PLANT SCIENCE TODAY
Vol 12(sp3): 01–08
https://doi.org/10.14719/pst.10401

eISSN 2348-1900

RESEARCH ARTICLE

Characterization and breeding value of morphological mutants derived from electron beam and gamma rays in rice (*Oryza sativa* L.)

Lalitha R[1], Arunachalam P[2*], Mothilal A[3], Vanniarajan C[4], Souframanien J[5], Senthil N[6] & Hemalatha G[7]

[1]Pushkaram College of Agriculture Sciences, Affiliated to Tamil Nadu Agricultural University, Thiruvarankulam 622 303, Tamil Nadu, India
[2]Department of Plant Breeding and Genetics, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India
[3]Krishi Vigyan Kendra (KVK), Vridhachalam 606 001, Tamil Nadu, India
[4]Anbil Dharmalingam Agricultural College and Research Institute, Tiruchirappalli 620 027, Tamil Nadu, India
[5]Nuclear Agriculture and Biotechnology Division, Bhabha Atomic Research Centre (BARC), Mumbai 400 085, Maharashtra, India
[6]Centre for Plant Molecular Biology and Biotechnology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[7]Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India

*Correspondence email - parunachalam@tnau.ac.in

Received: 02 July 2025; Accepted: 24 September 2025; Available online: Version 1.0: 02 January 2026

Cite this article: Lalitha R, Arunachalam P, Mothilal A, Vanniarajan C, Souframanien J, Senthil N, Hemalatha G. Characterization and breeding value of morphological mutants derived from electron beam and gamma rays in rice (*Oryza sativa* L.). Plant Science Today (Early Access). https://doi.org/10.14719/pst.10401

Abstract

Asia dominates global rice production, accounting for around 90 % of the world's total. Rice is considered as one of the model crops for physical irradiation in mutation studies. Among the physical sources of gamma rays, mutagenic studies have been conducted over several years, but nowadays focus on the emerging physical irradiation source of electron beam due to its action towards biomaterial is effective than gamma rays. The seeds of rice variety Anna (R) 4 were subjected to gamma rays and electron beam irradiation with four different doses (200, 250, 300 and 350 Gy). The primary panicles were collected from each plant in M_1 generation, forwarded to M_2 and M_3 generation as panicles-to-progeny row progenies. The identified mutants from irradiated populations were characterised using DUS test guidelines, followed by prepotency assessment for selected mutants. The maximum frequency was recorded in the electron beam (0.057) than in the gamma rays (0.034) irradiated population. Among the irradiation doses, 300 Gy of electron beam showed a higher frequency (0.099). The morphological mutants related to grain mutants, high tillering, early flowering mutants and flower organisation mutants were recorded maximum in the electron beam than in the conventionally used gamma rays. In the M_3 generation, the mutants of grassy and extreme dwarf, extra glume type and grain mutant showed true to type. The present study revealed that the electron beam showed a higher frequency of morphological mutants than the gamma rays.

Keywords: electron beam; gamma rays; morpho-mutants; mutation breeding; rice

Introduction

Rice is considered a major cereal crop, with Asian countries contributing 90 % of global rice production. India is the second-largest producer and exporter of rice. Enhancing the genetic potential to improve productivity continues to be the universal goal of rice breeding. Creation of genetic variation is the prime focus to attain the objective of any crop breeding programme. The hybridisation is commonly adopted to create genetic variability in the segregating population; special methods like mutation breeding have been widely followed to create the variation. Between 1950 to 2021, approximately 852 rice mutant varieties were publicly released to farmers, contributing significantly to agricultural improvement through physical and chemical mutagenesis, as well as somaclonal variation (1). Among them, 81.3 % (693) of total rice mutants were developed using physical mutagens. Induced mutation is helpful to expand the genetic variability and to isolate agronomically superior desirable mutants. Mutation breeding utilises three types of mutagenesis, i.e. induced mutagenesis either through physical or chemical treatment, site-directed mutagenesis and insertion mutagenesis (2, 3). Radiation techniques have generated enormous genetic variations, which are a source of phenotypic diversity and are a major driver of evolutionary diversification (4-6).

The main focus of this study is to determine the morphological changes and breeding value of the mutants generated from the electron beam and gamma rays. Electron beam is a new source of induced mutagen applied in the study, which primarily induces single–strand breaks (SSBs) and double-strand breaks (DSBs) in DNA, leading to gene mutations. However, it has minimal impact on cell wall function, plasma membrane integrity and protein structure (7). It produces absorbed dose rate towards biomaterials reaching up to 10^{10} $Gy.s^{-1}$, higher than gamma rays (60 $Gy.s^{-1}$) and also it acts as short pulses (8). A set of gamma rays and electron beam mutagenised plants in M_2 generation was carefully observed and evaluated to isolate various types of mutants related to plant architecture, such as plant height, tillering habit, leaf morphology, floral organisation and grain mutants.

Materials and Methods

The seeds of drought-tolerant and long slender grain rice variety Anna (R) 4 were obtained from the Agricultural Research Station, Paramakudi, Tamil Nadu, India (Table 1). Initially, each 1000 well-filled seeds of Anna (R) 4 were exposed to four different doses (200, 250, 300 and 350 Gy) of gamma rays and electron beam at Bhabha Atomic Research Centre, Mumbai. The lethal dose LD_{50} was previously optimised in Anna (R) 4 rice variety, which is 376.57 Gy for gamma rays and 273.27 Gy for electron beam (9). The M_1 generation was grown in the field and seeds were harvested from the primary panicles from 200 plants (200 panicles) in each dose of gamma rays and electron beam. The harvested seeds were forwarded to the M_2 generation as panicles to the progeny row. The seeds of 1600 panicles were raised in a nursery bed from June to October 2018 (*Kharif*). After eliminating the chlorophyll mutants, the remaining viable seedlings of 12400 and 5400 from gamma rays and electron beam, respectively, were raised in the main field. Morphologically distinct mutants were identified through visual assessment based on DUS (Distinctness, Uniformity and Stability) test guidelines at three different developmental stages (seedling, vegetative and reproductive) in M_2 generation. A total of 423 and 307 macro-mutants were identified in the M_2 populations of gamma ray– and electron beam–irradiated mutants, respectively, of the rice variety Anna (R) 4. The dose-wise mutation frequencies (Number of viable mutants / Number of plants observed) in M_2 generation were calculated.

During January to May 2019, the seeds from macro-mutants collected in M_2 generation were forwarded to M_3 generation as panicle to row progeny to assess the true breeding value. The floral organisation mutant and grain type mutants were observed using a microscope and grain scanner (Satake Grain Scanner RSQI 10A), respectively, whereas the grassy and extreme dwarf mutants' germination was determined by the roll towel method.

Table 1. Salient features of Anna (R) 4 rice variety used for mutation studies

Variety		Anna (R) 4
Parentage	:	Pantdhan 10 × IET 9911
Duration (in days)	:	100 -105
Average grain yield (kg/ha)	:	3700
Thousand grain weight (g)	:	25.7
Grain length/breadth ratio	:	3.45
Growth habit	:	Semi-dwarf, erect and non-lodging
Rice quality and colour	:	Long slender white rice
Special features	:	Drought tolerance

Results and Discussion

A total of 423 and 307 numbers of macro-mutants were identified in the M_2 population from gamma rays and electron beam irradiation, respectively, of Anna (R) 4. In M_2 generation, the morphological mutants such as early and late flowering (flowering duration); grassy and extreme dwarf, dwarf, tall (plant type); single tiller, low tiller and high tiller (tillering habit); narrow and broad type (leaf size); extra glume mutant; short, medium and long awns (awned mutant); unfertile seed and vegetative mutant (sterile mutant) and medium slender grain type mutant were observed in both the irradiation treatment of gamma rays and electron beam. Open beak grain type (gamma rays- 250 Gy), beaked spikelet type (Electron beam – 250 Gy) and mutant spikelet with two florets were also observed (Electron beam - 350 Gy). The above-mentioned morpho-mutants observed during this study are discussed, as shown in Fig.1.

Flowering mutants

The rice plant is considered a model for the analysis of flowering in short-day plants. Earliness is a predominant factor, as it minimises the effect of climate change and fits in multiple cropping systems. Two classes of mutants were observed, viz. early (68-79 days) and late flowering (95-110 days) in comparison with Anna (R) 4 (83-85 days). The maximum number of early flowering mutant had recorded in 300 Gy of gamma rays (21 No.) and 250 Gy of electron beam (25 No.) as compared to late flowering mutants (Fig. 2). The maximum number of early (0.009) and late (0.003) flowering

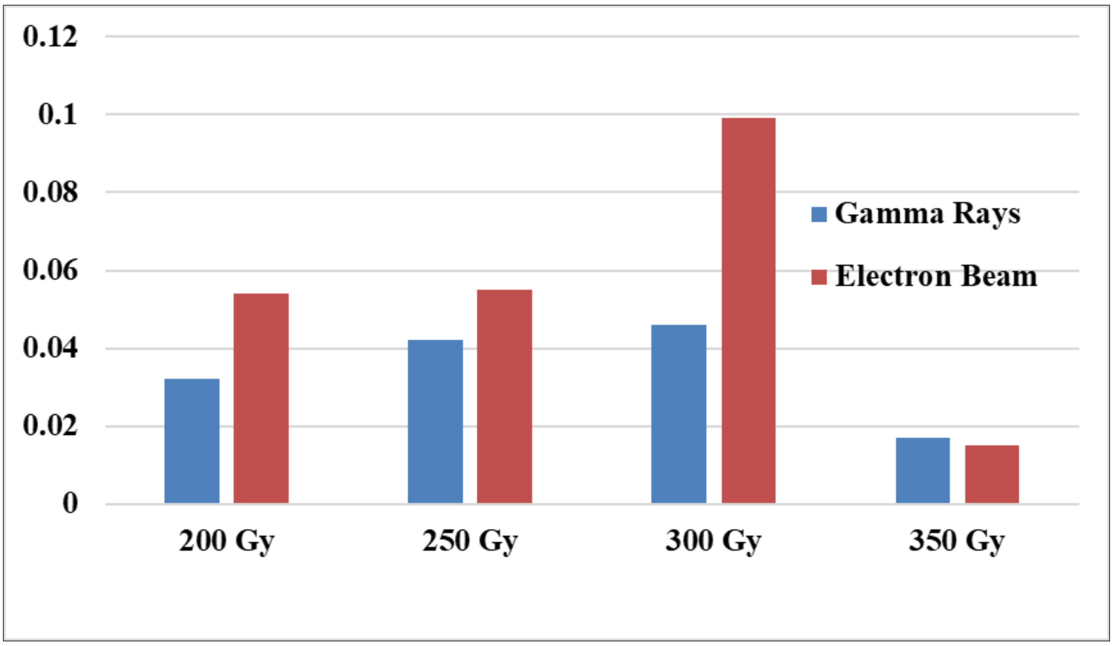

Fig. 1. Mutation frequency of gamma rays and electron beam irradiation of Anna (R) 4 rice in M_2 generation.

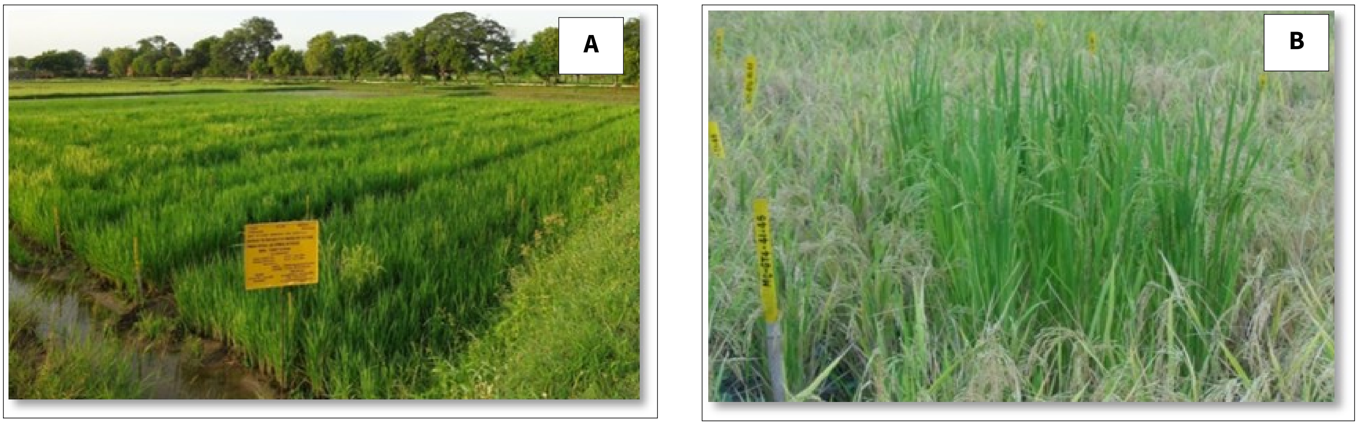

Fig. 2. Field view of flowering mutants: **A.** Early flowering, **B.** Late flowering.

mutants was recorded in electron beam irradiation compared with the gamma rays of 0.004 and 0.002, respectively. The prior studies also reported that the mutants were earlier than the wild types in rice (10-12).

Plant stature, tillering habit and leaf mutants

Plant height is taken as an important deciding factor for achieving grain yield enhancement. The vegetative growth phase is marked by active tillering, steady increases in plant height and regular leaf emergence. The duration of this phase is a key factor in determining the overall growth period of a cultivar. Most of the countries attained self-sufficiency in food production after the introduction of semi dwarf varieties during the green revolution period. The mutants with grassy and extreme dwarf mutants, each one from gamma rays (350Gy - 32 cm) and electron beam (300Gy -55.8 cm), were observed. The gamma rays mutant produced the maximum number of tillers (40 numbers) with the internode length of 9.8 cm and also increased the maturity duration up to 160 days. The average height of the dwarf plant type was 82 cm and the tall stature was more than 110 cm, as compared with the control (102.8 cm). Tall mutant genotypes are more susceptible to lodging, whereas shorter mutant genotypes exhibit greater resistance to lodging pressure due to their compact stature. Mostly, dwarfism or elongation of the plant was mainly controlled by the gibberellin (*D35, SD1* and *D18*) and brassinosteroid (*BRD1*) enzyme-related genes (13-15). Both genes affect the internode elongation of the plant; in addition, they reduce the leaf sheath to leaf blade ratio and root length.

The tillering habit determines the shoot architecture and grain production in grasses. In this study, three types of mutants were observed, viz. single tiller (monoculm mutant), low tillers (< 5 tillers) and high tillers (> 15 tillers), with the frequency of 0.007 (Gamma rays) and 0.015 (Electron beam). Both mutant populations had similar behaviour with respect to the production of different categories of tillering habit mutants and among the mutants, low tillering was observed with a maximum of 63 (gamma rays) and 59 (electron beam) numbers (Fig. 3). The rice gene *MONOCULM1* is required for the establishment and maintenance of axillary meristem. The loss of function of *MOC1* due to mutation resulted in affecting the tillering ability and panicle branches production (16). Leaves are the major part to receive sunlight, produce food and are a key determinant for plant architecture. The narrow and broad leaf mutants were recorded in both the irradiation treatment with similar leaf length to the control Anna (R) 4 variety. The frequency of the mutants was higher in the electron beam (0.001) than in the gamma rays (0.0002) with the average of 0.4 cm (narrow leaf) and more than 2.5 cm (broad leaf) were observed in relation to the control, 2.2 cm for leaf breadth.

Floral organisation mutant

A flower is considered a reproductive structure in a plant. It carries the genetic information from one generation to another. The involvement of several genetic mechanisms in the development of the floret is the so-called ABC model. The floral organ identity is decided by the ABC class gene combinations (17). The ABC model

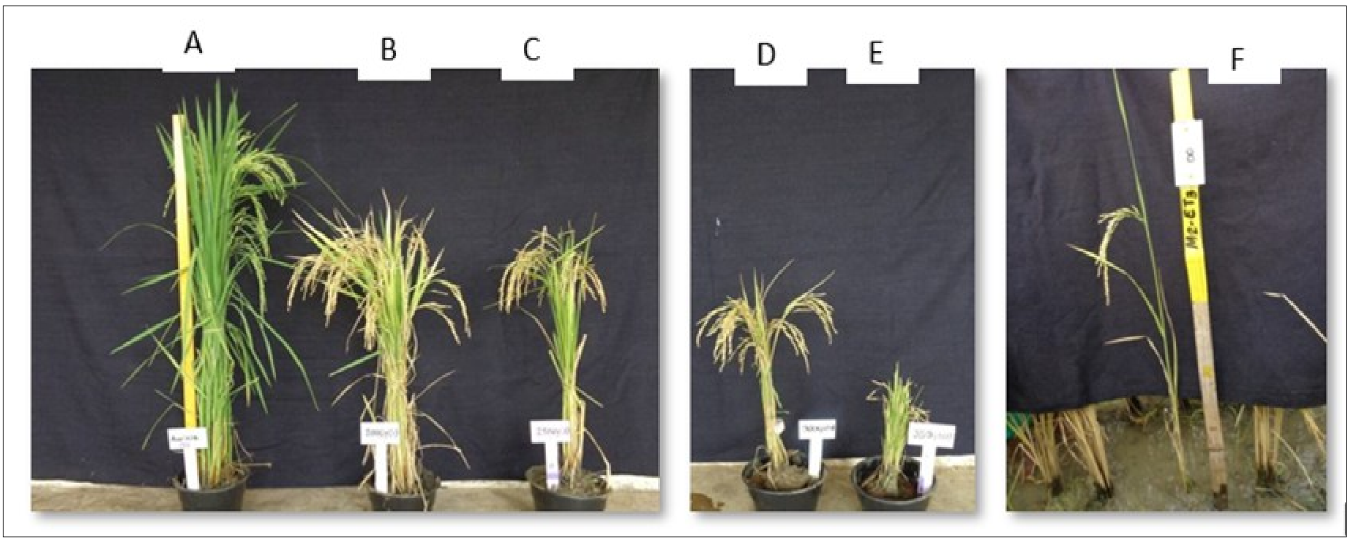

Fig. 3. Representative viable mutants in M_2 generation related to plant height and duration mutants: **A.** Control (Anna (R) 4): Plant height - 102.4 cm (90 days), **B.** GR- 200 Gy: Plant height - 82.5 cm (89 days), **C.** GR- 250 Gy: Plant height - 71.4 cm (87 days), **D.** EB- 300 Gy: Plant height - 58 cm (128 days), **E.** GR- 350 Gy: Plant height - 28 cm (133 days), **F.** Single culm mutant; GR represents gamma rays; EB represents electon beam.

was further extended as the ABCDE/ABCE model based on E-class function encoded by *SEP* and *AGL-6*-like genes involved in the development of all floral organs (18, 19).

Extra glume mutant

The different types of spikelet mutants were observed in individual panicles of 200 Gy, 250 Gy of gamma rays and in 250 Gy of electron beam. The spikelet mutant having extra-glume type with long (29 numbers) and short (18 numbers) palea, open spikelet with filled (1 number) and ill-filled (7 numbers) spikelet, extra glume with open spikelet (5 numbers), extra glume with grain (2 numbers) and without grain (19 numbers), long sterile glume spikelet (9 numbers) and 5 numbers of leafy hull sterile (5 layers) were observed in a single panicle of the mutant plant (Fig. 4).

Open beak spikelet

The five numbers of plants in 250 Gy of gamma rays had open beak spikelets, viz. all the spikelets in the panicle of the plant showed fully, partially and 1/4th opened at maturity stage with matured grain and also looked like a normal plant stature.

Single spikelet with two florets

This type of panicle with spikelet was observed in 350 Gy (1 no.) of electron beam treated using Anna (R) 4 rice variety. The types and numbers of spikelet present in a panicle viz. double grain in single spikelet formed as separate (2 numbers) and joined (3 numbers), open spikelet with malformed grain (7 numbers), extra glume with open spikelet (6 numbers), double spikelet [one sterile and another fertile with malformed grain] (2 numbers), normal spikelet with one sterile glume another converted into palea like organ (2 numbers) and sterile spikelet (15 numbers). The mutant plant and panicle also showed a reduction in their size compared with the normal plant.

Among mutants, both irradiation produces extra glumes or the floral parts that look like lemma and palea (leafy) structure with a similar frequency of 0.001, which indicates that the mutation can cause an increase in the number of floral organs and identity. Double grain in a single spikelet with separate or joined and an increase in the number of floral organ mutants was obtained in 350Gy of electron beam-treated Anna (R) 4 rice. These types of extra glumes are formed due to the defect of *OsMADS1*, which controls the determination of floral meristem identity in rice corresponding to the *Leafy Hull Sterile 1* locus from *Arabidopsis thaliana* within the same clade as *SEP1*, *SEP2 and 4* (20). Gamma irradiation at 250 Gy induced mutant (0.0004) in Anna (R) 4 rice variety showed an open spikelet with beaked (curved) lemma and palea, which had fully or partially opened with mature malformed grains.

Grain type mutants

Awned mutant

Awns act as a seed dispersal mechanism in many crops and it is the structures that extend from the apex of the lemma midvein. The three different lengths of awn were observed, viz. short (0.8 cm), medium (1.76 cm) and long (2.86 cm) awned grain in Anna (R) 4 mutant population. Medium awned mutants were observed at maximum with a frequency of 0.011 and also more number of

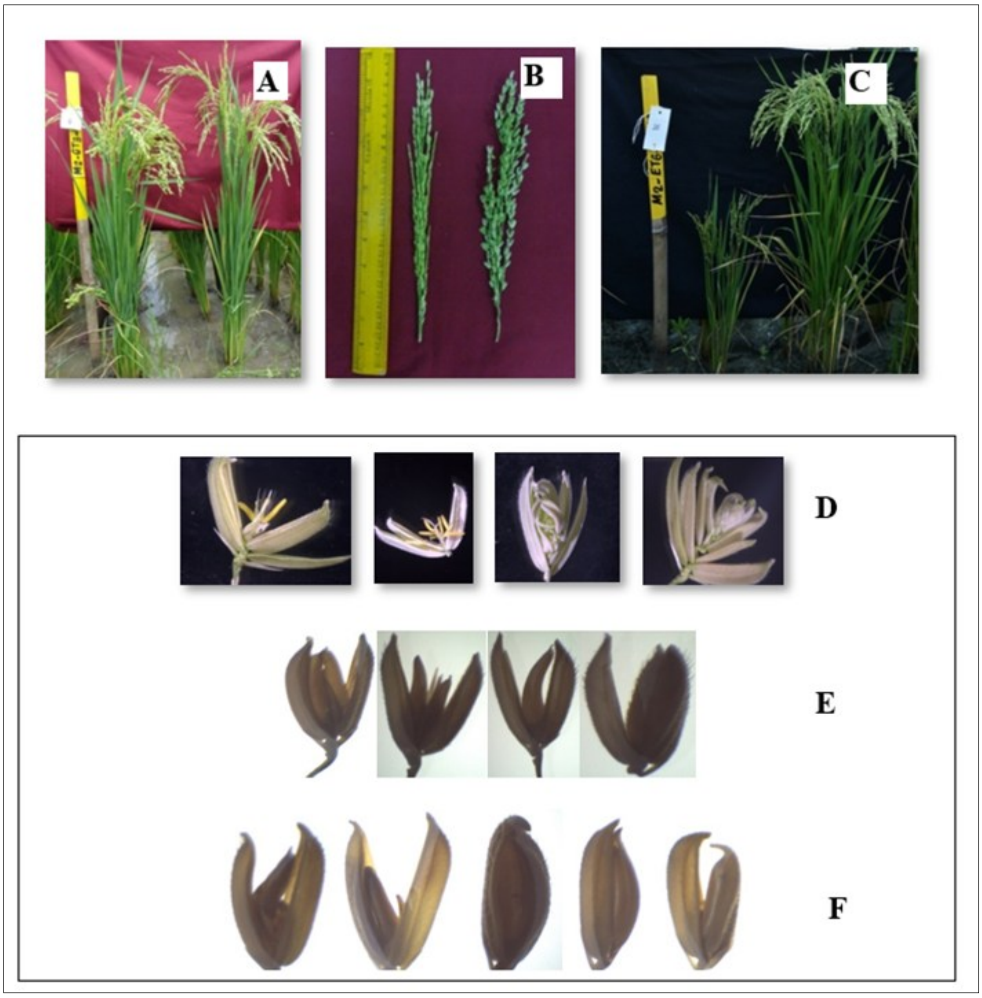

Fig. 4. Floral organisation mutants: **A.** Extra glume and leafy hull sterile mutant with control (Anna (R) 4) plant, **B.** Extra glume and leafy hull sterile mutant with control (Anna (R) 4) panicles, **C.** Single spikelet with two floret mutant plant with control Anna (R) 4 plant, **D.** Spikelet of extra glume and leafy hull sterile mutant, **E.** Spikelet of single spikelet with two floret mutants, **F.** Spikelet of open beak mutants.

awned mutants in gamma rays (0.013) than in electron beam (0.007). The long awned mutant (1 no.) was recorded only in the electron beam at the dose of 200 Gy with 2.86 cm awn length, while the other treatments had short and medium awns (Fig. 5). During domestication, the selection was against the awns for reducing the difficulties faced at harvesting, processing and storing the grains (21, 22).

Grain size mutant

Grain length, grain width, grain length-width ratio and grain thickness are the four major factors that determine the grain weight (23). Grain length was the strongest determinant for grain size as reported in earlier studies (24). The medium slender grain size was found in gamma rays ranging from 6.07 to 6.53 mm and 5.71 to 6.53 mm in electron beam and the maximum number of mutants was observed in 300 Gy of electron beam (63 nos.). The grain type of Anna (R) 4 rice variety comes under long slender (6.90 mm), whereas the mutants from gamma rays and electron beam were medium slender. The maximum reduction in grain size in mutants was observed in electron beam irradiation (0.015) than the gamma rays (0.003) in the M_2 population. A high frequency of desirable grain mutants was observed in the electron beam irradiated population than in the gamma rays (10).

Beak-shaped grain and sterile mutant

The four mutant plants in 250 Gy of electron beam, spikelets had a beak-like structure at the tip of the grain with a normal grain size of long, slender. Whereas the sterile mutant was recorded in 200 Gy of gamma rays, the plants produced a low number of panicles with infertile spikelets and the morphological appearance looked like a giant with long leaves up to 52 cm in length, 1.8 cm in width and slightly dark green in colour. While in 250 Gy of electron beam, plants exhibited a normal stature and the spikelets were beaked and ill filled.

Frequency and spectrum of viable mutants

The overall frequency of viable mutants was higher in electron beam (0.057) irradiated Anna (R) 4 rice as compared with gamma rays (0.034). Among the doses, 300 Gy of electron beam and gamma rays individually scored maximum frequency of 0.099 and 0.046, respectively. A spectrum of morphological mutants was observed in both gamma rays and the electron beam. Early flowering (0.009), high tillering habit (0.002) and grain type (0.015) mutants were recorded as high in electron beam, whereas awned spikelet scored maximum in gamma rays (0.013). The mutants like plant height (0.003) and floral organisation mutant (0.001) were similar in both irradiations. The previous studies also indicate that the frequency of total mutants in electron beam was found to be higher than gamma rays with respect to rice and mungbean (25, 26). The frequency and spectrum of individual macro-mutants are given in Table 2.

Assessing the breeding value in macromutants

Based on the availability of seeds and the importance of morphological mutants like grassy and extreme dwarf, single tiller, open beak spikelet, spikelet with two floret types, extra glume mutants and beaked grain mutants of Anna (R) 4 rice, grain mutants (medium grain) were forwarded to M_3 generation to assess their true breeding value. The grassy and extreme dwarf mutant (350 Gy - gamma rays), extra glume mutant and grain mutants showed true breeding nature, while the grassy and extreme dwarf mutant (300 Gy - electron beam) and beaked grain mutants were found to be segregating. The other mutants, like open beak spikelet, single tiller performed as a normal plant, whereas the spikelet with two florets did not germinate in the field. The mutant performance of grassy and extreme dwarf mutants was assessed at the seedling stage and in the field. The seedling performance was assessed by the roll towel method; the average shoot and root length of Anna (R) 4 was 13.20 and 23.20 cm, respectively; their mutants had 10.30 and 8.85 cm at

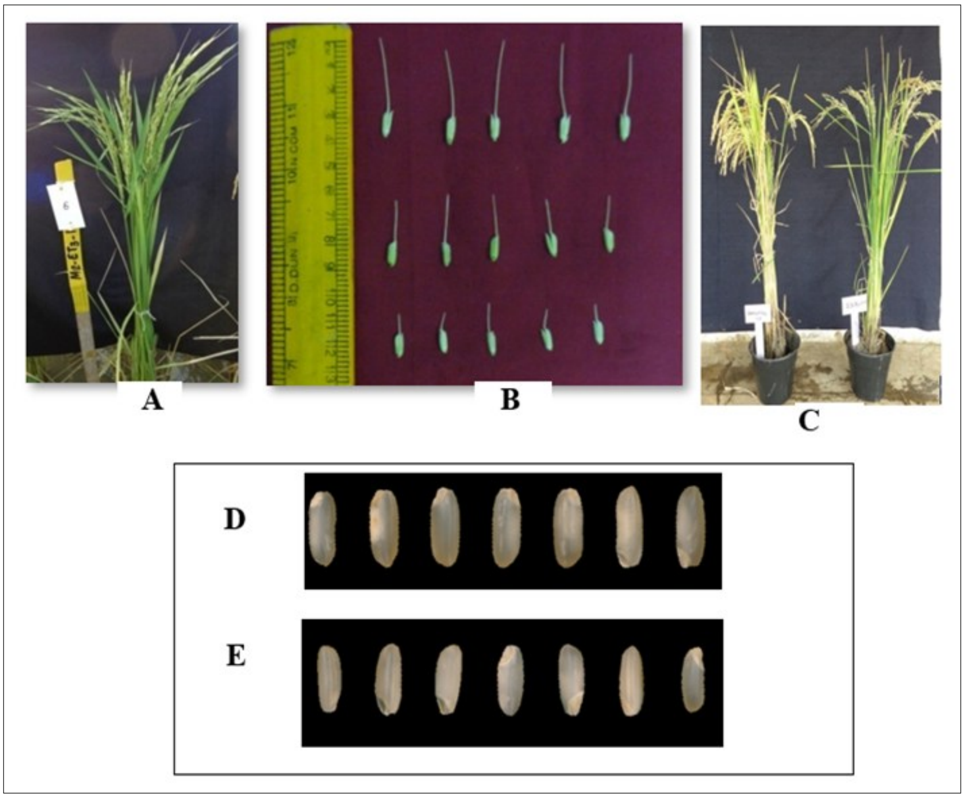

Fig. 5. Grain type mutants: **A.** Awned mutant plant, **B.** Awn length variation mutant, **C.** Sterile mutant (Gamma rays -200 Gy), **D.** Grain size mutant - Control (Anna (R) 4) Grainlength - 6.90 mm; L/B - 3.42, **E.** Mutant of electron beam grain length - 5.71mm; L/B - 2.97; L/B denotes length breadth ratio.

Table 2. Frequency of morphological mutants in M_2 generation from Anna (R) 4 rice cultivar

	Gamma rays (N= 12240 plants)					Electron beam (N=5400 plants)				
Macromutants	**200 Gy**	**250 Gy**	**300 Gy**	**350 Gy**	**No. (frq.)**	**200Gy**	**250 Gy**	**300 Gy**	**350 Gy**	**No. (frq.)**
No. of plants observed	3633	3355	2720	2523	12,240	1506	1460	1278	1156	5400
Flowering mutants	0.002 (6)	0.012 (40)	0.011 (29)	0.002 (5)	0.007 (80)	0.007 (10)	0.027 (39)	0.013 (16)	0.003 (3)	0.013 (68)
Early	6	20	21	5	0.004 (52)	7	25	16	3	0.009 (51)
Late	-	20	8	-	0.002 (28)	3	14	-	-	0.003 (17)
Plant height mutants	0.003 (12)	0.007 (24)	-	0.003 (7)	0.003 (43)	0.001 (1)	0.003 (5)	0.006 (8)	0.002 (3)	0.003 (17)
Grassy & extreme dwarf	-	-	-	1	0.00008 (1)	-	-	1	-	0.0002 (1)
Dwarf	12	14	-	3	0.002 (29)	1	5	4	2	0.002 (12)
Tall	-	10	-	3	0.0007 (13)	-	-	3	1	0.001 (4)
Tillering habit	0.005 (19)	0.009 (32)	0.007 (19)	0.006 (16)	0.007 (86)	0.022 (34)	0.009 (14)	0.023 (30)	0.005 (6)	0.015 (84)
Single culm	3	4	2	3	0.001 (12)	10	-	5	-	0.003 (15)
Low tiller	16	23	15	9	0.006 (63)	24	10	19	6	0.01 (59)
High tiller	-	5	2	4	0.001 (11)	-	4	6	-	0.002 (10)
Leaf	0.001 (3)	0.001 (2)	-	0.001 (3)	0.0005 (8)	0.003 (5)	0.001 (2)	0.002 (3)	0.002 (2)	0.002 (12)
Narrow	-	2	-	-	0.0002 (2)	5	2	-	-	0.001 (7)
Broad	3	-	-	3	0.0004 (6)	-	-	3	2	0.001 (5)
Floral Organization	0.002 (9)	0.002 (7)	-	-	0.001 (16)		0.003 (4)		0.0001 (1)	0.001 (5)
Extra glume mutant	9	2	-	-	0.001 (11)	-	4	-	-	0.001 (4)
Open-beak grain type mutant	-	5	-	-	0.0004 (5)	-	-	-	-	-
Overexpression of miR172b plants	-	-	-	-	-	-	-	-	1	0.0002 (1)
Awned grain	0.015 (56)	0.008 (28)	0.025 (69)	0.003 (9)	0.013 (162)	0.02 (30)	-	0.005 (7)	-	0.007 (37)
Short	15	8	4	-	0.002 (27)	12	-	-	-	0.002 (12)
Medium	41	20	65	9	0.011 (135)	17	-	7	-	0.004 (24)
Long	-	-	-	-	-	1	-	-	-	0.0002 (1)
Grain type	0.004	0.002	0.003	0.0008	0.003	0.001	0.008	0.049	0.002	0.015
Medium slender	14	7	8	2	0.003 (31)	2	12	63	2	0.015 (79)
Others	0.00001 (1)	-	-	-	0.00001 (1)	-	0.003 (5)	-	-	0.0009 (5)
Beaked grain type	-	-	-	-	-	-	4	-	-	0.0007 (4)
Sterile mutant	1	-	-	-	0.00001 (1)	-	1	-	-	0.0002 (1)
Total	0.032 (116)	0.042 (140)	0.046 (125)	0.017 (42)	0.034 (423)	0.054 (82)	0.055 (81)	0.099 (127)	0.015 (17)	0.057 (307)

the 14th day. Compared to shoot length, root length has been much reduced in grassy and extreme dwarf mutants. In the field, the average plant height of mutants was 24.15 cm, flag leaf length 9.75 cm and leaf breadth 0.4 cm, panicle length 8.8 cm, number of productive tillers per plant 45, whereas the number of grains per panicle was 5 to 10 (Fig. 6). From this mutant two possible candidate genes involved in strigolactone biosynthesis were identified (27).

In the M_3 generation, grain mutants exposed to electron beam irradiation showed a greater reduction in grain length (5.45–6.23 mm) than those exposed to gamma rays (5.50–6.46 mm), with mean grain lengths of 5.78 mm and 6.23 mm, respectively. Taken together, this study indicates that the maximum number of morphological mutants were identified in emerging physical mutation source of electron beam rather than the conventionally used gamma rays source.

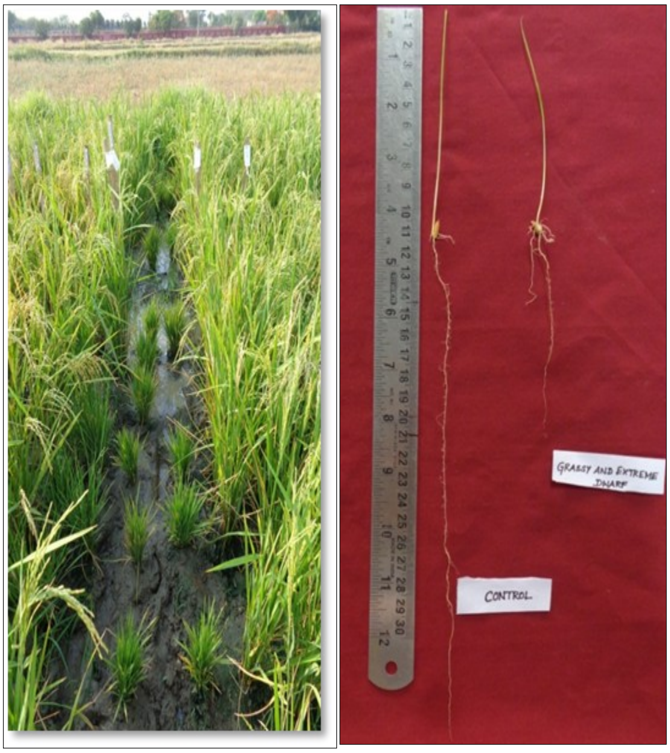

Fig. 6. A. Field view of grassy and extreme dwarf mutants induced by 350 Gy of gamma rays in M_3 generation. **B.** Seedling length of Anna (R) 4 and the extreme dwarf mutant observed on the 14th day by the roll towel method.

Conclusion

The present study revealed that a wider range of mutants was identified in the M_2 generation of electron beam than that of gamma rays. Hence electron beam is considered a potential mutagen for creating genetic variability. The stable morphological mutants isolated in this study are to be characterised further to understand their genetic basis. The variations observed in viable mutants in the traits such as days to maturity, plant height and grain type could be utilised for further selection to develop an improved rice variety with desirable grain type and maturity duration.

Acknowledgements

The authors are thankful to Agricultural College and Research Institute, Madurai for extending laboratory, field facilities for this research and extend their sincere thanks to Government of India, Board of Research in Nuclear Sciences (BRNS), Department of Atomic Energy, Mumbai, for providing research grant [No.35/14/13/2017-BRNS] for this study.

Authors' contributions

LR carried out the experiment and wrote the manuscript. AP planned the experiment, carried out the experiment, wrote the manuscript and did the funding acquisition. MA planned the experiment and wrote the manuscript. VC, SN and HG planned the experiment. SJ planned the experiment and also did the project administration.

Compliance with ethical standards

Conflict of interest: The authors declare that no potential conflict of interest.

Ethical issues: None

References

1. International Atomic Energy Agency IAEA mutant variety search. 2021. https://mvd.iaea.org/#search
2. Kharkwal MC, Shu QY. The role of induced mutations in world food security. In: Induced Plant Mutations in the Genomics Era. Rome: FAO; 2009. p. 33–38.
3. Forster BP, Shu QY. Plant mutagenesis in crop improvement: basic terms and applications. In: Plant Mutation Breeding and Biotechnology. Wallingford (UK): CABI; 2012. p. 9–20. https://doi.org/10.1079/9781780640853.0009
4. Jankowicz-Cieslak J, Mba C, Till BJ. Mutagenesis for crop breeding and functional genomics. In: Biotechnologies for Plant Mutation Breeding: Protocols. 2017. p. 3–18. https://doi.org/10.1007/978-3-319-45021-6_1
5. Gowthami R, Vanniarajan C, Souframanien J, Pillai MA. Comparison of radiosensitivity of two rice (*Oryza sativa* L.) varieties to gamma rays and electron beam in M_1 generation. Electron J Plant Breed. 2017;8(3):732-41. https://doi.org/10.5958/0975-928X.2017.00111.9
6. Sao R, Sahu PK, Sharma D, Vishwakarma G, Nair JP, Petwal VC, et al. Comparative study of radio-sensitivity and relative biological effectiveness of gamma rays, X-rays, electron beam and proton beam in short grain aromatic rice. Indian J Genet. 2020;80(04):384-94. https://doi.org/10.31742/IJGPB.80.4.3
7. Mondal S, Petwal VC, Badigannavar AM, Bhad PG, Verma VP, Goswami SG, et al. Electron beam irradiation revealed genetic differences in radio-sensitivity and generated mutants in groundnut (*Arachis hypogaea* L.). Appl Radiat Isot. 2017;122:78-83. https://doi.org/10.1016/j.apradiso.2017.01.016
8. Zhu H, Xu J, Li S, Sun X, Yao S, Wang S. Effects of high-energy-pulse-electron beam radiation on biomacromolecules. Sci China Ser B Chem. 2008;51(1):86-91. https://doi.org/10.1007/s11426-008-0017-4
9. Lalitha R, Arunachalam P, Mothilal A, Senthil N, Hemalatha G, Vanniarajan C, et al. Radiation effect on germination and seedling traits in rice (*Oryza sativa* L.). Electron J Plant Breed. 2019;10(3):1038-48. https://doi.org/10.5958/0975-928X.2019.00133.9
10. Gowthami R, Vanniarajan C, Souframanien J, Veni K, Renganathan VG. Efficiency of electron beam over gamma rays to induce desirable grain-type mutation in rice (*Oryza sativa* L.). Int J Radiat Biol. 2021;97(5):727-36. https://doi.org/10.1080/09553002.2021.1889702
11. Gautam V, Swaminathan M, Akilan M, Gurusamy A, Suresh M, Kaithamalai B, et al. Early flowering, good grain quality mutants through gamma rays and EMS for enhancing per day productivity in rice (*Oryza sativa* L.). Int J Radiat Biol. 2021;97(12):1716-30. https://doi.org/10.1080/09553002.2021.1987563
12. Chowdhury N, Islam S, Mim MH, Akter S, Naim J, Nowicka B, et al. Characterization and genetic analysis of the selected rice mutant populations. SABRAO J Breed Genet. 2023;55(1):25–37. https://doi.org/10.54910/sabrao2023.55.1.3
13. Mori M, Nomura T, Ooka H, Ishizaka M, Yokota T, Sugimoto K, et al. Isolation and characterization of a rice dwarf mutant with a defect in brassinosteroid biosynthesis. Plant Physiol. 2002;130(3):1152–61. https://doi.org/10.1104/pp.007179
14. Hong Z, Ueguchi-Tanaka M, Umemura K, Uozu S, Fujioka S, Takatsuto S, et al. A rice brassinosteroid-deficient mutant, ebisu dwarf (d2), is caused by a loss of function of a new member of cytochrome P450. Plant Cell. 2003;15(12):2900–10. https://doi.org/10.1105/tpc.014712

15. Itoh H, Tatsumi T, Sakamoto T, Otomo K, Toyomasu T, Kitano H, et al. A rice semi-dwarf gene, Tan-Ginbozu (D35), encodes the gibberellin biosynthesis enzyme ent-kaurene oxidase. Plant Mol Biol. 2004;54:533–47. https://doi.org/10.1023/B:PLAN.0000038261.21060.47

16. Li X, Qian Q, Fu Z, Wang Y, Xiong G, Zeng D, et al. Control of tillering in rice. Nature. 2003;422(6932):618–21. https://doi.org/10.1038/nature01518

17. Coen ES, Meyerowitz EM. The war of the whorls: genetic interactions controlling flower development. Nature. 1991;353 (6339):31–7. https://doi.org/10.1038/353031a0

18. Robles P, Pelaz S. Flower and fruit development in Arabidopsis thaliana. Int J Dev Biol. 2005;49(5–6):633–43. https://doi.org/10.1387/ijdb.052020pr

19. Rijpkema AS, Vandenbussche M, Koes R, Heijmans K, Gerats T. Variations on a theme: changes in the floral ABCs in angiosperms. Semin Cell Dev Biol. 2010;21(1):100–7. https://doi.org/10.1016/j.semcdb.2009.11.002

20. Agrawal GK, Abe K, Yamazaki M, Miyao A, Hirochika H. Conservation of the E-function for floral organ identity in rice revealed by the analysis of tissue culture-induced loss-of-function mutants of the OsMADS1 gene. Plant Mol Biol. 2005;59:125–35. https://doi.org/10.1007/s11103-005-2161-y

21. Luo J, Liu H, Zhou T, Gu B, Huang X, Shangguan Y, et al. An-1 encodes a basic helix-loop-helix protein that regulates awn development, grain size and grain number in rice. Plant Cell. 2013;25(9):3360–76. https://doi.org/10.1105/tpc.113.113589

22. Hua L, Wang DR, Tan L, Fu Y, Liu F, Xiao L, et al. LABA1, a domestication gene associated with long, barbed awns in wild rice. Plant Cell. 2015;27(7):1875–88. https://doi.org/10.1105/tpc.15.00260

23. Tan YF, Xing YZ, Li JX, Yu SB, Xu CG, Zhang Q. Genetic bases of appearance quality of rice grains in Shanyou 63, an elite rice hybrid. Theor Appl Genet. 2000;101:823–9. https://doi.org/10.1007/s001220051549

24. Takeda K. Inheritance of grain size and its implications for rice breeding. In: Khush GS, editor. Rice Genetics II. Manila: International Rice Research Institute. 1991. p. 181–189. https://doi.org/10.1142/9789812814272_0018

25. Manikandan V, Vanniarajan C. Induced macromutational spectrum and frequency of viable mutants in M2 generation of rice (*Oryza sativa* L.). Int J Curr Microbiol Appl Sci. 2017;6:1825–34. https://doi.org/10.20546/ijcmas.2017.607.220

26. Dhole VJ, Souframanien J, Reddy KS, Petwal VC. Comparison of effectiveness and efficiency of electron beam over gamma rays to induce novel mutations in mungbean (*Vigna radiata* L. Wilczek). Appl Radiat Isot. 2023;194:110719. https://doi.org/10.1016/j.apradiso.2023.110719

27. Ariharasutharsan G, Karthikeyan A, Geetha S, Raveendran M, Lalitha R, Ananda-Lekshmi L, et al. Prioritization of candidate genes regulating the dwarfness in rice by integration of whole-genome and transcriptome analyses. Funct Integr Genomics. 2025;25(1):19. https://doi.org/10.1007/s10142-025-01532-1

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.