bihar, Gujarat, Haryana, Odisha, Punjab, UP, Rajasthan, West Bengal, North Eastern states	Smooth pods, matures in 100-105 days, Suitable for rice fallows, drought tolerance, wider adaptability
TPG 41	2004	All India	20 days seed dormancy, Medium maturity (120 days), Large seed (75-80g/100 seeds), High oleic acid (60%).
TG 38	2006	Bihar, Odisha, West Bengal, North Eastern states	Matures in 100-105 days, more 3-seeded pods, High shelling %, more round seeds, Suitable for rice fallows.
TLG 45	2007	Maharashtra	Medium maturity (115-120 days), Large seed (75-80g/100 seeds)
TBG 39 (Trombay Bikaner)	2008	Rajasthan	More branches, Large seed (75-80g/100 seeds), Maturity of 115-120 days, Moisture stress tolerance, high oleic acid (59%)
TDG 39 (TGLPS 3)	2009	Karnataka	
TG 51	2008	Bihar, Odisha, West Bengal, North Eastern states	Early maturity (90 days), high shelling %, medium large seed (50-55g/100 seeds), more 3-seeded pods, Escapes end-season drought, Suitable for rice fallows.
TG 47 (Bheema, RARST-1)	2011	Andhra Pradesh	Maturity of 110-115 days, Large seed (65-70g/100 seeds), More 3-seeded pods.
TAG 73	2021	Maharashtra	More 3-seeded smooth pods, high shelling out turn, stay green at harvest.
GG 37 (Sorath Gaurav)	2023	Gujarat	
Soybean			
TAMS 38	2005	Maharashtra	Early maturing, resistant to *Myrothecium* leaf, spot bacterial pustule
TAMS-98-21	2007	Maharashtra	Resistant to bacterial pustules, *Myrothecium* leaf spot, soybean mosaic virus diseases

Mustard			
TM 2	1993	Assam	Black seed, appressed pod
TM 4	1993	Assam	Yellow seed
TPM 1	2007	Maharashtra	Small leaf, yellow seed, tolerant to powdery mildew
TBM-204	2019	West Bengal	Yellow seed, 41% oil, large seed, 110-15 days maturity, dark green leaves, prominent constriction on siliqua, moderately resistant to Alternaria leaf spot.
TAM-108-1	2021	Maharashtra	Large seed, more siliqua density, long main fruiting axis, less incidence of powdery mildew under early to normal sowing condition
THPM-1	2021	Himachal Pradesh	Broad leaf, prominent hairs, wider adaptability
BBM-1	2021	Jharkhand	Large seed, drought tolerant, moderately tolerant to Alternaria, white rust & powdery mildew
TBM-143	2022	West Bengal	Appressed pods, yellow seeds, lodging or shattering resistant
Sunflower			
TAS 82	2007	Maharashtra	Black seed coat, tolerance to necrosis disease
Linseed			
TL 99	2020	Assam, Bihar, Jharkhand, Nagaland, UP, West Bengal	Low linolenic acid (2-5%), 37% oil, 125-130 days maturity, moderately resistant to Alternaria blight, powdery mildew and resistant to rust.

Improvement of Pulse crops:

Pulses (food legumes) are an important group of crops that provide high quality protein complementing cereal proteins for country's majority vegetarian population. As the largest global producer and consumer of pulses, India is cultivating pulses on 31.03 million ha with production of 27.69 million tonnes in 2021-22, which is less than the requirement. India has imported 2.52 million tonnes worth of Rs. 15,780 crores pulses in 2022-23 to meet domestic demand. Pulses also consumed as green pods, nutritious fodder for cattle, improve soil structure and fertility and they fit into crop rotations, mixed/inter-cropping system and dryland farming. BARC has systematic programme for genetic improvement of pulse crops involving blackgram/urdbean, greengram/mungbean, cowpea, pigeonpea, chickpea and cluster bean through mutation and recombination breeding in order to bring diverse genetic variability[9]. Gamma rays are commonly used with effective doses ranging from 100-200 Gy in pigeonpea to 200-300 Gy in cowpea to 300-400Gy in mungbean, urdbean and chickpea. Similarly, doses for electron beam are standardized as 270 Gy for cowpea, 300 Gy for chickpea, 400 Gy for urdbean and 500 Gy for mungbean[9].

BARC has developed 24 varieties in pulse crops, which include nine in mungbean, eight in urdbean, five in pigeonpea and two in cowpea (Table 4). Most of Trombay pulse varieties developed by mutant-genotype or inter-mutant (TAT-10 in pigeonpea) hybridizations, while some varieties (TAP-7 in mungbean, TT-6 in pigeonpea and TRC77-4, TC-901 in cowpea) are direct mutants [9]. In urdbean, large seed mutants, UM-196 (dark green leaf mutant) and UM-201 were hybridized with variety T-9 to evolve three varieties, TAU-1, TAU-2 and TPU-4. Similarly in pigeonpea, cross between a fast neutron induced large seed mutant variety TT-6 and ICPL 84008 had developed three early maturing varieties, TT-401, TJT-501 and PKV-TARA. While in mungbean, an early maturing variety TMB-37 was developed by crossing Kopargaon and TARM-2. Trombay pulse varieties like TU-40 in urdbean, TM-96-2, TM-2000-2 in mungbean and TRC-77-4 in cowpea are also suitable for cultivation in rice fallows. Cowpea variety, TC-901 is the first summer suitable variety in the country.

Many of the Trombay pulse varieties are popular among the farmers. Around 155 tonnes breeder seeds of these varieties have been distributed to the farmers in different states to realize their superior yield and disease resistance. The urdbean mutant TAU-1 is the most popular variety with more than 50% coverage in the urdbean area of Maharashtra. Urdbean variety TU-40 has become popular in the southern states. The mungbean variety, TMB-37 though initially released for North-East plain zone, is gaining popularity across the country and has been re-adopted in 2018 by Punjab owing to its large seed, yellow mosaic virus resistance and suitability for summer cultivation. The early maturing pigeonpea variety, TJT-501 occupies around 60% of the pigeonpea area in Madhya Pradesh. The farmers of Maharashtra are reaping high yields by cultivating pigeonpea variety PKV-TARA especially under drip irrigation.

Fig. 5 Plants of mungbean variety, TRCRM-147 (a), urdbean variety, TJU 339 (b), cowpea variety, TC-901 (c) and pigeonpea variety, TJT-501 (d)

Table 4: Trombay varieties in pulse crops released for cultivation in India

Variety	Year of release	States	Varietal features
Mungbean/ Greengram			
TAP-7	1983	Karnataka, Maharashtra	Early maturing, Tolerant to powdery mildew
TARM-2	1994	Maharashtra	Resistant to powdery mildew, tolerant to yellow mosaic virus
TARM-1	1997	Andhra Pradesh, Gujarat, Karnataka, Maharashtra, Kerala, Madhya Pradesh, Odisha, Tamil Nadu	Resistant to powdery mildew, tolerant to yellow mosaic virus
TARM-18	1997	Maharashtra	Early maturing, Resistant to powdery mildew
TMB-37	2005	Assam, Bihar, Jharkhand, Uttar Pradesh, West Bengal	Large seed, Tolerant to yellow mosaic virus, suitable for summer
	2018	Punjab	
TJM-3	2007	Madhya Pradesh	Resistant to powdery mildew, yellow mosaic virus, *Rhizoctonia* root rot
TM-96-2 (Trombay Pesara)	2007	Andhra Pradesh	Resistant to *Corynespora* leaf spot, powdery mildew, large seed, suitable for rice fallows
TM-2000-2 (Pairy Mung)	2010	Chhattisgarh	Resistant to powdery mildew, synchronous podding & maturity, suitable for rice fallow
TRCRM-147	2023	Karnataka	Large seed, Resistant to Yellow mosaic virus, suitable for summer
Urdbean/ Blackgram			
TAU-1	1985	Maharashtra, Karnataka	Large seed, Wider adaptability
TPU-4	1992	Gujarat, Maharashtra, Madhya Pradesh,	Large seed

TAU-2	1993	Maharashtra	Resistant to powdery mildew, yellow mosaic virus, Rhizoctonia root rot
TU 94-2	1999	Andhra Pradesh, Karnataka, Kerala, Tamil Nadu	Resistant to yellow mosaic virus
TU-40	2013	Andhra Pradesh, Karnataka, Tamil Nadu	Resistant to powdery mildew, yellow mosaic virus, suitable for rice fallows
TRCRU-22	2023	Karnataka	Resistant to Yellow mosaic virus, medium-large seed
TJU 130	2023	Madhya Pradesh	Resistant to yellow mosaic virus, powdery mildew and anthracnose
TJU 339	2023	Madhya Pradesh	Resistant to yellow mosaic virus, powdery mildew and anthracnose
Pigeonpea			
TT-6	1985	Andhra Pradesh, Gujarat, Karnataka, Kerala Madhya Pradesh, Maharashtra	Erect plant type, Early maturing, Large seed
TAT-10	1985	Maharashtra	Early maturing, Erect plant type
TT-401	2007	Chhattisgarh, Gujarat, Madhya Pradesh, Maharashtra	Tolerant to pod fly, pod borer and *Fusarium* wilt
TJT-501	2009	Madhya Pradesh, Maharashtra, Gujarat, Chhattisgarh	Resistant to *Fusarium* wilt & tolerant to *Phytophthora* blight
PKV-TARA	2013	Maharashtra	Tolerant to sterility mosaic, *Fusarium* wilt diseases
Cowpea			
Khalleshwari (TRC-77-4)	2007	Chhattisgarh	Dwarf plant type, medium large seed, dual purpose, Suitable for rice fallows
TC 901	2018	Gujarat, Maharashtra, Madhya Pradesh, Rajasthan, Uttarakhand, West Bengal	Early & synchronous maturity, Suitable for summer season and tolerant to yellow mosaic & root rot diseases

Improvement of cereal crops:

Rice (*Oryza sativa*) is the supreme staple Indian food crop covering an area over 46.38 million ha with 130.29 million tonnes production ensuring country's food security. In rice, most of the traditional landraces have distinct grain quality which fetch premium market price. However, their cultivation is marginalized because of late maturity, poor yield and crop lodging due to tall stature[10]. Successful application of radiation induced mutagenesis for rice improvement has evolved seven improved varieties (Table 5). Among these, five gamma ray mutants, Trombay Chhattisgarh Dubraj Mutant-1 (TCDM-1) (Fig. 6a), Vikram-TCR, CG Jawaphool Trombay (CGJT), Trombay Chhattisgarh Vishnubhog Mutant (TCVM) and Trombay Chhattisgarh Sonagathi Mutant TCSM) have been released for commercial cultivation in Chhattisgarh. For Maharashtra, a mutant derivative, Trombay Karjat Rice-Kolam (TKR-Kolam) has been released. TCDM 1, CGJT and TCVM have aromatic grains. TKR Kolam has superfine grain and better taste like other Kolam rice varieties. Most of these varieties are lodging tolerant with semi-dwarf stature, enhanced milling & head rice recovery and higher grain yield. Grains of Vikram-TCR are suitable for puffed rice making, while that of CGJT and TCVM for kheer making.

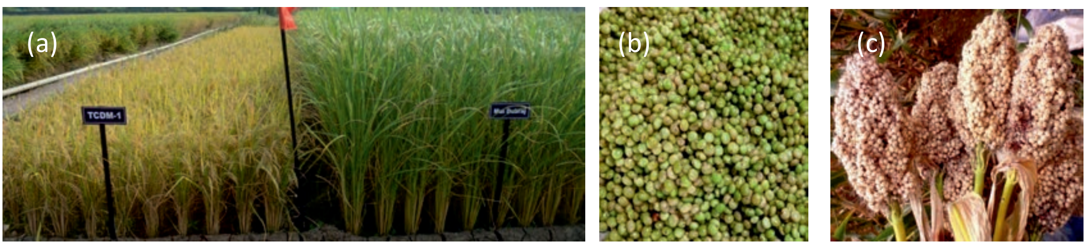

Fig. 6 Field view of rice variety, TCDM 1 (a), hurda type grains of TKPS-5 (b) and grain type TRJP 1-5 (c) of sorghum

Sorghum is a climate resilient cereal crop cultivated for grain, fodder and biofuel under drought prone areas with low input conditions. Its cultivation is on 3.81 million ha with 4.23 million tonnes production. In order to create genetic variability for yield contributing traits and disease resistance, mutation breeding has been employed using both physical and chemical mutagens[11]. A gamma ray mutant, TRJP1-5 with superior grain and fodder yield has been released for Karnataka. It has synchronous maturity, bold and lustrous seeds with better rheological properties (roti making), besides moderately tolerant charcoal rot, rust and blight diseases. Another mutant for hurda (consumed at green stage) type, TAKPS-5 (Suruchi) is early maturing with compact and easily threshable panicles giving better hurda yield. The grains showed more spongy tissues with improved organoleptic properties and was commercialized in Maharashtra (Fig. 6 b,c).

Table 5: Trombay varieties in other crops released for cultivation in India

Variety	Year of release	States	Varietal features
Rice			
Hari	1988	Andhra Pradesh	Long slender grain, semi-dwarf, non-lodging type
TCDM-1	2019	Chhattisgarh	Semi-dwarf, aromatic grain, higher milling recovery, lodging resistant
TKR-Kolam	2020	Maharashtra	Semi-dwarf, Short slender superfine grains
Vikram-TCR (Trombay Chhattisgarh Rice)	2021	Chhattisgarh	Semi-dwarf, Lodging resistant, drought tolerant, suitable for puffed rice making
Chhattisgarh Jawaphool Trombay (CGJT)	2021	Chhattisgarh	Aromatic short slender grain, suitable for *kheer* making
Trombay Chhattisgarh Vishnubhog Mutant (TCVM)	2021	Chhattisgarh	Aromatic short grain, semi-dwarf, suitable for *kheer* or *pulav* making
Trombay Chhattisgarh Sonagathi Mutant (TCSM)	2021	Chhattisgarh	Semi-dwarf, late maturity, coarse grain, suitable for rainfed farming
Sorghum			
TAKPS-5 (Suruchi)	2023	Maharashtra	Hurda variety, early maturing, non-lodging, compact panicles, spongy and sweet grains with better flavour and shelf life
TRJP 1-5 (SPV-2538)	2023	Karnataka	Synchronized flowering, large seeds, good roti making quality, medium duration, suitable for deep black soils
Jute			
TKJ-40 (Mahadev)	1983	Odisha	High fibre yield, photoperiod sensitive

BARC has adopted, multi-pronged approaches to reach Indian farming community with Trombay varieties. It has undertaken large-scale seed production, participated in *Kisan Melas*, exhibitions of SAUs and conducted field demonstrations under the Public Awareness Programme on Peaceful Uses of Atomic Energy. As per the national indent, more than 1000 tonnes of breeder seed were multiplied and supplied to National Institutes; National Seed Corporation, State Seed Corporations of Andhra Pradesh, Bihar, Chhattisgarh, Gujarat, Maharashtra, Odisha, Rajasthan and West Bengal; State Agricultural Departments & Universities; Non-Governmental Organizations and farmers. Apart from this, various SAUs also distributed hundreds of tonnes breeder seed of BARC varieties. Such of the seed was further multiplied, distributed and spread horizontally to thousands of farmers in the country.

Categorically, a thoughtful merger of mutation and recombination breeding has a greater prospective in the genetic improvement of crop plants as demonstrated at BARC, Trombay. Planned breeding efforts were successful in bringing mutant genes into appropriate genetic backgrounds in different crops. Crop improvement is a continuous breeding process wherein new mutants are to be developed in line with future needs of the farmers as per changing climatic conditions and consumer needs, growing population and shrinking agricultural land by employing gamma rays, proton beam, electron beam based mutagenesis and targeted mutagenesis. Equally, breeding efficiency needs to be enhanced by identifying molecular markers for traits of interest and employing speed breeding tools.

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