Radiation Technology for Genetic Enhancement of Crop Plants

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Abstract

The potential amount of energy concealed in the atoms has peaceful applications in agriculture for improvement of crop plants. In nature, occurrence of genetic change (mutation) is evolutionarily slow process. The frequency of such mutations can be increased through radiations. These radiations bring genetic changes at chromosomal, gene or DNA level, which are manifested into desirable characters in crop plants. BARC has been engaged in mutation breeding since early sixties using X rays, beta particles, gamma rays and electron beam. Using radiation based mutants and their derivatives in crosses; BARC has developed 49 varieties with improved traits in different crops in collaboration with State Agricultural Universities and ICAR research institutes. These varieties have been released and notified for farmer cultivation across our country. Several of BARC varieties have been cultivated extensively by the farmers from different states and immensely benefitted them by enhancing their farm income.

Keywords: *Agriculture, Mutation, Gamma rays, Mutation breeding, Oilseeds, Pulse crops*

1. Introduction

Agriculture in India has many challenges viz., growing population, erratic climatic situation, changing consumer food preference and expanding urban areas. Further, it is essential to deliver necessary nutrients in addition to having sufficient food to promote a healthy life. Towards which, development of crop varieties with improved nutrients, tolerance to diseases, pests, drought, salinity, heat, cold conditions will be ideal approach to manage above concerns. Crop improvement using various breeding methodologies including recent molecular tools, is a continuous process. Radiation based crop improvement method is instrumental in evolving improved varieties with enhanced crop productivity and increasing crop production.

Towards peaceful uses of atomic energy for societal benefit, Bhabha Atomic Research Centre (BARC) has been contributing in the field of agriculture through its research, development and deployment activities. In agricultural research, radiations from radioisotopes are employed to create better characters (genetic variability) in turn to develop newer crop varieties; to control insect pests and to trace the pesticide residues, uptake of fertilizers and other nutrients.

In any crop improvement activity, a basic necessity is to ensure genetic variability for target traits. In nature, new variability is generated by spontaneous genetic changes (mutations) due to effect of natural radiations and other factors. These changes occur at extremely low frequency (one in million). Using atomic radiations and/or other chemical mutagens, mutation frequency can be enhanced to several folds (one in thousand). Development of such mutants (induced mutagenesis) has been successfully employed as an important method of improvement in most of the crops [1]. Consequently, more than 3300 improved mutant varieties were developed throughout the world, which also include around 340 varieties from our country [2]. These varieties contributed significantly for the enhancement of farmers' income in turn for the country's economy.

2. Mutagens and Mutation Breeding

In induced mutagenesis experiments, the main aim was to develop superior varieties with enhanced seed yield and nutrients, earliness, desired seed size and dormancy, tolerance to diseases, insects, drought, salinity, heat etc. The radiation source (mutagen) used for mutant induction was X-rays, fast neutrons, beta rays, gamma rays and recently electron beam. The effective dose ideal for mutant induction was close to LD_{50} (50% of Lethal dose) depending on radio-sensitivity factors.

Seeds of existing popular cultivars, varieties, mutants, selections, hybrids or advanced lines of target crop are treated with X rays, gamma rays or electron beam (M_1 generation). These treated seeds in different crops are sown in the agricultural fields. Usually genetic variants (mutants) are identified from next generation (M_2) onwards. In the subsequent generations, breeding behavior of the induced mutants is studied and is followed till the induced mutant becomes genetically stable (attaining homozygosity). These stabilized mutants after initial testing followed by large scale evaluation over the seasons and locations, are released as new mutant variety for specific region, location or season (Table 1). Sometimes, such mutants are crossed with other mutant or variety in order to integrate the beneficial traits from both the parents (Recombination or cross breeding).

3. Genetic Improvement of Crop Plants

BARC had commenced radiation based induced mutagenesis for the genetic improvement of crop plants since late fifties. Using radiation induced mutagenesis, hundreds of mutants with several desirable agronomic features were developed in different crop plants at BARC. Such mutants were directly utilized or judiciously blended (recombination breeding) to develop 49

Table 1: Steps involved in the development and release of mutant and mutant derived crop varieties

Steps	Institution involved	Time required (Year)	Activity
Induction	BARC	1	Treatment of seeds with radiation (Mutagenesis) or crossing of mutants with other mutants, varieties or desired parent.
Identification	BARC	1-2	Detection of plants with desired genetic change (mutant) or desired combination of traits (recombinant) from large population in second generation and their isolation.
Stabilization	BARC	4-6	1. Studying the true breeding nature of selected mutant or recombinant plants for desired trait for four generations. 2. Selection of stabilized (attained the highest homozygosity), true breeding mutants or recombinants with desired traits.
Assessment	BARC	2	1. Testing of selected mutants or recombinants along with existing varieties for improvement of yield and other traits over the seasons. 2. Identification of mutants or recombinants with greater yield and other improved traits.
Evaluation	Indian Council of Agricultural Research (ICAR)	3-4	1. Evaluation of new mutant 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 mutant or recombinants with superior yield and other desired traits compared to check varieties for a given zone and season. 3. Recommendation of the new mutant or recombinant for release by the identification committee for a given zone and season.
	State Agricultural Universities (SAU)	4-5	1. Evaluation of new mutant or recombinants along with such new lines developed by 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 mutant or recombinants with superior yield and other desired traits compared to check varieties for a given region and season of the state. 3. Recommendation of the new mutant or recombinant for release by the university scientific committees for a given region and season of the state.
Central Release	Department of Agriculture & Cooperation	1	Approval for the release of new mutant or recombinant 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 for state trials.
Notification	Ministry of Agriculture & Farmers Welfare	1	Gazette notification of the new mutant or recombinant developed in national and state trials for commercial cultivation in a given zone and state, respectively.

varieties in oilseed crops (groundnut, linseed, mustard, soybean, sunflower), pulse crops (cowpea, mungbean, pigeonpea, urdbean), rice and jute, which have been released and notified for cultivation across the country (Table 2, 3 and 4). Some of the desirable traits in these crops are improved seed yield and nutrients, earliness, greater seed size, seed dormancy and resistance to diseases and moisture stress. The improved characters not only enhanced 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. Mutation breeding experiences in these crops has been continuing to address the broader vision of attaining food and nutritional security. Since from the beginning, synergistic research collaborations and memorandum of understandings (MoUs) between BARC and institutes of Indian Council of Agricultural Research (ICAR) and Agricultural Universities in different states have facilitated successful development and dissemination of BARC varieties wide across the country (Table 5).

3.1 Oilseed crops: Groundnut

Groundnut (*Arachis hypogaea* L.) being an important edible food, feed and oilseed crop, is cultivated on 5.0 million hectares with a production of 8.0 million metric tonnes occupying nearly 19% of the cultivated area and contributing 27% of the production of oilseeds in India. Groundnut is commonly used for edible oil, protein, minerals, vitamins and other bioactive compounds. Its kernels are consumed directly after roasting, boiling or frying, used in confections or crushed for edible oil. Being a high energy food, groundnut seeds contain 45-50% edible oil, 25-30% protein, 10-20% carbohydrates and rich source of vitamins E, K and B complex, phosphorous, potassium, calcium and magnesium.

In groundnut mutation studies, major goals were to develop varieties with high seed yield, large seed, earliness, better shelling out turn, improved oil quality, ideal fresh seed dormancy and tolerance to diseases, drought and salinity. In the early years, X-rays were used for groundnut mutagenesis followed by gamma rays and recently electron beam [3]. The effective dose for gamma rays was 200-350 Gy [4].

Groundnut induced mutagenesis at BARC had developed initially mutant gene pool having many divergent mutants, which was basis for developing mutant or mutant derived improved varieties. Persistent breeding efforts using induced mutants in recombination breeding has developed and released 15 Trombay groundnut (TG) varieties for cultivation in different states (Table 2). First variety, TG 1 was the X-ray induced large seed mutant of Spanish Improved, followed by one more X-ray mutant variety, TG 3 for Kerala and Odisha. Inter-mutant crosses had evolved TG 17 for Maharashtra. Crosses involving both TG 1 and TG 17 had developed 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 states, respectively. Multiple crosses involving these mutants and M 13 has evolved four varieties, TAG 24 for Maharashtra, Karnataka and West Bengal; TG 39 for Karnataka and Rajasthan; TLG 45 for Maharashtra and RARST-1 (TG 47) for Andhra Pradesh. Genetic diversification of these mutants was continued by involving more parents, Girnar 1, JL 24 mutant, Gujarat dwarf mutant and early genetic stock Chico for incorporation of newer characters, which has developed five varieties, TG 26, TG 37A, TG 38, TPG 41 and TG 51 for different states [5].

In BARC, prominent contribution has been the evolution of TG varieties (TG 39, TPG 41, TLG 45, RARST-1) with large seed (100-seed weight >60g) and early maturity (110-120 days) suitable for table purpose and export under bold types. Seeds of the varieties like TG 37A, TG 38 and TG 51 are preferred for the export under Java type of groundnuts. In TAG 24, TG 26 and

RARST-1, semi-dwarf habit, small thick dark green leaves, better assimilate partitioning and high harvest index permit pegs to enter the soil early to have better and uniformly developed pods. The compact plant of TAG 24, TG 26, TG 38 and TG 47 facilitate farmers for high density planting for attaining greater productivity. Fresh seed dormancy of 2-3 weeks in TKG 19A, TG 22, TG 26 and TPG 41 prevents seed germination at the maturity stage due to unseasonal rains. Early maturity in TAG 24, TG 26 and TG 51 is helpful to escape end-season drought and to fit into different cropping systems like rice fallows, residual moisture situation and post-potato crop. Early maturity also makes farmers to harvest early and bring the produce early to the market in turn fetching the better price (Fig. 1). Drought tolerance in TAG 24, TG 37A and TG 39 make them suitable for cultivation in water limited areas (Fig. 2, 3). High oleic acid (60%) in TG 39 and TPG 41 impart better oil shelf life and health benefits. Most of these TG varieties have considerably benefited thousands of farmers, traders and exporters.

Figure 1: Farm woman with bumper harvest of TG 51

Figure 2: Popular TG variety, TG 37A

Figure 3: Field view of TG 39 on farmer field near Kolhapur

In state groundnut breeding programmes, TG varieties were used as parents in the development and release of 13 varieties by different agricultural universities in Andhra Pradesh, Gujarat, Karnataka, Maharashtra, Rajasthan and Telangana. In addition, TG varieties are being included as check varieties in the national and state evaluation trials. Moreover, around 300 TG induced mutants and recombinants are maintained for their genetic purity.

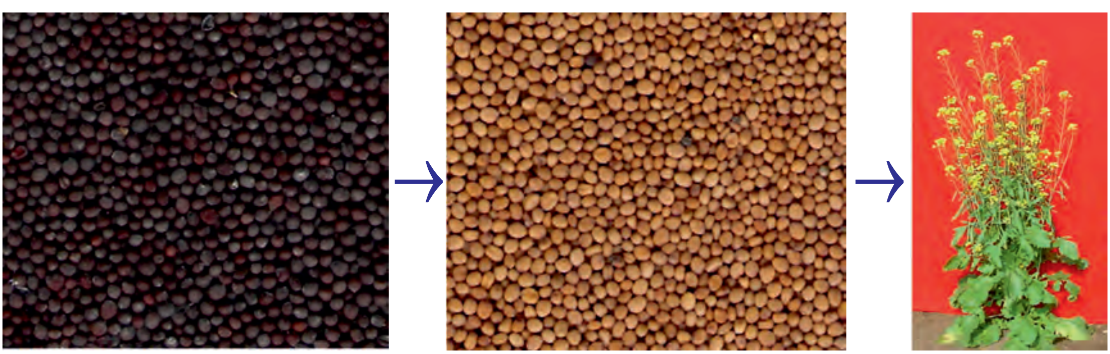
BARC has undertaken large-scale breeder seed production of TG varieties so as to realize the yield potential by the farmers. Based on the allocation by the Ministry of Agriculture & Farmers Welfare and demand from other seed agencies, around 700 tonnes breeder seed of TG varieties was produced and supplied by BARC to State Seed Corporations, National Seed Corporations, State Agriculture Departments, State Agricultural Universities, ICAR institutes, NGOs, Seed companies and farmers for further foundation and certified seed production. Farmers use certified seeds for sowing.

Among different TG varieties, TAG 24, TG 37A, TG 38, TG 39, TPG 41, TLG 45 and TG 51 have become popular in Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Maharashtra, Odisha, Rajasthan,Tamil Nadu, Uttar Pradesh and West Bengal due to incorporation of desirable traits through planned breeding. Farmers in several states have obtained superior yields to the tune of 5000 kg/ha by cultivating TG varieties as compared to around 2000-3000 kg/ha in their local varieties. Some farmers from Andhra Pradesh and Maharashtra have obtained record pod yields of 7,000 kg/ha. Recently, TG 39 has earned price advantage to the Gujarat farmers by securing the highest market price. Commercially, several millions worth of TG varieties were traded in many groundnut markets.

3.2 Oilseed crops: Mustard

India is the third most rapeseed-mustard producer after China and Canada contributing 12% to world's production. It is cultivated on an area of 6.27 million hectares with a production of 6.7 million tonnes and a productivity of 1350 kg/ha. It is the key edible oilseed crop accounting for nearly one-third of the oil produced in India. Among the various *Brassica* species, *B. juncea*, commonly called as Indian mustard is the major cultivated crop in India. Sensitiveness of mustard to various biological and non-biological stress factors requires crop modification for sustainable growth. Mutation induction could play an important role to pave the way to overcome some of these problems. Mutation breeding in Indian mustard at BARC has resulted in the development of wide spectrum of mutations for morphological, physiological, biochemical, yield and yield contributing characters. These mutations are extensively utilized in recombination breeding to evolve improved genotypes/varieties.

A large spectrum of mutations for various characters has been isolated using gamma rays. Some of the important ones are yellow seed coat, dwarf, non-locular siliquae and altered fatty acid composition. 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 (TM1) was isolated by BARC from variety 'Rai 5' using beta rays from Phosphorus-32 (^{32}P) radioisotope. Recurrent selection in the same mutant has resulted in high yielding variety, TPM 1 (Fig. 4). In recent years, yellow seed coat mutants (TM50, TJD1) were isolated through gamma ray mutagenesis of most popular variety 'Varuna'. These mutants have been used in crosses and developed a large number of high yielding yellow seed coat genotypes. A gamma ray induced dwarf mutant was isolated from 'Varuna' with plant height of 85-90cm compared to 165-170cm of the parent and maturity of 70 days, which is half of parent. However yield potential of mutant is equivalent to parent indicating effective source–sink relationship. Besides dwarfness, same mutant has earliness, yellow seed-coat and reduced erucic acid content. Keeping number of siliquae and seed weight constant, increasing seed number per siliqua will directly help in increasing seed yield. Two mutations for non-locular siliquae/replumless mutants have also been isolated. The number of seeds/siliqua is in the range of 19-25 with enhanced siliqua density compared to 12-15 seeds/siliqua in the existing germplasm. Traditional rapeseed-mustard oil is an exception to other vegetable oils by containing 47% of erucic acid. Two mutants namely, TPM1 and TJD1 have reduced erucic acid up to 25%. These mutants are being evaluated for genetic control of reduced erucic acid and development of zero erucic acid recombinant lines.



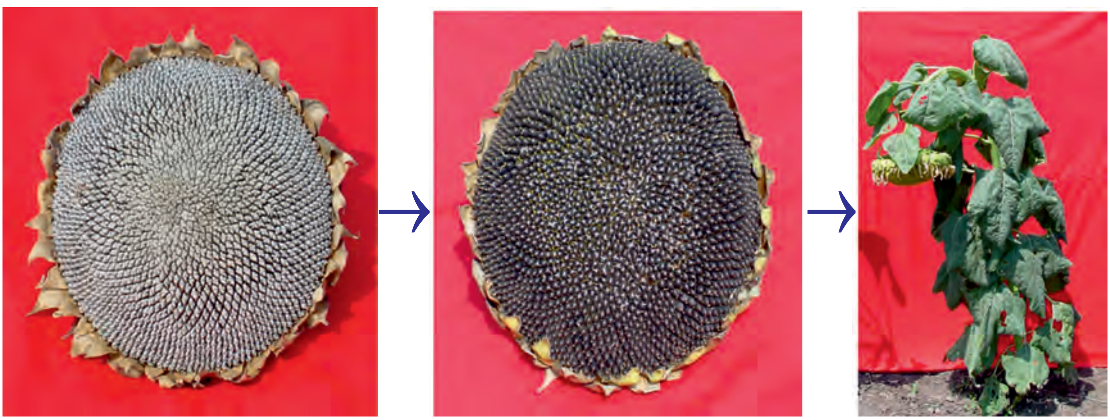
Brown seed parent, Rai5 | Yellow seed mutant | TPM1

Figure 4: Development of mustard mutant variety, TPM 1

Depending on the yield potential, mutant can be directly released as variety or it could be used in hybridization to develop high yielding recombinant lines. Using mutation breeding approach, BARC has released four varieties in mustard (Table 2). Two mustard varieties namely TM2 and TM4 have been released for Assam state, TPM1 is for Maharashtra and TBM204 is for West Bengal [6]. Four more genotypes namely TM108-1, TM172, TM179 and TM143 are in the advance stage of release.

3.3 Oilseed crops: Sunflower

Sunflower (*Helianthus annuus* L.) is one of the youngest cultivated crops in India. Demand of sunflower oil is ever increasing due to health benefits. Existing yield potential of around 1200-1500 kg/ha is mainly due to development of hybrids. Gamma ray mutagenesis was initiated to isolate black seed coat in 'Surya' variety having zebra stripped seed coat and yield potential equivalent to hybrids. Mutations for black, white and variegated seed coat colour were isolated. Black seed coat mutants had 2-7 per cent more oil content than parent. These mutants were used for varietal development. TAS 82 is one of the black seed coat mutant variety was released for cultivation in Maharashtra (Fig. 5) [7].



Variegated seed Parent, Surya | Black seed mutant | TAS 82

Figure 5: Development of sunflower mutant variety, TAS 82

3.4 Oilseeds crops: Soybean

Soybean (*Glycine max* (L.) Merr.) is a major oilseed crop of India and is mainly grown in rainy season. It has uplifted the socio-economic status of farmers particularly rural population in India. Soybean seed contains 18-23% oil and about 38-40% protein. Being a protein rich crop, it can be used to meet acute protein deficiency domestically. In India, it is cultivated on about 11.50 million hectares with over 10.50 million tonnes production and contributing about 25% to the domestic edible oil sector. By exporting soybean meal, our country earned substantial foreign exchange to the tune of 3730 crore rupees. Indian soybean productivity is comparatively low as compared to different parts of the world due to poor seed viability and lack of high yielding varieties with earliness, photoperiod insensitiveness, resistance to diseases, insects and other abiotic stresses.

In soybean, mutational studies were carried out to assess different genotypes for selecting appropriate mutagenic doses, determination of effectiveness and efficiency of different mutagenic treatments, breeding behaviour of mutants and identification and utilization of desirable mutants affecting morphological and quality characters for developing varieties. Radiation induced mutagenesis has generated diverse genetic variability both for quantitative and qualitative traits in soybean. BARC has developed two soybean varieties viz., TAMS 38 and TAMS 98-21 with superior seed yield, non-pod shattering, resistance to diseases and pests for Maharashtra farmers (Table 2; Fig. 6) [8]. TAMS 98-21 is gamma ray mutant of JS 80-21 with 21% higher yield over check JS-335 and is resistant to diseases. While another variety, TAMS-38 has been developed by cross breeding. Both the varieties were cultivated extensively by the farmers in Vidarbha region of Maharashtra. Large amount of breeder seed was multiplied and distributed to the farmers. At present, efforts are being made to develop high yielding soybean breeding lines having high oil, resistance to biotic and abiotic stresses, low trypsin inhibitor content, low phytic acid content, altered protein profile, altered fatty acid content and high harvest index.

3.5 Oilseed crops: Linseed

Linseed (*Linum usitatissimum*) is one of the important post-rainy or winter oilseed crops of India and is used for oil, feed and for the manufacture of paints, varnish, linoleum and printing ink. Compared to the world average, Indian linseed productivity is very low due to lack of high yielding varieties and to its cultivation under moisture stress situation with low or no inputs. Its oil contains mainly unsaturated fatty acids like oleic acid (16–24 %), linoleic acid (18–24 %) and linolenic acid (36–50 %). High drying quality of linseed oil due to higher level of linolenic acid make it suitable for industrial purposes. However, it is unfit for edible oil as it develops off-flavours during storage due to its susceptibility to oxidation. Development of varieties with low linolenic acid will enable linseed oil to use as edible oil. The high yielding, low linolenic acid line, TL99 was developed by BARC and released for commercial cultivation in Assam, Bihar, Jharkhand, Nagaland, Uttar Pradesh and West Bengal (Table 2; Fig. 6) [9]. TL 99 is the first Indian variety released for edible oil. It has a yield of 1200-1300 kg/ha with 125-130 days maturity, 37% oil and 500 kg/ha oil yield. TL 99 has unique fatty acid composition having very low linolenic acid (2 to 5 %) and can be used for edible oil. It is moderately resistant to powdery mildew, *Alternaria* blight and resistant to wilt and rust diseases.

Soybean TAMS 98-21 Soybean TAMS 38 Linseed TL 99

Figure 6: Trombay soyabean and linseed varieties

3.6 *Pulse crops*

Pulses or food legumes are one of the important sources of dietary proteins for the substantial vegetarian population of the country. They form an integral part of the diet complementing the carbohydrate rich staple cereals with proteins which is almost two to three times that of wheat

Table 2: Release of Trombay varieties in oilseed crops for commercial cultivation in India

Variety	Year of release	States	Special features	Average yield (kg/ha)
Groundnut				
TG 1	1973	All India	High yield, 50 days seed dormancy, more branches, large seed (65-70g/100 seeds), 125-130 days maturity.	1800-2000
TG 17	1985	Maharashtra	25-30 days seed dormancy, No secondary branches, high harvest index (40%).	1500-1700
TG 3	1987	Kerala	High yield, suitable for rice fallows.	1500-1800
Somnath (TGS 1)	1991	Gujarat	Large seed (60-70 g/100 seeds), Semi-runner type. Maturity of 115-120days.	2000-2200
TAG 24	1992	Maharashtra, Odisha, Karnataka, West Bengal, Rajasthan	Semi-dwarf, Small dark green thick leaves, Earliness (95-100 days), high harvest index, high partitioning %, wider adaptability, salinity & drought tolerance.	2500-3000
TG 22	1994	Bihar	Medium large seed (55-60g/100 seeds), 50 days seed dormancy. Maturity of 105-110 days.	1800-2000
TKG 19A	1996	Maharashtra	Large seed (70-75g/100 seeds), 30 days seed dormancy. Maturity of 115-120 days.	2200-2500
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	2500-3000
TG 37A	2004	Bihar, Gujarat, Haryana, Odisha, Rajasthan, Punjab, UP, West Bengal, North Eastern states	Smooth pods, drought tolerance, wider adaptability, matures in 100-105 days, Suitable for rice fallows.	2200-2500
TPG 41	2004	All India	Large seed (75-80g/100 seeds), Medium maturity (120 days), 20 days seed dormancy, High oleic acid (60%).	2500-3000
TG 38	2006	Bihar, Odisha, West Bengal, North Eastern states	Matures in 100-105 days, High shelling of 78%, more 3-seeded pods, more round seeds, Suitable for rice fallows.	2200-2500
TLG 45	2007	Maharashtra	Large seed (75-80g/100 seeds), Medium maturity (115-120 days)	2500-3000
TBG 39 (Trombay Bikaner)	2008	Rajasthan	Large seed (75-80g/100 seeds), Medium maturity (115- 120 days), high olecic acid (59%), more number of branches, Moisture stress tolerance.	2500-3000
TDG 39 (TGLPS 3)	2009	Karnataka		
TG 51	2008	Bihar, Odisha, West Bengal, North Eastern states	Early maturity (90 days), high shelling of 78%, medium large seed (50-55g/100 seeds), more 3-seeded pods, Escapes end-season drought, Suitable for rice fallows.	2500-3000
TG 47 (Bheema, RARS-T-1)	2011	Andhra Pradesh	Large seed (65-70g/100 seeds), Maturity of 110-115 days, more 3 seeded pods.	2500-3000

Soybean				
TAMS 38	2005	Maharashtra	Early maturing, resistant to bacterial pustule, *Myrothecium* leaf spot	1800-2200
TAMS 98-21	2007	Maharashtra	Resistant to *Myrothecium* leaf spot, bacterial pustules, soybean mosaic virus diseases	2200-2600
Mustard				
TM 2	1987	Assam	Appressed pod	1300-1400
TM 4	1987	Assam	Yellow seed	1400-1500
TPM 1	2007	Maharashtra	Yellow seed, Tolerant to powdery mildew	1400-1500
TBM-204	2019	West Bengal	Yellow seed, 41% oil, 110 days maturity, moderately resistant to Alternaria leaf spot.	1300-1400
Sunflower				
TAS 82	2007	Maharashtra	Black seed coat, tolerance to necrosis disease	1300-1400
Linseed				
TL 99	2019	UP, Bihar, Jharkhand, West Bengal, Assam & Nagaland	Low linolenic acid (2-5%), 37% oil, 120-130 days maturity, moderately resistant to powdery mildew, Alternaria blight and resistant to rust.	1200-1300

and rice. As the largest global producer and consumer of pulses, India has made considerable progress in improving the productivity to 841 kg/ha in 2017-18, although it is far behind achieving self-sufficiency. India imports pulses annually to the tune of 5-6 million tonnes (worth 18,748 crore rupees) to meet domestic demand.

For genetic improvement of pulses against pests and diseases, abiotic stresses, physiological and biochemical traits, existence of sufficient genetic variability is a pre-requisite, which is very limited. To address this issue, a combination of mutation and recombination breeding approach is being pursued. Though different mutagens are available for use in mutagenesis, gamma rays have been found to be the most potent and many of the Trombay pulse varieties have been developed directly or indirectly through gamma ray irradiation. The effective doses for mutation breeding in different pulse crops have been standardized for gamma rays through radio-sensitivity assays (mungbean, urdbean, chickpea: 300-400 Gy; pigeonpea: 100-200 Gy; cowpea: 200-300 Gy). In recent times, radiosensitive assays for electron beam have been standardized and LD_{50} for different crops have also been ascertained (mungbean: 500 Gy; urdbean: 400 Gy; chickpea: 300 Gy and cowpea: 270 Gy).

BARC has been actively engaged in the genetic improvement of pulse crops namely blackgram/urdbean, greengram/mungbean, pigeonpea, cowpea and recently in chickpea and cluster bean. BARC has developed eight varieties in mungbean, five each in urdbean and pigeonpea and two in cowpea which is almost one third of the total pulse mutant varieties released in the country (20 of 56 varieties) (Table 3) [10]. Most of these Trombay pulse varieties are mutant derivatives 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. In urdbean, large seed mutants, UM-196 (dark green leaf mutant) and UM-201 were hybridized with popular cultivar T-9 resulting in three improved varieties, TAU-1, TAU-2 and TPU-4. Likewise, in pigeonpea, a fast neutron induced large seed mutant variety TT-6 was hybridized with ICPL 84008 and three early maturing and high yielding varieties (TT-401, TJT-501 and PKV-TARA) have been developed. In mungbean, crosses involving Kopergaon and TARM-2 have resulted in the development of early maturing variety

TMB-37 for North East Plain zone. Some of the mutant varieties like TM-96-2, TM2000-2 (mungbean), TU-40 (urdbean) and TRC-77-4 (cowpea) are also suitable for rice fallows. Nation's first summer suitable cowpea variety TC-901 has been released recently (Fig. 7).

Figure 7: Trombay cowpea variety TC-901 suitable for summer cultivation

Figure 8: Field view of popular Trombay urdbean variety, TAU-1

Many of the Trombay pulse varieties are very popular among the farmers owing to their superior yield attributes. Near about 1550 quintals breeder seeds have been produced and distributed to the farmers during the last five years (2014-2019). The urdbean mutant TAU-1 is the most successful variety occupying more than 50% of the urdbean area in Maharashtra (Fig. 8). The recently released high yielding urdbean variety TU-40 is gaining popularity in the southern states as evident from the surge in breeder seed indent from few quintals to almost 40 quintals for 2019-20 by the Department of Agriculture and Cooperation. The mungbean variety, TMB-37 though initially released for north east plain zone is gaining popularity across the country and has recently been re-adopted in 2018 by Punjab state owing to its large seed size, yellow mosaic virus resistance and suitability for summer cultivation (Fig. 9). The early

Figure 9: Field view of popular Trombay mungbean variety TMB-37

Figure 10: Cluster demonstration of popular Trombay pigeonpea variety TJT-501

maturing pigeonpea variety, TJT-501 occupies almost 60% of the area under pigeonpea in Madhya Pradesh (Fig. 10). The farmers of Maharashtra are reaping high yields by cultivating pigeonpea variety PKV-TARA especially under drip irrigation [11].

Table 3: Release of Trombay varieties in pulse crops for commercial cultivation in India

Variety	Year of release	States	Special features	Average yield (kg/ha)
Mungbean / Greengram				
TAP-7	1983	Karnataka, Maharashtra	Tolerant to powdery mildew	700-800
TARM-2	1992	Maharashtra	Resistant to powdery mildew	1000-1100
TARM-1	1995	Andhra Pradesh, Gujarat, Karnataka, Kerala, Maharashtra, Madhya Pradesh, Odisha, Tamil Nadu	Resistant to powdery mildew	700-800
TARM-18	1995	Maharashtra	Resistant to powdery mildew	1000-1100
TMB-37	2005	Assam, Bihar, Jharkhand, Uttar Pradesh, West Bengal	Tolerant to yellow mosaic virus	1100-1200
TJM-3	2007	Madhya Pradesh	Resistant to Yellow mosaic virus, powdery mildew and *Rhizoctonia* root rot diseases	900-1000
TM-96-2 (Trombay Pesara)	2007	Andhra Pradesh	Resistant to *Corynespora* leaf spot, powdery mildew	1000-1200
TM-2000-2 (Pairymung)	2010	Chhattisgarh	Resistant to powdery mildew, suitable for rice fallow	900-1000
Urdbean / Blackgram				
TAU-1	1985	Maharashtra	Large seed, Wider adaptability	800-1000
TPU-4	1992	Madhya Pradesh, Maharashtra	Large seed	900-1000
TAU-2	1992	Maharashtra	High yielding	900-1000
TU 94-2	1999	Andhra Pradesh, Kerala, Karnataka, Tamil Nadu	Resistant to yellow mosaic virus	900-1000
TU-40	2013	Andhra Pradesh, Karnataka, Kerala, Tamil Nadu	Resistance to powdery mildew	1000-1200
Pigeonpea				
TT-6	1983	Andhra Pradesh, Gujarat, Karnataka, Kerala, Madhya Pradesh, Maharashtra	Large seed	1200-1300
TAT-10	1985	Maharashtra	Early maturing	900-1000
TT-401	2007	Chhattisgarh, Gujarat, Madhya Pradesh, Maharashtra	High yielding, tolerant to pod borer and pod fly damage	1500-1600
TJT-501	2009	Madhya Pradesh, Maharashtra, Gujarat, Chhattisgarh	High yielding with early maturing, tolerance to *Phytophthora* blight	1800-1900
PKV-TARA	2013	Maharashtra	Resistant to *Fusarium* wilt disease	1900-2000

Cowpea				
Khalleshwari (TRC-77-4)	2007	Chhattisgarh	Suitable for rice based cropping system	700-800
TC 901	2018	Gujarat, Maharashtra, Madhya Pradesh, Rajasthan, Uttarakhand Uttar Pradesh, West Bengal	Suitable for summer season and resistant to cowpea mosaic virus	1000-1100

4. Genetic Improvement in Other crops

4.1 Rice

Rice is the most staple food crop of India covering an area over 44.0 million hectares with 110 million tonnes production ensuring food security to under-privileged, poverty alleviation and improved livelihood due to increased farm income. Rice is facing challenges related to unpredictable climate, soil alkalinity, occurrence of new races of diseases and changing consumer preferences. It is vital to increase crop diversity with greater selection efficiency to address current and future challenges of rice production. Most of the traditional rice landraces have their own special grain quality fetching premium price, but their cultivation is being marginalized because of late maturity, poor yield and crop lodging due to tall stature [12].

Figure 11: Field view of rice variety, Vikram TCR

Figure 12: Field view of rice variety, TKR Kolam with its grains

Radiation induced mutagenesis has been successfully employed in rice improvement resulting in the release of five varieties (Table 4). Among these, Trombay Chhattisgarh Dubraj Mutant-1 (TCDM-1), Vikram-TCR and CG Jawaphool Trombay, all being gamma ray mutant, have been released for commercial cultivation in Chhattisgarh, while a mutant derivative, Trombay Karjat Kolam Rice (TKR Kolam) for Maharashtra (Fig. 11 and 12) [13]. TCDM 1 has retained the aroma and grain quality of parent variety, Dubraj. TKR Kolam has superfine grain and better taste like other Kolam rice varieties. Both varieties are lodging tolerant with dwarf plant stature, medium duration of 130-140 days, better milling recovery and head rice recovery resulting in higher grain yield with less broken grains which is characteristic feature of premium rice. Vikram-TCR is high yielding, dwarf, non-shattering and non-lodging, mid-early maturity with long slender grain, drought tolerance and better puffed rice making quality. CG Jawaphool Trombay is high yielding, semi-tall, mid-early maturity, non-shattering and non-lodging with aromatic short grains and better *Kheer* making quality.

Table 4: Release of Trombay varieties in other crops for commercial cultivation in India

Variety	Year of release	States	Special features	Average yield (kg/ha)
Rice				
Hari	1988	Andhra Pradesh	Long slender grain, tolerant to Bacterial leaf blight and blast.	3500-4000
TCDM-1	2019	Chhattisgarh	Semi-dwarf, medium slender, Aromatic, medium amylose and higher milling% (69.5%), tolerant to bacterial leaf blight, neck blast and stem borer.	4500-5000
TKR Kolam	2020	Maharashtra	Short slender superfine grains, Lodging resistant	4200-4500
Vikram TCR (Trombay Chhattisgarh Rice)	2021	Chhattisgarh	Lodging resistant, early maturing, drought tolerant, better puffed rice making quality	6000-6500
CG Jawaphool Trombay	2021	Chhattisgarh	Short slender grain, aromatic rice, good for kheer making	3500-4000
Jute				
TKJ-40 (Mahadev)	1983	Odisha	High yielding	2000-2500

4.2 Sorghum (Jowar)

Sorghum is one of the major cereal crops cultivated for human consumption, livestock feed and biofuel. In order to create genetic variability for yield contributing traits and disease resistance, mutation breeding has been employed using physical and chemical mutagens. A mutant, TRJP1-5 was developed with 25% superior grain yield and moderate resistance to charcoal rot. Another mutant for hurda (green stage sorghum) type, TAKPS-5 was induced with 28% higher green hurda yield and improved organoleptic properties. Both TRJP1-5 and TAKPS-5 are undergoing advanced stage yield trial in Karnataka and Maharashtra, respectively towards their commercialization [14].

4.3 Banana

Banana (*Musa* spp,) is an important monocotyledonous perennial herbaceous fruit crop, cultivated in more than 130 countries and consumed by almost 500 million people worldwide.

Bananas are the fifth-most traded crop worldwide with India being the largest producer at approximately 29 million tonnes. One of the main problem in the cultivation of high yielding bananas are the lodging of plants during fruiting due to the heavy bunch weight, strong wind, heavy rains resulting in significant losses to the growers. In order to make the banana plant sturdier and strong, inducing dwarf mutants with comparable yield is essential. *In vitro* mutagenesis was initiated at BARC in an important cultivar, Giant Cavendish, a tall, high yielding but susceptible to lodging. Multiple shoot cultures were irradiated with gamma rays and a few desirable dwarf mutants were obtained [15]. These dwarf mutants were evaluated at National Research Centre for Banana (NRCB), Trichy, Tamil Nadu and one of the dwarf mutant TBM-9 performed better with a bunch weight of 29 kg and crop duration of 294 days. This mutant is currently under evaluation in ICAR-AICRP-Fruits multilocation trials. The results clearly shown that *in vitro* mutagenesis is a feasible approach for inducing useful mutants in banana.

4.4 Sugarcane

Sugarcane (*Saccharum* spp.) is a commercially important crop contributing to major global sugar production and as raw material for sugar producing and allied industries. India is the single largest sugar producing country in Asia. Changing environmental conditions adversely affect sugarcane crop, necessitating the development of improved crop varieties for yield along with tolerance to different stresses. It is hence desirable to develop novel sugarcane lines with improved productivity. Popular sugarcane cultivars (CoC-671, Co 86032) have been used for radiation based *in vitro* mutagenesis in combination with cellular screening and selection for salt tolerance at BARC. Several mutant clones have been isolated and field tested to identify promising mutants [16]. In case of CoC-671, 40 mutant clones were found promising for different agronomic traits. Of these, mutants, AKTS-01 and AKTS-02 were found superior for total plant height, millable cane height and number. In case of Co86032 and Co 740, field selection based on agronomic characters resulted in 18 and 17 mutant clones, respectively. The studies imply that *in vitro* mutagenesis is an effective tool for the induction of genetic variability for agronomic and juice quality traits in sugarcane.

Planned multi-pronged approaches have been followed at BARC to disseminate BARC varieties across the country. BARC has participated in exhibitions, *Kisan Melas* and conducted field demonstrations under the Public Awareness Programme on Peaceful Uses of Atomic Energy in order to create awareness about the Trombay crop varieties. Genetically pure nucleus seed of different varieties has been maintained at BARC. Such nucleus seed has been utilized to take up breeder seed production as per the national indent from various seed agencies and seed growers. With this system, more than 1000 tonnes of breeder seed were multiplied and supplied to National Seed Corporation, State Seed Corporations of Andhra Pradesh, Bihar, Chhattisgarh, Gujarat, Maharashtra, Odisha, Rajasthan and West Bengal; National Institutes; State Agricultural Universities; State Agricultural Departments; Non-Governmental Organizations and farmers. Apart from this, different State Agricultural Universities also distributed hundreds of tonnes breeder seeds of BARC crop varieties. Such of the seed was further multiplied, distributed and spread horizontally to thousands of farmers in the country.

Induced mutants themselves or their employment in recombination breeding with cultivars and / or other mutants produced several divergent crop varieties with improved agronomic traits at BARC. It is always felt that incorporating specific desirable genes into “good genetic backgrounds” is one of the impediments in the ideal use of plant genetic resources. It appears that planned breeding efforts were successful in bringing mutant genes into appropriate genetic

Table 5: Institutes/State Agricultural Universities having Memorandum of Understanding (MoUs) and research collaborations with BARC, Mumbai

Institutions / Universities	Crops
ICAR-Indian Institute of Pulse Research, Kanpur, Uttar Pradesh	Pigeonpea, Mungbean, Urdbean, Cowpea
ICAR-Directorate of Groundnut Research, Junagadh, Gujarat	Groundnut
ICAR-Directorate of Rapeseed-Mustard Research, Bharatpur, Rajasthan	Mustard
ICAR Indian Institute of Soybean Research, Indore, Madhya Pradesh	Soybean
ICAR-National Research Centre for Banana, Trichy, Tamil Nadu	Banana
ICAR-Indian Institute of Oilseeds Research, Hyderabad, Telangana	Linseed
Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra	Pigeonpea, Mungbean, Urdbean, Groundnut, Sunflower, Mustard, Sorghum, Soybean
Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra	Groundnut, Mustard, Urdbean
Vasantrao Naik Marathwada Krishi Vidyapeeth, Latur, Maharashtra	Groundnut
Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Maharashtra	Rice, Groundnut
Vasantdada Sugar Institute, Pune, Maharashtra	Sugarcane
University of Agricultural Sciences, Raichur, Karnataka	Mungbean, Urdbean, Sorghum
University of Agricultural Sciences, Dharwad, Karnataka	Groundnut
Acharya N.G. Ranga Agricultural University, Tirupati, Andhra Pradesh	Groundnut
Assam Agricultural University, Jorhat, Assam	Mustard
Jawahar Nehru Krishi Viswavidyalaya, Jabalpur, Madhya Pradesh	Pigeonpea, Mungbean
Rajmata Vijayaraje Scindia Krishi Vishwavidyalaya, Gwalior, Madhya Pradesh	Mungbean, Urdbean, Sesame, Groundnut
Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh	Cowpea, Rice
Junagadh Agricultural University, Junagadh, Gujarat	Groundnut
Navsari Agricultural University, Navsari, Gujarat	Groundnut, Sugarcane
Birsa Agricultural University Kanke, Jharkhand	Groundnut
Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palanpur, Himachal Pradesh	Mustard
Rajasthan Agricultural University, Bikaner, Rajasthan	Groundnut
Agriculture University, Jodhapur, Rajasthan	Mustard, Groundnut
Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal	Mustard, Groundnut, Mungbean

backgrounds at Trombay. Conclusively, a judicious blend of mutation and recombination breeding has a greater potential in the genetic improvement of crop plants as exemplified by crop breeding efforts undertaken at BARC, Trombay.

5. Future prospects

Crop improvement is a continuous breeding process wherein new mutants and breeding lines in different crops are to be developed to accomplish the future needs of the farmers in line with the changing climatic conditions and consumer needs; to keep pace with growing population and shrinking agricultural land. Novel mutants are to be induced to cater these needs by employing gamma rays, proton beam, electron beam based mutagenesis, targeted mutagenesis. Breeding efficiency is to be enhanced by identifying molecular markers for traits of interest. Such markers would enhance the breeding cycle for faster availability of the desired genotypes. Mutant genes have also become a valuable resource for understanding their structure and function.

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