Research Article

Evaluation of Gamma Rays-Induced Effects on Vegetative, Floral and Yield Parameters of Okra Varieties

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Abstract | Radiations on fresh fruits as well as on vegetables not only have a quick and direct impact upon the chemical constitution, but also have an indirect consequence of physiological and biochemical alteration. There is a lack of systematic evaluation of dose-dependent gamma radiation effects across different okra genotypes. Besides investigation for varietal-specific radiosensitivity and optimal mutagenic doses is important for yield enhancement of okra genotypes. In this study, we applied 100, 150, 200 and 250 Gy doses of gamma radiations on seeds of two varieties of Okra (*Abelmoschus esculentus*) Nutech and Tarnab. We analyzed the gamma radiations effect on different morphological parameters of the plant and found that seed germination was a bit delayed in both Nutech and Tarnab radiated varieties. Similarly, plant height and no. of leaves reduced for both Nutech and Tarnab at 200Gy. Similarly, a significant increase was observed for no. of flowers plant^{-1} which alternatively results in more fruits and more seeds per plants after successful fertilization at higher exposure of doses at 150Gy,200Gy and 250Gy. However, no significant change was observed in no of seeds plant^{-1} of both varieties before and after radiations. Over all Nutech variety responded more positively as compared to Tarnab variety. Our data suggested that radiation has a random effect at different doses and its variations can be seen from plants to plants and tissues to tissues. In conclusion moderate dosses of radiations are always good for bringing certain desired characteristics.

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Introduction

Okra (*Abelmoschus esculentus* L.) is a valuable vegetable crop grown for its green, edible fruits. It belongs to the family Malvaceae and is also rarely referred to as *Hibiscus esculentus* (Bentham and Hooker, 1867). Okra is a good source of many nutrients such as carbohydrates, proteins (rich in lysine and tryptophan), vitamins A, B, and C, dietary fiber, calcium, zinc, folic acid, and iodine (Gemede *et al*., 2015; Holser *et al*., 2004; Wang *et al*., 2025). It is a leafy green vegetable packed with nutrients hence holds a distinct position among vegetables across the globe providing fiber, essential vitamins, and mineral content (Fadeyibi and Adewale, 2025). These traits of okra not only support digestive processes while strengthening the body's defenses and well-being they also quietly deliver what bodies need (Fatima *et al*., 2024). However, in Okra cultivation, adoption of cutting-edge agricultural practices and technology that might increase output is further hindered by the lack of improved varieties (Keba, 2019).

There aren't many better okra types that are suited to regional circumstances and resistant to pests and diseases (Massrie, 2025). Okra output can be increased by creating new cultivars (Massrie, 2025). For this purpose, the genotypes of well-known cultivars that are appropriate for contemporary agricultural and commercial requirements can be improved and modified via the application of mutagenesis. Sorghum *(Sorghum bicolour* L.) (Human *et al*., 2020), wheat (*Triticum aestivum* L.) (Bayarsaikhan *et al*., 2022), rice (*Oryza sativa* L.) (ICAR, 2023), and adlay (Nakagawa and Kato, 2017) are among the food crop varieties that have been produced using this method however the work is limited in Okra. One of the important physical agents is gamma radiation, which is used to improve the characteristics and productivity of many plants including rice, maize, cowpea, potato, and bean (Hegazi and Hamideldin, 2010). Gamma rays and X-rays are non-particulate electromagnetic radiations with very short wavelengths (Singh and Datta, 2010). Gamma irradiation for modifying the genetic makeup of plants appears to be a promising technique compared with conventional plant breeding (Majeed *et al*., 2018) and they tend to be an efficient abiotic elicitor for the generation of mutant varieties, more attractive trait plants, and fruits with increased bioactive potential (Mahood and Sarropoulou, 2025).

Previously, radiation techniques have been successfully utilized for mutation breeding in many crops, and maximum plant height, grain, and straw yield were achieved (Chakraborty *et al*., 2024) while lethal effect of radiation doses exceeding 20 Krh/min on germination and general growth of *Pinus* species has also been reported (Thapa, 2004). Vegetative growth and yield characters of pea (*Pisum sativum* L.) were negatively affected by radiation doses above 10 Gy (Majeed *et al*., 2017), but in the same way an increase in vegetative growth, floral, and fruit traits of okra at 2000 rad of gamma irradiation has also been documented (Yakoro *et al*., 2023). This propagation technique has opened new strategies for hereditary improvement in plant life (Mollah *et al*., 2009). Ionizing radiation provides an effective means of creating variation compared with normal propagation practices, and induced mutagenesis can be an ideal strategy for crop improvement (Gaur *et al*., 2018). In pulses, a number of varieties have been developed through mutation breeding (Ahloowalia *et al*., 2004; Solanki and Dhankhar, 2011). Ionizing radiation also has the advantage of reducing or even delaying fruit ripening processes, thereby extending the shelf life of fruits and vegetables with significant economic benefits (Loaharanu, 1995). Induced mutation is used as a tool to study the character and function of genes responsible for plant growth and improvement. It has been an important technique for cultivar development and for enhancing natural genetic resources, particularly for the selection of mutants with desirable agronomic traits (Taheri *et al*., 2014).

More than 2,700 varieties derived from mutations in 170 different species have been officially released worldwide (Luo *et al*., 2013). Therefore, the present study was designed to evaluate the effect of different doses of gamma irradiation on the growth, yield, and yield-related traits of two okra (*Abelmoschus esculentus* L.) cultivars, Nutech and Tarnab. By analyzing key morphological and reproductive parameters in the M_1 generation, this study seeks to identify dose-dependent responses that could be exploited for the development of improved okra genotypes with enhanced productivity and agronomic potential.

Materials and Methods

The current research work was performed during the crop season to investigate the beneficial effect of gamma radiations on two Okra (*Abelmoschus esculentus* L.) cultivars, Nutech and Tarnab. The seeds of cultivars were obtained from Tarnab Farm seed stock.

Gamma irradiation

Before radiation, the moisture content of all seeds was equilibrated as mentioned by Wang *et al*. (2017). Gamma-rays experiment was conducted using gamma Cobalt-60 source at the Nuclear Institute for Food and Agriculture (NIFA) Peshawar, Pakistan. 15 seeds of each variety were exposed to doses of 100 Gy, 150Gy, 200Gy, and 250Gy.

Field experiment

Field experiments were carried out in the Samang region, westward to the Shaheed Benazir Bhutto University, Sheringal, Dir Khyber Pakhtunkhwa, Pakistan. Seeds were sown in pots and all pots were equally spaced with an equal amount and same composition of soil in each pot. The experimental design was randomly giving each dose having 5 replicates. 15 seeds per pot were distributed equally. The plot size was sketched as 15m length with 10m width containing 3 replications and 15 remedies. Each row changed into 70 cm aside from the nearby one whilst plant to plant distance was kept as 30 cm. A dosage of nitrogen and phosphorus pentoxide fertilizer was supplemented two times to the field in the course of the growing time of the okra crop. The pots were checked regularly for water requirements.

Parameters

The data recorded of the following parameters in M_1 Generation i.e., days to germination, plant height, number of leaves plant^{-1}, number of flowers plant^{-1}, number of fruits plant^{-1} and number of seeds plant^{-1}.

Calculation and statistical analysis

All data was taken in replicates. Data was collected using Excel 2016 and statistical analysis were done by using SPSS (version 23). All graphs were generated in graph pad prism 9.

Results

Days to germination

At the control level (0 Gy), Tarnab exhibited a shorter mean time to germination (approx. 6 days) compared to Nutech (approx. 7 days), suggesting a higher baseline physiological vigor in the Tarnab variety. Upon exposure to moderate radiation doses ranging from 100 to 200 Gy, both cultivars experienced a notable delay in germination, however, Tarnab's transition from the control to 100 Gy showed a more abrupt increase in days required to germinate (reaching over 8 days) before stabilizing. The most critical divergence was observed at the maximum dose of 250 Gy, where Nutech reached its peak delay of approximately 9 days marked by a highly significant statistical difference ($p < 0.01$). These findings suggest that while both cultivars are sensitive to ionizing radiation, Nutech possesses a lower threshold for high-dose gamma exposure, resulting in more pronounced inhibitory effects on the biological processes essential for seed emergence as shown in Figure 1 and Table 1.

Table 1: *Effect of varying doses of gamma radiation on the germination, vegetative growth, and reproductive yield of Tarnab and Nutech cultivars.*

Parameter	Cultivar	Control (0 Gy)	100 Gy	150 Gy	200 Gy	250 Gy
Days to germination	Tarnab	6.0	8.0	8.0	8.0	8.0
	Nutech	7.0	7.0	7.0	7.0	9.0
Plant height (cm)	Tarnab	86	76	74	62	80
	Nutech	96	96	84	68	80
No. of leaves plant^{-1}	Tarnab	15	13.5	14.5	11	14
	Nutech	16	15	12.5	13	18
No. of flowers plant^{-1}	Tarnab	7	12	23	17	21
	Nutech	9	16	18	24	18
No. of fruits plant^{-1}	Tarnab	9	10	21	14	18
	Nutech	10	13	16	22	15
No. of seeds plant^{-1}	Tarnab	155	220	215	215	210
	Nutech	240	295	305	300	270

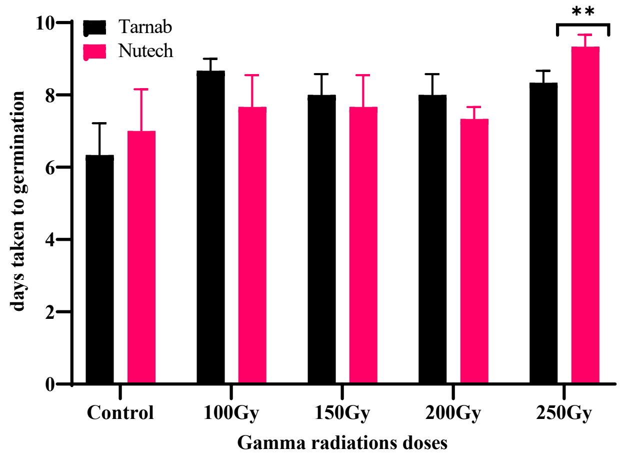

Figure 1: *Graphical representation of gamma rays on time used to germinate for Nutech and Tarnab Okra varieties. Graphs represent mean with SD (P<0.001).*

Plant height

The phenotypic expression of plant height exhibited a general downward trend as radiation intensity increased, particularly within the 100 Gy to 200 Gy range. While the Nutech cultivar initially maintained a superior height in the control and 100 Gy groups (96 cm), it experienced a sharper decline in vertical growth as the dosage intensified. This suppressive effect reached its peak at 200 Gy, where both cultivars recorded their lowest growth measurements, approximately 62 cm for Tarnab and 68 cm for Nutech, a point of high statistical significance ($p < 0.01$) that highlights a critical threshold for vegetative inhibition. Interestingly, at 250 Gy, a slight recovery in plant height was observed in both varieties, though they remained below control levels (Figure 2, Table 1).

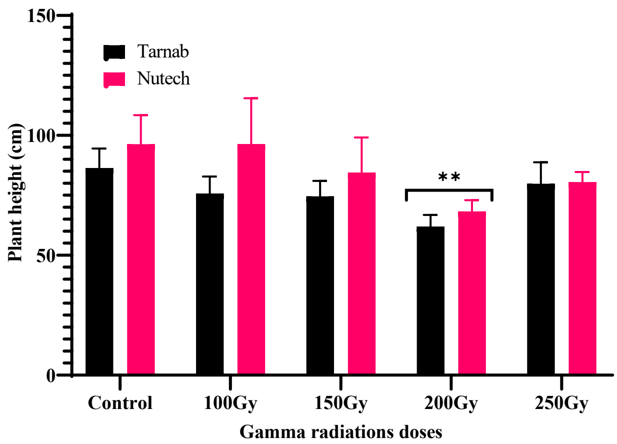

Figure 2: *Graphical representation radiation doses to plant heights in okra varieties. Data were noted in replicates. (P <0.001). High doses have a negative effect.*

Number of leaves plant^{-1}

The analysis of the experimental data reveals that gamma irradiation significantly modulates leaf production in both the Tarnab and Nutech cultivars, with a distinct inhibitory trend observed as radiation intensity increases toward the median dose. In the control groups, Nutech exhibited a slightly higher baseline for leaf production (16 leaves) compared to Tarnab (15 leaves). As the dosage progressed to 100 Gy and 150 Gy, both cultivars showed a gradual reduction in leaf count, indicating a disruption in the vegetative transition or apical meristematic activity. This suppressive effect reached its most critical point at 200 Gy, where both varieties recorded their lowest number of leaves 11 for Tarnab and 13 for Nutech. This specific decline at 200 Gy is marked by high statistical significance ($p < 0.01$), highlighting a physiological threshold where ionizing radiation most severely hinders leaf differentiation. Interestingly, at the highest dose of 250 Gy, both cultivars demonstrated a recovery in leaf count, with Nutech notably surpassing its control level (18 leaves) and Tarnab returning toward its baseline (14 leaves). This "hormetic" response at 250 Gy suggests that while moderate doses are inhibitory, higher doses may trigger compensatory biological mechanisms that stimulate increased foliar development, albeit with higher variability (Figure 3 andTable 1).

Number of flowers plant^{-1}

Flower production increased substantially across all irradiated groups compared to the non-irradiated controls. At the baseline (0 Gy), both cultivars produced fewer than 10 flowers per plant, with Nutech exhibiting a slightly higher initial count. However, upon exposure to doses as low as 100 Gy, flower production nearly doubled for both varieties, a result marked by a statistically significant increase ($p < 0.01$). The data further reveals that peak flowering occurs at different thresholds for each cultivar: Tarnab achieved its maximum reproductive output at 150 Gy (23 flowers), while Nutech peaked later at 200 Gy (24 flowers). These elevated levels represent a highly significant divergence from the control groups ($p < 0.001$), suggesting that gamma radiation may induce a "stress-flowering" response or alter hormonal balances, such as the ratio of auxins to cytokinins, which favors floral initiation over vegetative biomass. Although a slight decline in flower count was noted at the highest dose of 250 Gy, the values remained significantly higher than the controls for both cultivars (Figure 4 and Table 1).

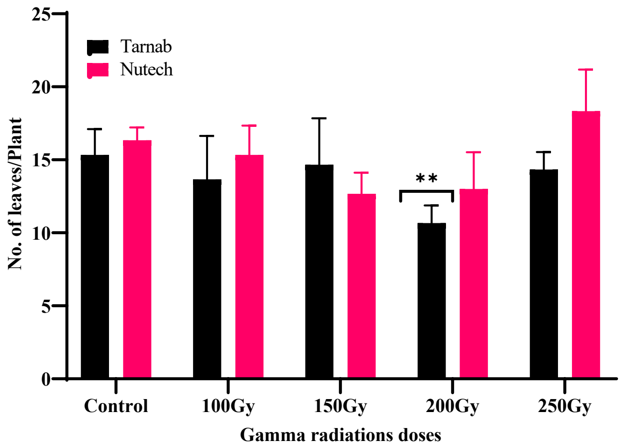

Figure 3: *Graphic representation of different gamma dose for leaves plant^{-1} in okra varieties. Data were noted in replicates. (P is <0.001).*

Number of fruits plant^{-1}

The analysis of fruit yield across the Tarnab and Nutech cultivars reveals that gamma irradiation significantly enhances reproductive output, following a trend closely mirrored by the previously observed flowering data. In the control group (0 Gy), both cultivars produced a baseline of approximately 9 to 10 fruits per plant. However, exposure to increasing doses of radiation triggered a substantial stimulatory effect, with fruit counts rising significantly at doses between 100 Gy and 250 Gy. Tarnab reached its maximum fruit yield at 150 Gy, producing approximately 21 fruits per plant. This represents more than a twofold increase over the control and is marked by high statistical significance ($p < 0.001$) while Nutech achieved its highest yield at 200 Gy, peaking at approximately 22 fruits per plant. This increase was also highly significant, suggesting that Nutech requires a slightly higher radiation threshold to reach its maximum reproductive potential. At the maximum dose of 250 Gy, both cultivars experienced a decline from their respective peaks, yet they remained significantly more productive than the control groups. Notably, at this dosage, Tarnab maintained a statistically significant lead over Nutech (18 vs. 15 fruits; $p < 0.01$) (Figure 5 and Table 1).

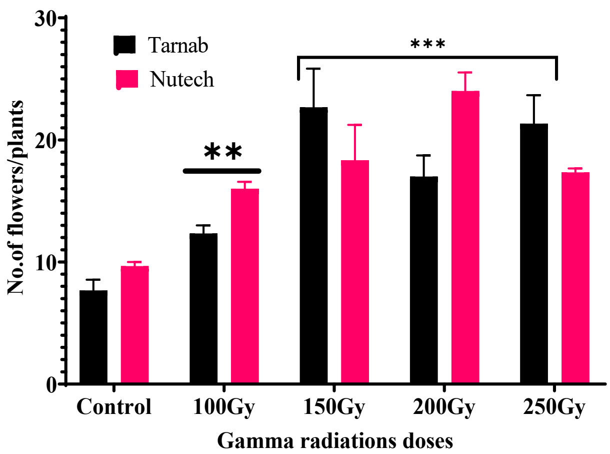

Figure 4: *Effect of gamma radiations on no. of flowers per plant. Data were noted in replicates. The data were highly significant (P is <0.001).*

Number of seeds plant^{-1}

The analysis of seed yield per plant reveals that gamma irradiation significantly stimulates reproductive output in both Tarnab and Nutech cultivars compared to their respective control groups. In the absence of radiation (0 Gy), Nutech exhibited a notably higher baseline seed count (240 seeds) than Tarnab (approx. 155 seeds). Upon exposure to gamma radiation, both varieties demonstrated a substantial increase in seed production, with Nutech consistently maintaining a superior yield across all treatment levels. The most significant enhancement in seed production was observed in the 100 Gy to 200 Gy range, where counts for Nutech reached approximately 300 seeds per plant, representing a highly significant increase over the control ($p < 0.001$). While Tarnab also showed a significant increase, peaking at roughly 220 seeds at the 100 Gy dose, its response was more stable and lower in magnitude compared to Nutech. At the maximum dose of 250 Gy, a slight decline in seed count was noted for both cultivars (210 for Tarnab and 270 for Nutech), yet these values remained significantly higher than the non-irradiated baselines as shown in Figure 6 and Table 1.

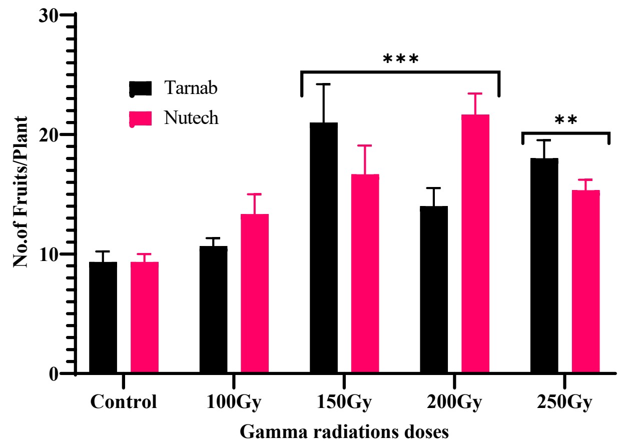

Figure 5: *Graphic Presentation of gamma rays' treatment in okra varieties of fruits per plant. Data were noted in replicates. P is <0.0001*

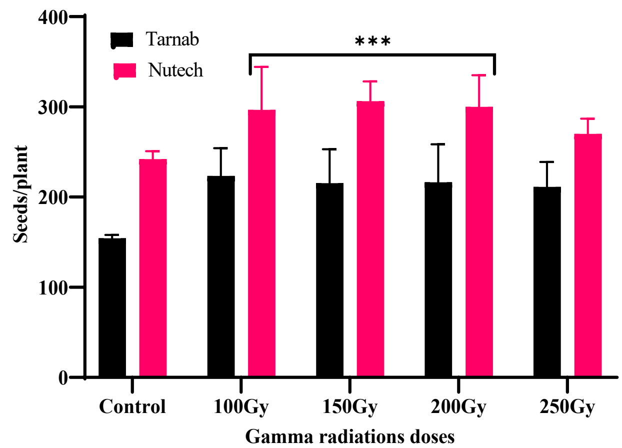

Figure 6: *The no. of seeds per plant. 5 fruits of okra were taken per plants. All data were taken in replicates (P value is <0.0001).*

Discussion

Seed germination is one of the most sensitive physiological stages to ionizing radiation. In this study, exposure to gamma rays resulted in delayed germination in both cultivars, particularly at higher doses. Higher doses reduce germination, seed vigor, and plant biomass across vegetable crops (Kantoglu *et al.*, 2025) whereas dose-dependent behavior of gamma irradiation can lead to different responses from crop (Sathyanarayana and Seelam, 2025). In current study, maximum delay was observed at 250 Gy in the Nutech variety, indicating that high radiation intensity can negatively affect the metabolic activities required for seed germination (Kiani *et al*., 2022). Such delays are generally associated with radiation-induced damage to cellular structures, including DNA, proteins, and membrane systems, which ultimately slow down enzymatic reactions involved in seed emergence while radiation may also disrupt hormonal regulation during early development, thereby affecting the initiation of germination processes (Hong *et al*., 2022). Reductions in germination efficiency after exposure to higher radiation doses often lead to physiological stress and reduced seed vigor (Choi *et al*., 2021). Present findings also revealed a reduction in plant height with increasing radiation intensity, particularly at the moderate 200 Gy dose as moderate gamma irradiation doses (100–200 Gy) are optimal for inducing beneficial morphological and agronomic changes in crop plants (Shabani and Dinari, 2022).

Both cultivars exhibited their lowest height values at this level, suggesting that gamma radiation can suppress vegetative growth when applied beyond a certain threshold. The reduction in plant height may be attributed to disturbances in cell division and cell elongation processes caused by radiation-induced chromosomal damage or oxidative stress (Li *et al*., 2022). Gamma radiation is known to generate reactive oxygen species (ROS) within plant tissues, which may damage cellular components and limit growth (Abozahra *et al*., 2025). Furthermore, reduced plant height may result from changes in hormonal balance, especially in gibberellins that regulate stem elongation although a slight recovery in plant height was observed at 250 Gy, the plants still remained shorter than the control groups, indicating that radiation stress continued to influence vegetative development.

Leaf production followed a similar trend to plant height, with a decline observed as radiation dose increased up to 200 Gy. Since leaves are essential for photosynthetic activity and biomass accumulation, any reduction in leaf number may reflect impaired meristematic activity in the shoot apex. Gamma radiation can interfere with the differentiation of leaf primordia by affecting cellular metabolism and genetic regulation in meristematic tissues (Abdullah *et al*., 2021). Interestingly, both cultivars showed a noticeable recovery in leaf number at the highest radiation dose of 250 Gy, with Nutech even surpassing its control value. This phenomenon may represent a hormetic response, where exposure to stress at certain levels stimulates compensatory physiological mechanisms that enhance growth traits. Hormesis in many plant species subjects to low or moderate radiation stress, where the plant activates repair systems and adaptive metabolic responses that improve certain physiological functions (Baldwin and Grantham, 2015).

In contrast to the inhibitory effects observed in vegetative traits, gamma irradiation had a strong stimulatory influence on reproductive characteristics such as flower and fruit production. Both cultivars exhibited a substantial increase in the number of flowers per plant following radiation exposure, with Tarnab reaching its maximum flowering at 150 Gy and Nutech at 200 Gy. This enhancement in flowering may result from radiation-induced alterations in hormonal balance (Amin *et al*., 2025), particularly in auxins, cytokinins, and gibberellins, which regulate floral initiation and development. Stress conditions induced by ionizing radiation may also shift plant resource allocation from vegetative growth toward reproductive development, a phenomenon often referred to as “stress-induced flowering.” Such physiological changes or adjustments enable plants to ensure reproductive success under adverse environmental conditions (Laanen *et al*., 2023).

The increase in flower number was closely associated with a corresponding rise in fruit production in both cultivars. Fruit yield more than doubled in irradiated treatments compared to the control, with the highest fruit numbers observed at 150 Gy in Tarnab and 200 Gy in Nutech. This relationship suggests that the stimulatory effect of radiation on reproductive organs ultimately translated into improved yield potential. Gamma irradiation may induce beneficial mutations or activate genes associated with flowering and fruit set, thereby enhancing reproductive efficiency however it is unclear that why plants alter their flowering pattern in response to IR as the exact mechanism behind this phenomenon is not yet known and one issue is the fact that often there is a non-linear dose relationship to chronic exposure, which is also seen in flower induction, making predicting of the response difficult (Kryvokhyzha *et al*., 2019; Laanen *et al*.,

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2021). The decline observed at the highest dose of 250 Gy indicates that although radiation can stimulate reproductive traits at moderate levels, excessive exposure may begin to exert inhibitory effects due to accumulated cellular damage.

Seed production per plant also showed a notable increase in irradiated treatments, particularly in the Nutech cultivar, which consistently produced higher seed counts than Tarnab across all doses. The highest seed production was recorded between 100 Gy and 200 Gy, suggesting that moderate radiation levels may enhance reproductive success and seed formation. Increased seed number may be associated with improved flower fertility, better pollination efficiency, or enhanced fruit development triggered by radiation-induced physiological changes (Kumari *et al*., 2025). However, a slight decline at 250 Gy indicates that extremely high radiation doses may reduce reproductive efficiency due to possible damage to reproductive tissues or reduced pollen viability (Zub *et al*., 2024). The comparative performance of the two cultivars indicates that Nutech exhibited a more favorable response to gamma irradiation than Tarnab. Nutech maintained higher values for several yield-related traits, including flower number, fruit production, and seed yield. This difference suggests that genetic background plays an important role in determining radiosensitivity and the ability of plants to tolerate or benefit from radiation stress (Ghasemi-Soloklui *et al*., 2025).

Variability in DNA repair mechanisms, antioxidant capacity, and physiological resilience among cultivars may influence their responses to mutagenic treatments (Caplin and Willey, 2018). Gamma irradiation produces both inhibitory and stimulatory effects depending on the applied dose and the plant genotype while higher doses tend to suppress early growth parameters such as germination, plant height, and leaf formation, moderate doses significantly enhance reproductive traits and yield components hence supporting the potential application of gamma radiation as a valuable tool in mutation breeding programs aimed at developing improved okra varieties with enhanced productivity. The identification of optimal radiation doses, particularly within the range of 150–200 Gy, may provide a practical basis for generating useful genetic variability and selecting superior mutants for future breeding efforts.

Conclusion

This research highlights the importance of the application of gamma irradiation as a potent mutagenic agent for the induction of favorable physiological and reproductive variations in okra. This research has demonstrated the occurrence of a clear dose-response bifurcation in the response of the plant, where high doses of up to 250 Gy are inhibitory to the development of the plant, reflected by delayed germination, reduced plant height, and delayed foliage development, whereas the application of the moderate dose range of 150–200 Gy has been found to significantly enhance the reproductive potential of the plant. Furthermore, the results of this research revealed that the Nutech variety is more resistant and has a greater capacity for yield enhancement compared to the Tarnab variety, which indicates the importance of the genetic background of the plant. This research has demonstrated the successful application of ionizing radiation for the recalibration of the plant's resource allocation capacity for the development of the reproductive organs, thereby establishing the dose range of 150–200 Gy as optimal for application of mutation breeding regarding development of high-yielding, resistant varieties of okra for future agricultural needs.

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Novelty Statement

This work systematically compares the dose-dependent responses of two okra genotypes to gamma irradiation, revealing genotype-specific radiosensitivity and identifying moderate radiation doses as a promising strategy for inducing beneficial agronomic variation.

Author's Contribution

Conceptualization: Muhammad Tayyab, Nasr Ullah Khan and Saira Naz, Lab and Field Experimentation, and Data Collection: Saira Naz, Wasif Rasool, Abdul Muqeet, Data Analysis: Saira Naz, Maham Jamshed, Iqra Arooj, Technical Assistance: Adnan Shehzad and Musa Khan, Manuscript drafting: Nasr Ullah Khan, Muhammad Tayyab and Saira Naz. All authors read the manuscript before submission.

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Data availability statement
All data are available in the manuscript file and supplementary file.

Generative AI and AI assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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