PHENOTYPIC PERFORMANCE AND EARLY SELECTION OF THREE CAYENNE PEPPER (*Capsicum annuum* L.) VARIETIES IN RESPONSE TO GAMMA IRRADIATION

KERAGAAN FENOTIPIK DAN SELEKSI AWAL TIGA VARIETAS CABAI RAWIT (*Capsicum annuum* L.) TERHADAP IRADIASI SINAR GAMMA

Firnanda Ranggawikya, Theresa Dwi Kurnia, Yuniel Melvando Zendrato*
Agrotechnology, Faculty of Agriculture and Business, Satya Wacana Christian University, Jl. Diponogoro no. 66, Salatiga City 50711, Central Java, Indonesia

*Correspondence : yuniel.zendrato@uksw.edu

Accepted: 24th March 2026 / Revised: 19th May 2026 / Approved: 30th July 2026

ABSTRACT

The development of cayenne pepper (*Capsicum annuum* L.) varieties through mutation breeding represents a strategic approach to enhancing agricultural productivity and food security. This research aimed to evaluate phenotypic diversity and select mutant genotypes from three distinct cayenne pepper varieties induced by gamma radiation. The study was conducted using a two-factor experiment: three cayenne pepper varieties and five gamma ray dose ranges (0, 100, 200, 300, and 400 Gy), arranged in a randomized complete block design (RCBD) with three replications. The results demonstrated that the interaction between varieties and irradiation doses significantly influenced seed viability, growth characteristics, and yield components. High irradiation doses (300 and 400 Gy) caused a drastic reduction in germination rates, falling as low as 42.50%, and increased seedling mortality up to 87.50%. Conversely, low-to-moderate doses effectively expanded quantitative variability in plant height, flowering age, and fruit dimensions. Quantitative analysis revealed that selected mutant genotypes exhibited superior phenotypic performance; genotype V2G1 demonstrated the highest yield potential with an average fruit weight of 3.26 g, while genotype V3G1 exhibited a desirable early-maturing trait. While qualitative characters such as fruit shape and plant growth habit remained largely stable, significant quantitative shifts confirmed the effectiveness of gamma radiation to increase the phenotypic variability. Based on a selection index integrating multiple agronomic traits, three mutant genotypes (V2G1, V3G1, and V1G1) were identified as the candidates for further improvement in chili breeding programs.

Key words: Cayenne pepper, gamma irradiation, mutation breeding, phenotypic, selection index.

ABSTRAK

Pengembangan varietas unggul cabai rawit (*Capsicum annuum* L.) melalui pemuliaan mutasi merupakan pendekatan strategis untuk meningkatkan produktivitas pertanian dan ketahanan pangan. Penelitian ini bertujuan untuk mengevaluasi keragaman fenotipik serta menyeleksi genotipe mutan unggul dari tiga varietas cabai rawit yang diinduksi dengan radiasi gamma. Penelitian dilakukan menggunakan percobaan dua faktor: tiga varietas cabai rawit dan lima dosis

ISSN: 2407-7933

Cite this as: Ranggawikya, F., Kurnia, T.D., Zendrato, Y.M. (2026). Pnenotypic performance and early selection of three cayenne pepper (*Capsicum annuum* L.) varieties in respone to gamma irradiation. *Jurnal Agro*, *13*(1), 127-141. https://doi.org/10.15575/j.agro.55061

sinar gamma (0, 100, 200, 300, dan 400 Gy) yang disusun dalam rancangan kelompok lengkap teracak (RKLT) dengan tiga ulangan. Hasil penelitian menunjukkan bahwa interaksi antara varietas dan dosis iradiasi berpengaruh nyata terhadap viabilitas benih, karakter pertumbuhan, dan komponen hasil. Dosis iradiasi tinggi (300 dan 400 Gy) menyebabkan penurunan drastis pada tingkat perkecambahan hingga mencapai 42,50% serta meningkatkan mortalitas bibit hingga 87,50%. Sebaliknya, dosis rendah hingga sedang efektif dalam meningkatkan keragaman kuantitatif pada tinggi tanaman, umur berbunga, dan dimensi buah. Analisis kuantitatif menunjukkan bahwa genotipe V2G1 menunjukkan potensi hasil tertinggi dengan rata-rata bobot buah 3,26 g, sedangkan genotipe V3G1 memiliki sifat genjah yang diinginkan dengan waktu berbunga. Sementara itu, karakter kualitatif seperti bentuk buah dan tipe pertumbuhan tanaman relatif stabil, perubahan kuantitatif yang signifikan mengonfirmasi efektivitas radiasi gamma dalam meningkatkan variabilitas fenotipik. Berdasarkan indeks seleksi yang mengintegrasikan berbagai sifat agronomis, tiga genotipe mutan (V2G1, V3G1, dan V1G1) diidentifikasi sebagai kandidat untuk pengembangan program pemuliaan cabai ke depan.

Kata kunci: cabai rawit, fenotipik, iradiasi gamma, pemuliaan mutasi, indeks seleksi.

INTRODUCTION

Cayenne pepper (*Capsicum annuum* L.) is a strategic horticultural commodity in Indonesia due to its high economic value and market demand that continues to increase annually. This crop is widely utilized as a food staple and culinary spice; thus, its availability significantly influences price stability and national food security. The growing population further drives the demand for chili, while domestic production still faces challenges in meeting this demand due to unstable yield fluctuations at the farmer level (Hanani et al., 2020; Jeksen et al., 2024; Muflikh & Kiloes, 2024).

Fluctuations in cayenne pepper yields are multifaceted, driven by a combination of biotic challenges, climatic variability, and suboptimal agronomic techniques (Puspitaningrum et al., 2024; Rinaldi et al., 2021), alongside inherent genetic limitations. The development of superior varieties with desirable genetic traits serves as a strategic solution for stabilizing sustainable production. These genetic traits are critical in dictating both environmental plasticity and the realization of yield potential. However, the success of such programs relies heavily on the availability of broad genetic variability as a baseline for selection and in achieving significant selection gains. Therefore, efforts to expand genetic diversity through breeding approaches are a crucial step in providing a base population rich in desired trait variations (Ahmad et al., 2024; Lozada et al., 2022; Nugroho et al., 2021).

Mutation breeding is an effective method for significantly increasing plant genetic diversity within a relatively short period (Bado et al., 2015; Hasan et al., 2025). One commonly used physical mutagen is gamma irradiation, which possesses the ability to penetrate biological tissues and induce changes in the plant's genetic material. The application of gamma irradiation is expected to trigger the emergence of new beneficial agronomic characters, thereby increasing the probability of selection success. Various studies have demonstrated that gamma irradiation can enhance morphological and agronomical diversity in chili plants, including growth characters, yield components, and qualitative traits such as fruit size, color, and plant architecture (Hashim et al., 2024; Nugroho et al., 2021; Shamsiah et al., 2022).

Nevertheless, the plant's response to irradiation is highly influenced by the interaction between the applied dose and the plant genotype (genotype × dose interaction). Doses that are too low tend to produce limited genetic variation, while excessively high doses can cause cellular damage, reduced seed viability, and inhibited plant growth. While radiation sensitivity is highly variety-specific, several studies indicate that the lethal doses (LD) for chili pepper typically falls within the range of 200 to 350 Gy (Oladosu et al., 2016; Akalp & Pirinc, 2025). High doses (300 and 400 Gy) were explicitly included to determine the upper threshold of radiosensitivity for these specific genotypes and to maximize the probability of inducing useful genetic variations, despite the expected higher mortality rates.

The evaluation of phenotypic and agronomic character changes in the early generations is a crucial stage for mapping the direction of genetic change and ensuring the efficiency of the breeding program. The first generation (M1) population serves as a critical initial population to be observed before advancing to more stable subsequent generations. Comprehensive characterization, encompassing both quantitative and qualitative morphological aspects, allows breeders to isolate mutant individuals with superior performance from a broad segregating population (Makhziah & Soedjarwo, 2023; Ulinnuha et al., 2023; Ulukapi & Fatih, 2018). Through a precise early selection approach, chili genotypes with superior agronomic potential can be identified more rapidly, providing a solid foundation for the development of future varieties. Applying the correct selection criteria at this early stage is vital to reduce the burden of managing large populations in the following generations, thereby making resource allocation in the breeding program more efficient (Anshori et al., 2024; Kirana et al., 2023). Consequently, this research was conducted to evaluate the effects of various gamma irradiation doses on the phenotypic performance and agronomic traits of three cayenne pepper varieties, and to determine the most effective selection index for identifying potential genotypes to accelerate subsequent breeding programs.

MATERIALS AND METHODS

The research was conducted in two stages: gamma irradiation of cayenne pepper seeds and the subsequent cultivation of the irradiated seeds. The seed irradiation process was performed at the Radiation Laboratory of the National Research and Innovation Agency (BRIN), Yogyakarta, in May 2025. The nursery, planting, and evaluation of plant growth and yield were conducted in an open field (coordinates: -7.3193130, 110.4937410) located in Sidorejo Lor, Sidorejo District, Salatiga City, Central Java (±460 m above sea level) from August 2025 to January 2026.

The plant materials used consisted of three cayenne pepper (*Capsicum annuum* L.) varieties: Ori 212 (V1), Rawita F1 (V2), and Pelita 8 F1 (V3). Seeds were selected based on uniformity in size, intact physical condition, and absence of mechanical damage. Physical mutation treatment was carried out using gamma-ray irradiation from a Cobalt-60 (Co-60). Five dose levels: 0 Gy (G0, as a control for this experiment), 100 Gy (G1), 200 Gy (G2), 300 Gy (G3), and 400 Gy (G4), were selected to represent low, moderate, and high irradiation levels suitable for evaluating phenotypic responses of cayenne pepper in this study. The irradiation duration was adjusted according to the required dose, with approximately 1 min 30 s for 100 Gy and proportionally increased for higher doses. The experiment was arranged in a two-factor randomized complete block design (RCBD) with three replications. The first factor was the variety (three levels), and the second factor was the irradiation dose (five levels), resulting in 15 combinations. The mathematical model used for the analysis was:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \rho_k + \epsilon_{ijk}$$

where Y_{ijk} is the observed value, μ is the grand mean, α_i is the effect of the *i*-th variety, β_j is the effect of the *j*-th irradiation dose, $(\alpha\beta)_{ij}$ is the interaction effect between variety and irradiation dose, ρ_k is the effect of *k*-th block and εijk is the experimental error. Each treatment genotype was grown in a larger population plot, from which five representative plants were randomly sampled for observations, totaling 225 experimental units for data analysis. The placement of experimental units within each replication was randomized to minimize the influence of environmental heterogeneity.

Irradiated seeds were sown in a medium consisting of a mixture of soil and manure in a 2:1 (v/v) ratio using 10 × 10 cm polybags. Sowing was conducted in an open area under UV plastic shading, with daily watering to maintain medium moisture. Seedlings were transplanted into 45 × 45 cm polybags at 3–4 weeks old or after developing 5–8 true leaves. The planting medium for the growth phase consisted of soil, manure or compost, and rice husk in a 2:1:1 (v/v) ratio. Polybags were arranged according to the experimental randomization with a spacing of approximately 60 cm. Plant maintenance was carried out uniformly across all treatments, including watering, fertilization, weeding, and pest and disease control. Fertilization was applied using NPK (16:16:16) twice, at 14 and 28 days after transplanting (DAT). Pest and disease management was performed conditionally based on field observations.

Observations included early growth traits, agronomic characters, yield components, and qualitative traits. Early growth parameters consisted of germination percentage and seedling mortality rate. The germination percentage was calculated as the ratio of germinated seeds to the total number of seeds sown, expressed as a percentage. Seedling mortality was calculated as the ratio of dead seedlings to the total number of germinated seeds. Agronomic characters observed included: a) plant height, measured from the soil surface to the highest growing point (cm); b) dichotomous height, measured from the soil surface to the first branching point (cm); c) stem diameter, measured on the main stem approximately 2–3 cm above the soil surface using a vernier caliper (mm); d) canopy width, measured as the outermost distance between plant branches (cm); e) leaf length, measured from the base to the tip of the leaf (cm); and f) leaf width, measured at the widest part of the leaf (cm). Harvesting was performed three times consecutively on fruits that had reached harvest maturity. Yield parameters included: g) fruit length (cm); h) fruit diameter (mm); i) weight per fruit (g); j) number of fruits per plant; and k) total fruit weight per plant (g). Qualitative characters observed included plant habit, leaf shape, flower position, fruit shape, and fruit color, which were evaluated using the chili descriptors developed by the International Plant Genetic Resources Institute (IPGRI).

Quantitative data were analyzed using Analysis of Variance (ANOVA) at a 95% confidence level. Prior to analysis, the assumptions of normality and homogeneity of variance were verified and satisfied for all parameters, including the percentage data. When the ANOVA indicated a significant effect, a follow-up Least Significant Difference (LSD) test was performed alpha 5% level. Qualitative data were presented descriptively and supported by visual documentation. Early selection was conducted using a weighted selection index based on the following traits: plant height, flowering age, fruit length, fruit diameter, weight per fruit, number of fruits per plant, and total fruit weight. Total fruit weight was assigned a weight of 1.5 as the primary character, flowering age and number of fruits per plant were weighted 1.2, while other characters were assigned a weight of one. The selection direction for all characters was set to "increase," except for flowering age, which was set to "decrease." Data analysis was performed using Microsoft Excel and the web-based statistical tool GRAPES: General R-based Analysis Platform for Experimental Statistics (www.kaugrapes.com).

RESULTS AND DISCUSSION

Germination Percentage and Seedling Mortality

The observation results presented in Table 1 indicate that gamma irradiation significantly influenced the germination percentage and seedling mortality of chili (*Capsicum annuum* L.) during the initial growth phase. Seed viability remained relatively stable in control, as observed in genotypes V1G0 (90.00%), V2G0 (82.50%), and V3G0 (85.00%), indicated the seeds maintained sufficient physiological integrity for normal germination processes. However, the high doses led to a drastic decline in germination, falling to a range of 42.50 – 55.00%. This reduction in viability indicates that high radiation exposure exceeded the physiological tolerance threshold of the seeds of chili. Biochemically, gamma irradiation causes structural genetic damage, disrupts cellular metabolism, and decreases the activity of enzymes responsible for mobilizing food reserves to support embryo growth (Hashim et al., 2024). These conditions result in inhibited embryo development and a significant decrease in seed viability, aligning with findings by Hayati et al. (2022) and Makhziah & Soedjarwo (2023), which state that increased gamma radiation doses correlate negatively with germination percentages in various crops.

Ori 212 (V1) and Pelita 8 (V3) at low doses showed lower mortality rates compared to Rawita F1 (V2). The highest seedling mortality was recorded in V1G4 (87.50%), followed by V2G4 (85.00%), V1G3 (77.50%), and V2G3 (75.00%), illustrating the detrimental impact of radiation on seedling survival. All 0 Gy doses showed the lowest mortality rates for each variety. The phenomenon of inter-genotypic variation in radio sensitivity is common in mutation breeding programs because each variety possesses distinct DNA repair mechanisms and metabolic sensitivities to mutagenic treatments (Choi et al., 2021; Oladosu et al., 2016; Qosim et al., 2024). These lower percentages indicate that the applied irradiation doses remained within the plant's tolerance range, thus avoiding fatal physiological damage. This differential response confirms that plant tolerance to gamma irradiation is highly influenced by varietal genetic and the dosage level.

Table 1. Germination percentage and seedling mortality of chili mutant M1

Interaction	Germination (%)	Seedling Mortality (%)
V1G0	90.00	12.50
V1G1	55.00	47.50
V1G2	75.00	50.00
V1G3	50.00	77.50
V1G4	50.00	87.50
V2G0	82.50	27.50
V2G1	55.00	57.50
V2G2	55.00	60.00
V2G3	60.00	75.00
V2G4	42.50	85.00
V3G0	85.00	22.50
V3G1	80.00	42.50
V3G2	52.50	57.50
V3G3	47.50	67.50
V3G4	52.50	62.50

Note: V1, V2, and V3 represent the cayenne pepper varieties used; G0–G4 represent the gamma irradiation dose levels

Combined Analysis of Variance for Variety and Gamma Irradiation on Cayenne Pepper Performance

The analysis of variance (Table 2) indicates that the variety factor (V), irradiation dose (G), and their interaction (V × G) significantly influenced the growth characters and yield components of cayenne pepper. Highly significant interactions ($p < 0.001$) for plant height, dichotomous height, flowering age, and harvest age suggest that physiological responses and developmental phases are not only determined by the genotype but also by the degree of genetic sensitivity of each variety to the irradiation dose received. Morphological traits such as stem diameter and canopy width also exhibited significant interactions ($p < 0.05$), reflecting modifications in cell division activities within vascular meristem tissues and disruptions in growth hormone balance caused by radiation exposure (Arumingtyas & Ahyar, 2022; Shamsiah et al., 2022). In contrast, leaf width was significantly affected only by the variety factor ($p < 0.001$) and was not influenced by the radiation dose, while leaf length was not affected by either factor. This indicates that the stability of leaf width and length is higher toward physical mutagen induction compared to other vegetative characters.

Table 2. Analysis of variance for variety and gamma radiation on cayenne pepper performance

Traits	Variety (V)	Gamma radiation (G)	V x G	CV(%)
Plant height (cm)	47.76**	16.27**	4.55**	14.18
Dichotomous height (cm)	4.96**	3.89**	3.84**	13.76
Stem diameter (mm)	0.15*	0.13*	0.92*	18.82
Canopy width (cm)	4.62*	7.00*	2.39**	19.51
Leaf length (cm)	0.39ns	1.45ns	1.30ns	18.46
Leaf width (cm)	13.55**	0.17ns	2.27ns	17.78
Flowering age (DAT)	76.33**	44.30**	7.41**	9.97
Harvest age (DAT)	209.33**	50.22**	8.23**	6.44

Fruit weight (g)	32.18**	52.97**	10.88**	11.56
Fruit length (cm)	9.56**	47.56**	4.96**	7.42
Fruit diameter (mm)	74.05**	33.84**	7.53**	9.67
Pedicel length (cm)	23.97**	38.08**	4.88**	6.80
Number of fruits	63.77ns	73.43**	15.95**	7.61
Total fruit weight (g)	31.11ns	43.46**	5.47**	15.77

Note: *, significant at α 0.05; **, significant at α 0.01; ns, not significant; CV, coefficient of variation.

Vegetative Phenotypic Characterization of the M1 Mutant Population

The post-hoc test results in Table 3 indicate that each cayenne pepper variety exhibited highly diverse vegetative responses to gamma irradiation doses. This diversity was observed across all growth parameters, where the interaction between genotype and irradiation dose showed performance that surpassed the control plants (G0), indicating a growth stimulation effect due to induced mutation at certain doses. Regarding plant height, genotypes V3G1 (56.78 cm) and V3G2 (48.98 cm) exhibited taller growth compared to their control (V3G0, 47.06 cm). A similar phenomenon was observed in the Rawita F1 variety (V2), where the V2G1 treatment (45.68 cm) significantly outperformed the V2G0 control (33.12 cm). This increase was also observed in stem diameter, with V3G1 (7.33 mm) and V2G1 (6.44 mm) possessing sturdier stems compared to their respective control plants.

Leaf morphometric data showed average length and width values of 7.27 cm and 3.13 cm, respectively, where irradiation treatment did not provide a statistically significant influence between genotypes. This indicates that leaf dimensions are genetically more conservative and tend to have a higher tolerance threshold toward phenotypic changes. The population means for plant height (35.90 cm), stem diameter (5.36 mm), and canopy width (22.65 cm) suggest that, overall, the M1 population maintained adequate growth vitality. Dichotomous height showed a unique response pattern, with the highest value obtained in V1G1 (33.49 cm). The emergence of individuals with larger stem diameters (such as V3G1) or more compact canopies is a critical agronomic trait sought in mutant selection to support high fruit weight. Each genetic background has a different level of meristematic tissue radiosensitivity, which affects the branching pattern of the plants. Morphological changes in stem diameter and canopy architecture directly affect photosynthetic capacity and plant sturdiness upon entering the generative phase (Bado et al., 2015; Riviello-Flores et al., 2022). This broad phenotypic variation proves that gamma irradiation is effective in triggering random but measurable genetic changes during the vegetative phase. Potential mutant lines can be identified early with this diversity to streamline the evaluation process in subsequent generations.

In the generative phase, yield components such as fruit weight, fruit dimensions (length and diameter), and total production showed highly significant interactions ($p < 0.001$). This proves that induced mutation significantly affects fertilization efficiency, fruit development, and the capacity for assimilate allocation to generative organs (Nugroho et al., 2021). Coefficient of variation (CV) values, which ranged from low to moderate (6.44%–19.51%), indicate an adequate level of experimental precision (Gomez & Gomez, 1984), ensuring that the observed phenotypic diversity is a direct biological response to the mutation treatment. Differences in response between varieties confirm that mutation effects are genotype-specific, where the genetic background plays a vital role in determining the spectrum of variation in the resulting agronomic characters.

Table 3. Morphological response and vegetative performance of M1 generation cayenne pepper varieties

Interaction	Plant Height	Dichotomous Height	Stem Diameter	Canopy Width	Leaf Length	Leaf Width
V1G0	43.72 bc	25.53 bc	6.88 ab	28.11 a	8.60	4.11
V1G1	28.53 defg	33.49 a	4.00 de	17.03 de	8.00	3.72
V1G2	31.79 de	29.97 ab	5.44 bcd	18.99 cde	6.86	3.67
V1G3	23.03 fg	32.33 a	3.66 e	15.85 e	6.28	3.28
V1G4	23.75 efg	30.88 ab	4.50 de	19.25 cde	7.25	3.60
V2G0	33.12 d	16.03 e	4.77 cde	28.77 a	7.37	3.06
V2G1	45.68 b	19.38 de	6.44 abc	29.55 a	7.92	2.54
V2G2	29.26 def	20.74 cde	5.44 bcd	20.06 bcde	7.86	3.83
V2G3	27.56 defg	30.88 ab	5.33 bcde	23.69 abcd	7.54	3.14
V2G4	20.22 g	23.44 cd	3.83 de	16.35 de	6.27	2.93
V3G0	47.06 b	21.40 cde	6.44 abc	26.05 abc	6.51	2.58
V3G1	56.78 a	16.16 e	7.33 a	30.05 a	8.21	3.10
V3G2	43.70 bc	22.71 cd	4.77 cde	19.00 cde	5.67	1.97
V3G3	48.98 ab	23.13 cd	6.66 ab	26.66 ab	8.00	2.88
V3G4	35.34 cd	29.21 ab	4.83 cde	20.27 bcde	6.71	2.57
Mean	35.90	25.53	5.36	22.65	7.27	3.13
LSD 5%	8.51	5.74	1.69	7.39	-	-

Note: values followed by different letters within the same column indicate significant differences based on the Least Significant Difference (LSD) test at the 5% level.

Evaluation of Yield Components and Generative Characters of the M1 Mutant Population

The generative phase response of cayenne pepper plants to gamma irradiation induction showed significant variability across genotypes and dose levels (Table 4). One crucial phenomenon observed was the shift in phenological phases in specific genotypes. Genotype V3G1 (45 DAT) exhibited an early-maturing character, with flowering and harvest ages significantly earlier than the rest of the population. Conversely, extreme generative phase retardation was detected in V2G3 and V2G4 (flowering > 100 DAT). This diversity indicates that gamma irradiation can modify the genetic regulation controlling the transition from the vegetative to the generative phase, which has direct implications for production efficiency and environmental adaptation plasticity (Zakir, 2018).

Evaluation of fruit components showed that genotype V2G1 exhibited a good performance with fruit weight (3.26 g), length (6.56 cm), and diameter (1.47 cm) surpassing the control parent (V2G0). The increase in fruit dimensions at low to moderate doses confirms that irradiation can optimize fruit development in the generative phase. However, high doses

(V1G4 and V2G4) resulted in a drastic decline across all yield parameters. The number of fruits and total weight per plant are primary selection parameters showing a wide spectrum of diversity across the three varieties. This variation in productivity is influenced not only by the intensity of flower initiation but also by the plant's physiological capacity to maintain successful fruit set until fruit maturity. Furthermore, morphometric changes in fruit pedicel length indicate modifications in fruit-supporting structures and assimilate distribution in reproductive organs (Qosim et al., 2024).

Table 4. Performance of yield components and generative characters of m1 generation cayenne pepper varieties

Interaction	Flowering Age	Harvest Age	Weight per Fruit	Fruit Length	Fruit Diameter	Pedicel Length	Total Number of Fruits	Total Weight
V1G0	60.33 cdef	117.33 b	2.55 bc	6.36 abc	1.34 bc	2.62 defg	20.55 bc	52.33 b
V1G1	64.00 cd	121.00 b	2.44 bc	6.51 ab	1.27 c	2.88 bcd	18.77 bcd	49.55 b
V1G2	64.00 cd	121.00 b	2.21 c	6.27 abc	1.32 bc	2.87 bcd	18.33 cd	43.11 bc
V1G3	95.00 b	159.66a	1.36 ef	4.86 e	0.76 fg	2.38 gh	13.50 e	26.66 defg
V1G4	93.00 b	159.00 a	1.25 fg	3.40 f	0.65 g	1.90 i	10.50 f	13.00 h
V2G0	65.00 cd	114.00 bc	1.65 de	6.15 abcd	1.68 a	2.62 defg	24.33 a	44.77 b
V2G1	56.66 def	102.33 cd	3.256 a	6.56 a	1.47 b	3.10 ab	24.33 a	67.55 a
V2G2	69.33 c	117.66 b	2.60 b	5.75 cd	1.45 bc	2.11 hi	17.33 d	50.55 b
V2G3	106.66 a	159.00 a	1.63 de	4.8 e	1.37 bc	2.47 fg	13.27 e	33.72 cdef
V2G4	108.66 a	160.33 a	1.35 efg	3.62 f	0.95 de	1.81 i	8.66 f	24.33 fg
V3G0	49.00 fg	83.00 e	1.77 d	6.32 abc	0.96 de	2.77 cde	25.00 a	34.00 cde
V3G1	45.00 g	77.66 e	1.83 d	6.44 abc	1.00 d	3.28 a	20.77 b	34.77 cd
V3G2	52.33 efg	83.66 e	1.35 efg	5.93 abcd	0.84 def	2.73 cdef	20.55 bc	25.00 efg
V3G3	49.33 fg	81.00 e	1.38 ef	5.84 bcd	0.94 def	2.98 bc	23.77 a	25.66 defg
V3G4	63 cde	97.66 d	1.00 g	5.46 de	0.81 efg	2.48 efg	19.38 bcd	19.27 gh
Mean	69.42	116.95	1.85	5.62	1.12	2.60	18.61	36.28
LSD 5%	11.57	12.59	0.35	0.69	0.10	0.17	2.63	9.57

Note: Values followed by different letters within the same column indicate significant differences based on the Least Significant Difference (LSD) test at the 5% level.

Comprehensively, the expansion of phenotypic diversity in the generative phase is a crucial genetic modality for all tested genetic backgrounds. The emergence of individuals combining early-maturing traits with high productivity provides a strategic opportunity to identify potential mutant candidates. These results provide a scientific basis that gamma irradiation induction can create agronomic novelties that exceed the original population, effectively serving as a selection basis for cayenne pepper variety improvement (Samuel et al., 2021; Ulinnuha et al., 2023). Based on the comprehensive evaluation, genotypes V2G1, V3G1, and V1G1 showed promising potential, marked by the vegetative and generative performances compared to the control plants and other genotypes in the M1 population

Qualitative Characterization and Morphological of M1 Mutant Cayenne pepper

The observation results indicate that gamma irradiation did not drastically alter the primary morphological traits of the cayenne pepper plants, with most qualitative characters maintaining high phenotypic stability (Table 5). Fruit color across all genotypes, including the control, consistently fell within the red to orange-red group, with intensity variations ranging from vivid reddish orange and vivid red to moderate red. This indicates that fruit color expression remains preserved as a key characteristic of the original varieties, despite differences in color sharpness among the irradiated genotypes.

Regarding vegetative characters, leaf color showed variations between strong yellow green and deep yellow green, which remain within the normal growth range of cayenne pepper. As documented in Figure 1, differences in performance were more visible in plant vigor, where low doses maintained optimal canopy appearance while high doses tended to trigger a stunted phenotype. This condition confirms that higher irradiation doses increase the cellular damage load, manifesting as growth inhibition, but do not fundamentally change the identity of vegetative organs. Stability was also found in the uniform flower position (erect) and the consistently dense plant growth type. Fruit shape characters were observed to be highly stable and consistent with the genetic background of each variety: campanulado y en bloque (V1), triangular (V2), and elongado (V3) (Figure 2).

Table 5. Qualitative performance response of cayenne pepper varieties to gamma radiation

Interaction	Fruit Color	Leaf Color	Fruit Shape	Leaf Shape	Plant Habit	Flower Position
V1G0	Vivid Reddish Orange	Strong Yellow Green	Campanulado Y En Bloque	Deltoid	Dense	Erect
V1G1	Vivid Reddish Orange	Strong Yellow Green	Campanulado Y En Bloque	Deltoid	Dense	Erect
V1G2	Vivid Reddish Orange	Strong Yellow Green	Campanulado Y En Bloque	Deltoid	Dense	Erect
V1G3	Vivid Reddish Orange	Deep Yellow Green	Campanulado Y En Bloque	Deltoid	Dense	Erect
V1G4	Vivid Reddish Orange	Deep Yellow Green	Campanulado Y En Bloque	Deltoid	Dense	Erect
V2G0	Vivid Reddish Orange	Deep Yellow Green	Triangular	Ciliate	Dense	Erect
V3G1	Vivid Reddish Orange	Deep Yellow Green	Triangular	Ciliate	Dense	Erect
V2G2	Vivid Reddish Orange	Strong Yellow Green	Triangular	Ciliate	Dense	Erect
V2G3	Vivid Reddish Orange	Strong Yellow Green	Triangular	Ciliate	Dense	Erect
V2G4	Vivid Reddish Orange	Deep Yellow Green	Triangular	Ciliate	Dense	Erect
V3G0	Moderate Red	Deep Yellow Green	Elongado	Ciliate	Dense	Erect
V2G1	Vivid Red	Deep Yellow Green	Elongado	Ciliate	Dense	Erect
V3G2	Moderate Red	Strong Yellow Green	Elongado	Ciliate	Dense	Erect
V3G3	Moderate Red	Deep Yellow Green	Elongado	Ciliate	Dense	Erect
V3G4	Moderate Red	Strong Yellow Green	Elongado	Ciliate	Dense	Erect

Figure 1. Plant performance of three cayenne pepper varieties induced by gamma irradiation

This uniformity confirms that qualitative characters controlled by major genes tend to be more resistant to mutation induction compared to quantitative characters (Rohcahyani et al., 2022). This suggests that the basic morphological identity of the varieties can be maintained despite going through the artificial mutation induction process. The observation results show that gamma irradiation in cayenne pepper plays a more significant role in increasing diversity in quantitative characters than in qualitative characters. Comprehensively, these qualitative data serve as morphological markers ensuring that the primary visual attributes of the varieties remain consistent. The emerging variations in color intensity, although not extreme, still provide important information regarding the visual response of each selected mutant genotype, which can be utilized in future characterization and variety registration processes.

Figure 2. Fruit performance of three cayenne pepper varieties induced by gamma irradiation. Scale = 1 cm.

weight (w = 1.5) and number of fruits per plant (NF) (w = 1.2), as both parameters are primary indicators of yield productivity. Other supporting traits, such as plant height, fruit weight, length, and diameter, remained integrated to ensure that the selected genotypes possess ideal fruit quality and plant architecture.

Based on the calculations in Table 6, genotypes V2G1 (11.48), V1G0 (6.43), V2G0 (4.38), V3G1 (3.95), and V1G1 (3.81) exhibited significantly positive selection index values and are the most potential

Early Selection of Mutant Genotypes Based on Selection Index

Early selection is a crucial stage in mutation breeding programs to identify high-yielding genotypes in the early generations (Gomes et al., 2025; Vieira et al., 2025). The evaluation of plant productivity cannot rely on a single trait, as it is a manifestation of complex interactions among various growth parameters. The selection index approach integrates multiple vegetative and generative components into a single numerical value, enabling breeders to perform accurate simultaneous selection. The use of a selection index at the early stage aims to reduce the population by eliminating inferior genotypes and maintaining individuals with the best combination of agronomic traits (Anshori et al., 2024; Ratna et al., 2024; Ridwan et al., 2025).

In this study, index values were determined based on traits that contribute directly to the plant's economic value. Flowering age (FA) was assigned a negative weight (w = -1.2) because the breeding objective is directed towards developing earlier-maturing (shorter harvest period) varieties. Conversely, total fruit weight (TW) was given the highest

candidates through the integration of vigorous vegetative performance and optimal generative productivity. Genotype V2G1 showed a sturdier stem diameter and significant fruit component superiority above the population mean, particularly in fruit weight (2.72) and total weight (2.52). Meanwhile, V3G2 contributed to plant architecture with a height score of 1.88, combined with a highly early-maturing flowering age (-1.13). The vegetative structure in these mutant genotypes, such as adequate dichotomous height and canopy area, plays a vital role in efficiently supporting the assimilate supply to the generative organs. Genotype V1G1 also maintained stability in fruit diameter and total fruit number, proving that gamma irradiation effectively improves specific traits without degrading the primary yield potential.

Table 6. Selection Index values for early selection of gamma-irradiated mutant cayenne pepper genotypes

Genotype	Standardization Value							Selection Index
	PH (w=1)	FA (w= -1.2)	FW (w=1)	FL (w=1)	FD (w=1)	NF (w=1.2)	TW (w=1.5)	
V2G1	0.88	-0.59	2.72	0.92	1.11	1.13	2.52	**11.48**
V1G0	0.71	-0.42	1.37	0.73	0.71	0.39	1.29	**6.43**
V2G0	-0.25	-0.21	-0.37	0.52	1.84	1.13	0.68	**4.38**
V3G1	1.88	-1.13	-0.02	0.81	-0.40	0.43	-0.12	**3.95**
V1G1	-0.66	-0.25	1.15	0.87	0.50	0.03	1.07	**3.81**
V2G2	-0.60	0.00	1.45	0.13	1.08	-0.25	1.15	3.49
V3G0	1.01	-0.95	-0.13	0.69	-0.51	1.27	-0.18	3.43
V1G2	-0.37	-0.25	0.70	0.64	0.64	-0.05	0.55	2.68
V3G3	1.18	-0.93	-0.88	0.22	-0.59	1.02	-0.85	0.99
V3G2	0.70	-0.79	-0.94	0.31	-0.91	0.39	-0.91	-0.80
V3G4	-0.05	-0.30	-1.63	-0.16	-1.02	0.15	-1.37	-4.37
V2G3	-0.75	1.73	-0.41	-0.81	0.82	-1.06	-0.21	-4.79
V1G3	-1.16	1.19	-0.92	-0.75	-1.16	-1.01	-0.77	-7.79
V2G4	-1.41	1.82	-0.94	-1.95	-0.57	-1.97	-0.96	-10.87
V1G4	-1.10	1.09	-1.15	-2.18	-1.54	-1.60	-1.87	-12.02

Note: PH = plant height; FA = flowering age; FW = fruit weight; FL = fruit length; FD = fruit diameter; NF = number of fruits per plant; TW = total fruit weight. The selection index is calculated based on standardized values.

The phenotypic performance of these selected genotypes reflects the success of mutation induction to increase the phenotypic variability. Conversely, the negative index values found in genotypes such as V1G4 and V2G4 confirm the inhibitory effects at high doses that drastically reduce yield components. Comprehensively, genotypes with high positive selection indices have strong validity for designation as elite candidate genotypes. These selected genotypes are recommended for progression to advanced selection stages for cayenne pepper breeding program with high productivity.

CONCLUSION

1. Gamma irradiation induction affects the performance of quantitative characters and several qualitative traits in cayenne pepper. High-dose exposure (300 Gy-400 Gy) drastically reduced seed viability, while low to moderate doses (100Gy) stimulated agronomic performances.
2. Mutant genotypes V2G1, V3G1, and V1G1 were identified as the promising mutant genotypes due to their combination of superior traits. These three genotypes are recommended as genetic material for cayenne pepper breeding programs to develop new, more productive, and efficient varieties.

REFERENCES

Ahmad, F., Kusumiyati, K., Soleh, M. A., &

Khan, M. R. (2024). Assessing the climate adaptive potential of imported Chili in comparison with local cultivars through germination performance analysis. *BMC Plant Biology*, *24*(553), 1–11. https://doi.org/10.1186/s12870-024-05168-4

Akalp, E., & Pirinc, V. (2025). Morphological changes of pepper varieties (*Capsicum annuum* L.) Resulted From UV-C Lights and Gamma-Ray Radiation Sources. *Applied Ecology and Environmental Research*, *23*(4), 6193–6203. https://doi.org/10.15666/aeer/2304_61936203

Anshori, M. F., Musa, Y., Dungga, N. E., Widiayani, N., Arifin, A. S., Masniawati, A., Firmansyah, F., Farid, M., Dirpan, A., & Amas, A. N. K. (2024). A new approach for selection of transgressive segregants in F3 populations based on selection index and anthocyanin content in cayenne pepper. *Frontiers in Sustainable Food Systems*, *8*(1288579). https://doi.org/10.3389/fsufs.2024.1288579

Arumingtyas, E. L., & Ahyar, A. N. (2022). Genetic diversity of chili pepper mutant (*Capsicum frutescens* L.) resulted from gamma-ray radiation. *IOP Conf. Series: Earth and Environmental Science*, *1097*. https://doi.org/10.1088/1755-1315/1097/1/012059

Bado, S., Forster, B. P., Nielen, S., Ali, A. M., Lagoda, P. J. L., Till, B. J., & Laimer, M. (2015). Plant Mutation Breeding: Current Progress and Future Assessment. In *Plant Breeding Reviews: Volume 39* (pp. 23–88). https://doi.org/10.1002/9781119107743.ch2

Choi, H., Han, S. M., Jo, Y. D., Hong, M. J., Kim, S. H., & Kim, J. (2021). Effects of Acute and Chronic Gamma Irradiation on the Cell Biology and Physiology of Rice Plants. *Plants*, *10*(439), 1–14. https://doi.org/10.3390/plants10030439

Gomes, F. D. S., Pimenta, S., Cristina, G., Custódio, A., Gomes, W. S., Ribeiro, J. C., Abreu, N. De, Júnior, D., Cristian, M., Pereira, T., Moulin, M. M., Oliveira, W. F. De, Karolyne, A., Barbosa, P., Christhine, H., Monteiro, D. F., Carolina, A., Gonçalves, P., Vinicius, M., & Monteiro, B. (2025). Selection Strategy for Breeding Pepper Lines with Ornamental Potential. *Horticulturae*, *11*(789), 1–16. https://doi.org/10.3390/horticulturae11070789

Gomez, K. A., & Gomez, A. A. (1984). *Statistical Procedures for Agricultural Research 2nd Edition*. John Wiley & Sons, Inc.

Hanani, A. A., Anindita, R., & Mutisari, R. (2020). Analysis of Market Integration Cayenne Pepper Capsicum frutescens L.) in Malang District. *Agricultural Socio-Economics Journal*, *1*, 23–30. https://doi.org/10.21776/ub.agrise.2020.020.1.4

Hasan, N., Choudhary, S., Naaz, N., Sharma, N., Budakoti, M., Joshi, D. C., Bhinda, M. S., & Laskar, R. A. (2025). Qualitative and quantitative characterization of mutations and genetic diversity analysis in M2 populations of chilli (*Capsicum annuum* L.). *Crop Design*, *4*(3), 100108. https://doi.org/10.1016/j.cropd.2025.100108

Hashim, A., Rafii, M. Y., Yusuff, O., Rahim, A., Juraimi, S., Misran, A., Chibuike, S., & Arolu, F. (2024). Genetic consequences of chronic gamma irradiation on agro morphological traits in chili under hydrogel enhance media. *Heliyon*, *10*(4), e25111. https://doi.org/10.1016/j.heliyon.2024.e25111

Hayati, P. K. D., Witari, S., Rozen, N., & Widiarsih, S. (2022). Effect of gamma irradiation on the germination, pollen viability, and morpho-agronomic of Pachyrhizus erosus cv . Kota Padang. *Biodiversitas*, *23*(3), 1231–1238.

https://doi.org/10.13057/biodiv/d230306

Jeksen, E. E., Asnah, & Dyanasari. (2024). Prospects for Increasing Production and Supply Chain of Cayenne Pepper in Indonesia. *Agro Bali: Agricultural Journal*, *7*(3), 944–956. https://doi.org/10.37637/ab.v7i3.1965

Kirana, R., Handayani, T., Harmanto, & Anwarudin, M. J. (2023). Selection of chili pepper hybrid variety candidate (*Capsicum annuum* L.) based upon flower characteristics. *IOP Conf. Series: Earth and Environmental Science*, *17*. https://doi.org/10.1088/1755-1315/1172/1/012023

Lozada, D. N., Bosland, P. W., Barchenger, D. W., Haghshenas-Jaryani, M., Sanogo, S., & Stephanie, W. (2022). Chile Pepper (*Capsicum*) Breeding and Improvement in the “Multi-Omics” Era. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.879182

Makhziah, M., & Soedjarwo, D. P. (2023). Radiosensitivity of Local Chili Varieties to Gamma Rays. *Jurnal Teknik Pertanian Lampung*, *12*(2), 423–430. https://doi.org/10.23960/jtep-l.v12i2.423-430

Muflikh, Y. N., & Kiloes, A. M. (2024). Insight into the buying behaviour of consumers for chilli in Indonesia : Households and food businesses in selected cities. *Applied Food Research*, *4*(1), 100413. https://doi.org/10.1016/j.afres.2024.100413

Nugroho, K., Trikoesoemaningtyas, Syukur, M., & Lestari, P. (2021). Analisis Keragaman Genetik Karakter Morfologi Populasi M2 Cabai Hasil Iradiasi Sinar Gamma. *Jurnal Agronomi Indonesia*, *49*(3), 273–279. https://doi.org/10.24831/jai.v49i3.38448

Oladosu, Y., Rafii, M. Y., Abdullah, N., Hussin, G., Rahim, H. A., Miah, G., & Usman, M. (2016). Principle and application of plant mutagenesis in crop improvement : a review. *Biotechnology & Biotechnological Equipment*, *30*(1), 1–16. https://doi.org/10.1080/13102818.2015.1087333

Puspitaningrum, D. A., Reka, W. Y., & Widayanto, B. (2024). Impact of climate change on cayenne pepper availability in Sleman District, Yogyakarta with dynamic system modelling. *IOP Conf. Series: Earth and Environmental Science*, *1302*. https://doi.org/10.1088/1755-1315/1302/1/012131

Qosim, W. A., Anas, A., Amien, S., Rachmadi, M., Ramdani, S., & Islami, R. Z. (2024). The effect of various doses of gamma ray irradiation on growth and chlorophyll changes of three adlay genotypes. *Kultivasi*, *23*(2), 209–216. https://doi.org/10.24198/kultivasi.v23i2.55619

Ratna, M., Chowdhury, A. K., Mahmud, F., Rohman, M. M., Ali, M. Z., Syed, M. A., Almoallim, H. S., Ansari, M. J., & Hossain, A. (2024). Morphological and yield trait-based evaluation and selection of chili (*Capsicum annuum* L.) genotypes suitable for both summer and winter seasons. *Open Agriculture*, *9*. https://doi.org/10.1515/opag-2022-0298

Ridwan, I., Farid, M., Haring, F., Widiayani, N., Yani, A., Amier, N., Alfan, M., Amal, I., Hendra, J., Ali, N., Alenazi, M. M., Seleiman, M. F., Suwarno, W. B., & Anshori, M. F. (2025). Optimized framework for evaluating F3 transgressive segregants in cayenne pepper. *BMC Plant Biology*, *25*(156), 1–15. https://doi.org/10.1186/s12870-025-06182-w

Rinaldi, J., Arya, N. N., Mahaputra, I. K., Suharyanto, Trisnawati, N. W., Sari, A. R. K., & Jati, E. N. (2021). The impact of Integrated Crop Management technical guidance of cayenne pepper crops to the farmer's in Klungkung Regency, Bali. *E3S Web of Conferences*, *02010*, 1–11. https://doi.org/10.1051/e3sconf/202130602010

Riviello-Flores, M. de la L., Cadena-Iñiguez, Jorge, Ruiz-Posadas, L. del M., Arévalo-Galarza, M. de L., Castillo-Juárez, I., Hernández, M. S., & Castillo-Martineze, C. R. (2022). Use of Gamma Radiation for the Genetic Improvement of Underutilized Plant Varieties. *Plants*, *11*(1161), 1–19. https://doi.org/10.3390/ plants11091161 Academic

Rohcahyani, F. E., Moeljani, I. R., & Suhardjono, H. (2022). Qualitative Characters Diversity of Prentul Kediri Cayenne Pepper Mutant (M1) Resulted from Gamma Ray Mutation Induction. *Jurnal Teknik Pertanian Lampung*, *11*(3), 483–493. https://doi.org/10.23960/jtep-l.v11i3.483-493

Samuel, O. K., Funsho, O., Charity, A., Stephen, A., & Sunday, I. (2021). Determination of morphological changes using gamma irradiation technology on capsicum species varieties. *Open Agriculture*, *6*, 135–142. https://doi.org/10.1515/opag-2020-0177

Shamsiah, A., Norumaimah, O., Amalina, F. S. N., Susiyanti, Rahim, A. H., & Shuhaimi, S. (2022). Effects of gamma irradiation on agromorphological characteristics of chili. *Food Research*, *6*, 45–52. https://doi.org/10.26656/fr.2017.6(S1).011

Ulinnuha, Z., Farid, N., & Dinuriah, I. (2023). Morphological characteristics of ornamental chilli mutants irradiated by gamma ray. *Agric*, *200*, 159–168.

Ulukapi, K., & Fatih, S. (2018). Study of the effect of irradiation (60 Co) on M 1 plants of common bean (Phaseolus vulgaris L.) cultivars and determined of proper doses for mutation breeding. *Journal of Radiation Research and Applied Sciences*, *11*(2), 157–161. https://doi.org/10.1016/j.jrras.2017.12.004

Vieira, R. A., Paula, A., Nogueira, O., & Fritsche-neto, R. (2025). Optimizing the selection of quantitative traits in plant breeding using simulation. *Frontiers in Plant Science*, *16*(1495662), 1–19. https://doi.org/10.3389/fpls.2025.1495662

Zakir, M. (2018). Mutation Breeding and its Application in Crop Improvement under Current Environmental Situations for Biotic and Abiotic Stresses. *International Journal of Research Studies in Agricultural Sciences*, *4*(4), 1–10. https://doi.org/10.20431/2454-6224.0404001