Selcuk Journal of Agriculture and Food Sciences
https://dergipark.org.tr/tr/pub/selcukjafsci
Research Article

(2026) 40 (1), 75-86 DOI:10.15316/selcukjafsci.1730345 e-ISSN: 2458-8377 Selcuk J Agr Food Sci

Evaluation of Seed Germination in Mung Bean (*Vigna radiata* L.) Varieties Vima 1 and Kutilang After Gamma Irradiation

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HIGHLIGHTS

- The mung bean (*Vigna radiata* L.) varieties used were Vima 1 and Kutilang.
- Gamma radiation was applied at doses of 0, 100, 200, 300, and 400 Gy.
- The study aimed to evaluate the physiological quality of seeds after gamma irradiation.
- The germination rate of mung bean seeds decreased at doses of 300–400 Gy.

Abstract

This study aimed to evaluate the effects of gamma irradiation on seed germination characteristics and seedling vigor in two mung bean (*Vigna radiata* L.) varieties, Vima 1 and Kutilang. Five levels of gamma irradiation doses were applied: 0 Gy, 100 Gy, 200 Gy, 300 Gy, and 400 Gy, using a factorial Completely Randomized Design with three replications. The observed parameters included seed viability (germination percentage, normal and abnormal seedlings, hard seeds, fresh but ungerminated seeds, and dead seeds), vigor index, as well as several seed and germination morphological traits. The results showed that gamma radiation significantly affected seed germination quality and morphological trait variation. The highest heritability and genotypic coefficient of variation (GCV) were observed in hypocotyl length, width, and diameter, indicating that these three traits are genetically controlled and have potential for selection. Conversely, seed size traits exhibited lower variability but remained stable across all treatments. Gamma doses of 100–200 Gy maintained seed vigor and germination above the Indonesian National Standard (SNI) (≥85%), while higher doses (300–400 Gy) resulted in a significant decline in both germination and vigor.

Keywords: Genotypic; Germination; Heritability; Mung bean; Mutation; Viability

1. Introduction

Mung bean (*Vigna radiata* L.) is one of the important food sources in Indonesia, mainly due to its high protein content, relatively short growing period, and ability to grow in various environmental conditions

Citation: Pamungkas, P. B., Wibisana, D. L., Amrih, D., & Nadia L. S. (2026). Evaluation of Seed Germination in Mung Bean (Vigna radiata L.) Varieties Vima 1 and Kutilang After Gamma Irradiation. *Selcuk Journal of Agriculture and Food Sciences*, 40 (1), 75-86. https://doi.org/10.15316/selcukjafsci.1730345

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Received date: 30/06/2025
Accepted date: 11/01/2026

(Zafar et al. 2023). Among the varieties developed nationally, Vima 1 and Kutilang have become leading varieties due to their high productivity and tolerance to environmental stress (Balitkabi 2021; Dewi and Mulyana 2020). Nevertheless, to address challenges such as climate change and growing nutritional needs, improving the genetic quality of crops is essential, particularly through breeding approaches.

One of the widely used methods in modern plant breeding is artificial mutation induction using gamma rays. This technique has been proven effective in creating greater genetic variability through changes in DNA structure, thereby enabling the emergence of new traits such as resistance to environmental stress or improved nutritional content (Chahal and Gosal 2002; Wijananto 2012). A commonly used radiation source is Cobalt-60 (Co^{60}), which emits high-energy photons and can induce mutations in seed tissues (Sadjad 1993).

The initial step of the mutation process is typically carried out by observing seed viability and vigor after irradiation treatment, including parameters such as germination rate, growth speed, and germination uniformity (Prabhandaru and Saputro 2017). These indicators are important as they reflect the seed's ability to grow normally. Previous studies, particularly on rice, have shown that the higher the irradiation dose, the more likely the germination rate will decrease, and the occurrence of abnormal seedlings will increase due to physiological or biochemical disturbances in seed tissues (Sharma et al. 2012; Suliartini et al. 2020).

Gamma rays not only damage DNA structure but also trigger the formation of free radicals that cause oxidative stress, thereby disrupting essential metabolic processes such as the activity of α-amylase, which plays a role in mobilizing food reserves during seed germination (Majeed et al. 2018). Therefore, it is important to evaluate the initial response of seeds to irradiation in order to determine the appropriate dose—sufficient to induce genetic variation, but not so high as to significantly reduce viability.

This study aimed to evaluate the effects of gamma irradiation on seed germination characteristics and seedling vigor in two mung bean varieties. The results of this study are expected to serve as a basis for the early selection of potential mutant plants and contribute to the development of functional mung bean varieties through radiation-induced mutation technology.

2. Materials and Methods

2.1 Materials

The study was conducted from March to May 2025 in the Biology Laboratory, Faculty of Agriculture, University PGRI of Yogyakarta, while the gamma irradiation process was carried out at the irradiation facility of the National Research and Innovation Agency (BRIN) Yogyakarta. The irradiation treatment was performed with graded doses of 0 Gy (control), 100 Gy, 200 Gy, 300 Gy, and 400 Gy

This study was designed using a factorial Completely Randomized Design (CRD), consisting of two factors and three replications for each treatment combination. The first factor was mung bean seed variety, which included two types: Vima 1 and Kutilang. The second factor was the gamma ray irradiation dose, which consisted of five levels: 0 Gy (control), 100 Gy, 200 Gy, 300 Gy, and 400 Gy. The combination of two mung bean varieties and five irradiation doses resulted in 10 treatment combinations. Each treatment combination was replicated three times, resulting in a total of 30 experimental units. Each unit used 100 mung bean seeds, bringing the total number of seeds used in this study to 3.000.

2.2 Methods

This research was carried out following systematically designed methodological steps, with the procedure outlined as follows:

1. Seed radiation – Seeds of mung bean varieties were first subjected to physical mutation induction using gamma irradiation. This irradiation process was carried out at the facilities of the National Research

and Innovation Agency (BRIN) located in Yogyakarta. The irradiation treatments were applied at five dose levels: 0 Gy (control), 100 Gy, 200 Gy, 300 Gy, and 400 Gy. For each dose level, 50 grams of seed samples were used as the treatment unit.

2. Soaking seeds – After the mung bean seeds were exposed to gamma irradiation at the designated doses, the next step was to soak the seeds in distilled water for 2 hours.
3. Physical diversity testing – The evaluation of the diversity of mung bean seed physical characteristics was carried out by including various key parameters related to seed shape, size, and surface structure (Waluyo et al. 2015). This served as part of a further morphometric analysis to detect potential variations resulting from mutation treatments.

3.1 The parameters observed in this physical diversity test:

1) Seed Surface Area – The measurement was carried out after the irradiation was completed and before the germination process began, using the following formula: (Waluyo et al. 2015).

$$A = \pi * \frac{L}{2} * \frac{W}{2} \text{ ..} \tag{1}$$

2) Degree of Roundness – The measurement was carried out after the irradiation was completed and before the germination process began, using the following formula: (Mohsenin 1986).

$$\varphi = \frac{D_g}{L} * 100\% \text{ ..} \tag{2}$$

3) Geometric Diameter – The measurement was carried out after the irradiation was completed and before the germination process began, using the following formula: (Olajide and Ade-Omowaye 1999).

$$D_g = L * W * T^{1/3} \text{..} \tag{3}$$

4) Thickness of Seed – The measurement was carried out after the irradiation was completed and before the germination process began, measured based on the distance between the upper and lower surfaces of the seed when placed horizontally (Waluyo et al. 2015).

5) Seed Length – The measurement was carried out after the irradiation was completed and before the germination process began, measured from end to end of the seed in a horizontal position (Waluyo et al. 2015).

6) Seed Width – The measurement was carried out after the irradiation was completed and before the germination process began, measured at the center of the seed (Waluyo et al. 2015).

7) Hypocotyl Width – Measurement of the widest part of the hypocotyl after 7 days of germination (Sadjad 1993).

8) Hypocotyl Length – Measurements were taken from the tip of the primary root to the base of the cotyledon after 7 days of germination (Sadjad 1993).

9) Hypocotyl Diameter – Measurements were taken after 7 days of germination using the following formula: (Sari et al. 2019).

$$Diameter = \frac{\text{Seed circumference}}{\pi} \text{ ..} \tag{4}$$

3.2 The results obtained from the parameters above will subsequently be used in the analysis of variance as follows:

1) Environmental variance, $\sigma_e^2 = MS_e$ .. (5)

2) Genotypic variance, $\sigma_g^2 = \frac{MS_g - MS_e}{r}$ .. (6)

3) Phenotypic variance, $\sigma_f^2 = \sigma_e^2 + \sigma_g^2$ .. (7)

4) Heritability, $h^2 = \left(\sigma_g^2 \big/ \sigma_f^2\right) * 100$ .. (8)

5) Genotypic coefficient of variation, $GCV = \left(\sqrt{\sigma_g^2}/x\right) * 100$ .. (9)

6) Phenotypic coefficient of variation, $PCV = \left(\sqrt{\sigma_f^2}/x\right) * 100$ .. (10)

4. Seed vigour and viability testing - Observations on seed vigor and viability parameters were conducted using the germination method on moist cotton media placed in a sterile germination box. Observations were carried out daily for seven consecutive days by recording and categorizing the germinated seeds into five groups: normal seedlings, abnormal seedlings, hard seeds, fresh but ungerminated seeds, and dead seeds. This classification was based on the morphology and development of seedling structures such as the primary root, plumule, hypocotyl, as well as the condition of the embryo and cotyledons.

4.1 The criteria for classifying a seedling as normal (N) are described below:

1) The primary root appears to grow well, accompanied by clear development of secondary roots. In some cases, the primary seminal root may not emerge, but at least two to three secondary seminal roots should develop strongly and healthily as an indicator of a normal seedling.

2) The primary leaves grow in parallel with the length of the coleoptile; under such conditions, the emerging leaves must appear healthy. The growing plumule may be curved, as long as it does not show signs of decay.

3) The hypocotyl exhibited optimal and intact development with no tissue damage observed.

4) Having one cotyledon for monocotyl sprouts and two for dicotyl.

5) Seeds with epigeal germination type can be categorized as normal seedlings if the emerging root is at least four times the length of the seed and shows complete morphological development without any structural abnormalities.

6) Seedlings that exhibit decay due to infection from other seedlings are still classified as normal, provided that all essential structures required for growth remain intact and identifiable (Kartahadimaja et al. 2013; Purnobasuki 2012).

4.2 The criteria for classifying a seedling as abnormal (AB) are explained below:

1) Both primary and secondary roots do not develop, or if they do, their growth tends to be weak and short in length.

2) The first leaf does not emerge, and the coleoptile lacks color. Sometimes, the plumule appears white or becomes rotten.

3) Damaged seedlings, without cotyledons, embryos, with broken tissues, and short primary roots.

4) Seedlings that exhibit abnormal shapes, with weak growth or disproportionate development of their essential parts (Kartahadimaja et al. 2013; Purnobasuki 2012).

4.3 The criteria for classifying a seedling into the hard seed (HS) category are as follows: Seeds that remain hard until the end of the germination test period, due to their inability to absorb water caused by an impermeable seed coat, are categorized as hard seeds and must be specifically recorded in the analysis results (Purnobasuki 2012).

4.4 The criteria for classifying a seedling into the fresh but ungerminated seed (FBU) category are as follows: seeds that do not germinate by the end of the testing period but still have the potential to grow into normal seedlings. These seeds are actually capable of absorbing water during the test but experience a delay or obstruction in their subsequent developmental process (Purnobasuki 2012).

4.5 The criteria for classifying a seedling into the dead seed (DS) category are as follows: seeds that decay before the germination process begins or show no growth until the end of the testing period, but whose condition is not categorized as dormant (Purnobasuki 2012).

4.6 The viability indicators used as references in this study include the following parameters:

1) Seed germination – Germination percentage was determined by counting the number of normally germinated seeds over a 7-day period using the ISTA (1999) formula as follows:

$$\text{Seed Germination} = \frac{\text{Number of normal seedlings}}{\text{Number of seeds tested}} * 100\% \;.. \qquad (11)$$

2) Vigor index – The vigor index was determined based on the uniformity and speed of normal seed germination. Germination was conducted by placing the seeds on germination media for 7 days. The percentage of the vigor index was calculated using the ISTA (2010) formula as follows:

$$\text{Vigor Index} = \frac{\varepsilon\,\text{Number of normal seedlings on the }4^{\text{th}}\text{day}}{\varepsilon\,\text{seed germinated}} * 100\% \;.. \qquad (12)$$

The observational data were analyzed using Analysis of Variance (ANOVA) at the 5% significance level. If a significant difference was found among treatments, the analysis was continued with Duncan's Multiple Range Test (DMRT) at the 5% level.

3. Results

3.1 Physical Diversity and Germination of Mung Bean Seeds

Table 1 presents the results of variance and heritability analysis on several seed physical traits and germination characteristics of mung bean. It shows that different levels of genetic variability were produced as a result of gamma ray-induced mutation treatments.

Table 1. Genetic Variance, Environmental Variance, Phenotypic Variance, and Heritability Values of Seed and Germination Characters in Mung Bean.

Character	σ_g^2	σ_e^2	σ_f^2	h² (%)	GCV (%)	PCV (%)
Hypocotyl Length (mm)	0,455	0,003	0,458	99,315	15,572	15,626
Hypocotyl Width (mm)	0,008	0,001	0,009	89,243	17,902	18,950
Hypocotyl Diameter (mm)	0,005	0,002	0,007	77,747	12,282	13,930
Seed Surface Area (mm²)	0,314	0,094	0,408	76,858	4,310	4,916
Degree of Roundness	0,003	0,001	0,004	74,500	6,630	7,682
Geometric Diameter (mm)	0,060	0,015	0,075	80,293	6,265	6,992
Thickness of Seed (mm)	0,017	0,003	0,020	86,957	7,545	8,091
Seed Length (mm)	0,029	0,010	0,039	74,480	3,021	3,500
Seed Width (mm)	0,015	0,002	0,018	87,080	3,463	3,711

Explanation: σ_g^2 is genotypic variance; σ_e^2 is environmental variance; σ_f^2 is phenotypic variance; h^2 is heritability; GCV is genotypic coefficient of variation (Low if from 2.25-6.21%), (Moderately low if from 6.21-10.17%), (Moderately high if from 10.17-14.13%), and (High if from 14.13-17.25%); PCV is phenotypic coefficient of variation (Low if from 0.00-1.85%), (Moderately low if from 1.85-3.69%), (Moderately high if from 3.69-5.54%), and (High if from 5.54-7%). The range values are determined based on the standard scale, ranging from 0 to the highest coefficient value.

On **Table 1**, the hypocotyl length trait has a genotypic variance (σ_g^2) of 0.455 and an environmental variance (σ_e^2) of 0.003, resulting in a phenotypic variance (σ_f^2) of 0.458. The heritability (h²) value for this trait is also very high, reaching 99.315%, accompanied by high genotypic and phenotypic coefficient of variation (GCV and PCV), at 15.572% and 15.626%, respectively. The hypocotyl width trait also shows a high heritability value of 89.243%, with GCV and PCV values of 17.902% and 18.950%, respectively. Meanwhile, hypocotyl diameter has a heritability of 77.747%, with GCV of 12.282% and PCV of 13.930%, indicating a similarly high level of variability.

Meanwhile, for the character of seed surface area, although both the genetic variance and environmental variance were relatively high, at 0.314 and 0.094 respectively, the genotypic coefficient of variation (GCV) was only 4.310%, categorized as low. The traits of roundness degree and geometric diameter had heritability values of 74.500% and 80.293% respectively, with GCVs of 6.630% and 6.265%, and phenotypic coefficients of variation (PCVs) of 7.682% and 6.992%, respectively.

In contrast, the characters of seed length, width, and thickness showed high heritability values of 74.480%, 87.080%, and 86.957%, respectively. The genotypic coefficient of variation (GCV) for seed thickness was classified as moderately low, ranging from 6.21% to 10.17%, while the GCV values for seed length and width were categorized as low because they were below 6.21%. The phenotypic coefficient of variation (PCV) for seed length, width, and thickness fell into the categories of moderately low, moderately high, and high, respectively.

In addition to testing the physical diversity and germination of mung bean seeds, viability testing was also conducted.

3.2 Viability of Mung Bean Seeds

In this test, the observed mung bean seeds were classified into five types based on their germination responses: normal seedlings, abnormal seedlings, fresh seeds that did not germinate, hard seeds, and dead seeds. A visual classification of each category is shown in **Figure 1**, while the percentage distribution of each group is presented in more detail in **Figure 2**. The categorization was carried out based on seed viability evaluation criteria described by Kartahadimaja et al. (2013) and Purnobasuki (2012).

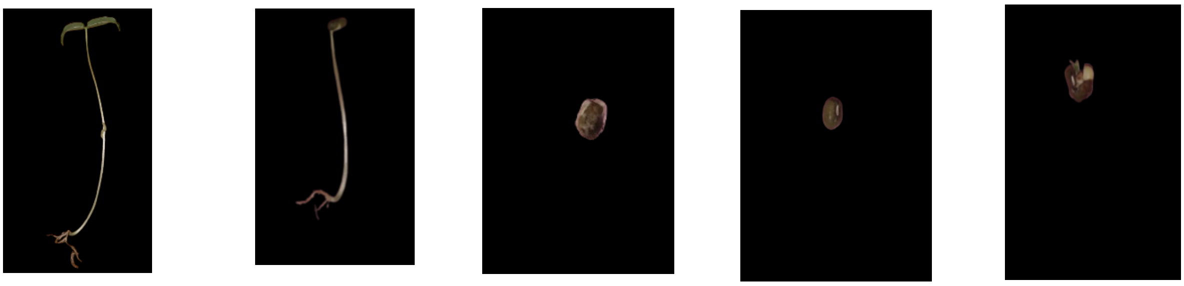
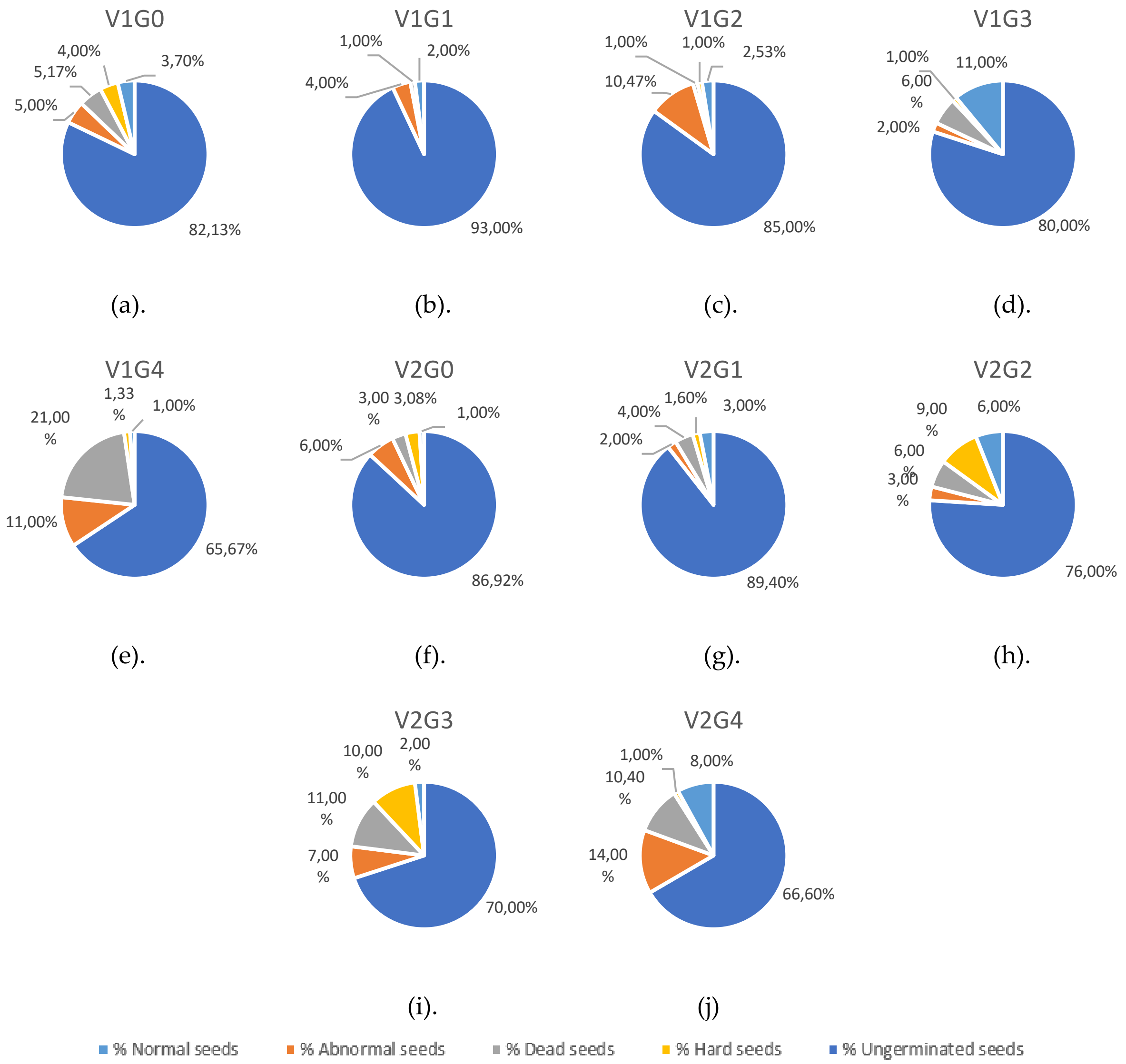

Seedling as normal (N) | Seedling as abnormal (AB) | Dead seed (DS) | Hard seed (HS) | Fresh but ungerminated seed (FBU)

Figure 1. Types of Seed Categories

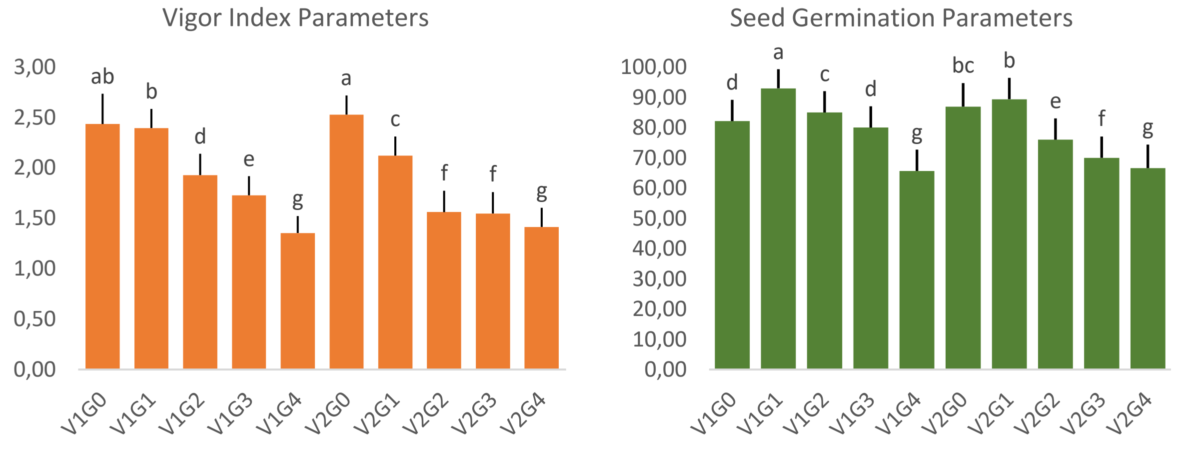


(a). (b). (c). (d).

(e). (f). (g). (h).

(i). (j)

Figure 2. Percentage of Mung Bean Seed Germination Categories Based on Treatment (a) V1G0; (b) V1G1; (c) V1G2; (d) V1G3; (e) V1G4; (f) V2G0; (g) V2G1; (h) V2G2; (i) V2G3; (j) V2G4.



(a). **(b).**

Figure 3. Effect of Radiation Dose on (a) Mung Bean Seed Vigor Index Parameters; (b) Mung Bean Seed Germination Parameters

Figure 1 presents a visualization of five seed categories based on morphological observations during the germination process.

In **Figure 2**, the percentage of mung bean germination categories at each radiation dose treatment is clearly shown. The V1G1 treatment has the highest proportion of normal seedlings, while treatments with higher radiation doses (especially V1G4 and V2G4) show the lowest percentage of normal seedlings. Increasing radiation doses are also accompanied by higher percentages of abnormal seedlings, dead seeds, and fresh seeds that did not germinate. This trend indicates a decline in seedling quality as the radiation dose increases.

Figure 3 (a) shows the seed vigor index parameter of mung bean under each radiation treatment. The highest vigor index was observed in the V2G0 treatment, while the lowest was found in V1G4 and V2G4. It is evident that low-dose treatments such as G1 and G2 increased seed vigor, but the index declined significantly at higher doses. Meanwhile, **Figure 3(b)** presents data showing that the highest germination rates of mung bean seeds were found in treatments V1G1 and V2G1, with a gradual decline observed as the radiation dose increased. Treatments V1G4, V2G3, and V2G4 exhibited the lowest germination rates. This pattern indicates a negative effect of high radiation doses on the seeds' ability to germinate optimally.

4. Discussion

The discussion focuses on two main observed aspects: the physical variability of mung bean seeds and their germination and viability after artificial mutation treatment. The physical variability of seeds was evaluated to determine the extent to which irradiation affected external morphological changes, such as size, shape, and surface structure. Meanwhile, seed viability parameters were analyzed to assess the seeds' ability to germinate and survive, which are fundamental criteria in the initial selection process of potential mutant lines.

4.1 Physical Diversity and Germination of Mung Bean Seeds

The high values of genetic variance (σ_g^2), heritability (h^2), and genotypic coefficient of variation (GCV) for the hypocotyl length trait (σ_g^2 = 0.455; h^2 = 99.315%; GCV = 15.572%) indicate that the observed variation is primarily genetic rather than environmental. This suggests a strong opportunity for early selection on this trait, as it is stably heritable. The traits of hypocotyl width and diameter also show a similar pattern (σ_g^2 = 0.005–0.008; h^2 = 77.7–89.2%; GCV = moderate to high), indicating that all three traits are responsive to mutation and have the potential to serve as strong markers in plant breeding selection. This condition is consistent with the findings of Malook et al. (2020) and Yoseph et al. (2022), who reported increased variability in mung bean following gamma irradiation.

Meanwhile, although traits such as seed surface area, roundness, and geometric diameter exhibited high heritability (74–80%), their genotypic coefficient of variation (GCV) fell into the low to moderately low category. This indicates that, while the variation is heritable, the intensity of mutation affecting seed size and shape was limited. This finding is consistent with Zhang et al. (2024), who observed that the phenotypic expression of seed size traits tends to be genetically stable but shows low variability in mung bean populations.

Furthermore, traits such as seed length, seed width, and seed thickness showed a relatively high heritability range (74–87%), but their genotypic coefficient of variation (GCV) fell into the low to moderately low category. This indicates that although changes in these traits are inheritable, their response to mutation is weak. Practically, such traits are less ideal for mutation-based selection, as mutations appear to produce insufficient phenotypic variation. A study conducted by Zhang et al. (2024), showed a similar pattern in several physical traits of mung bean seeds, where some traits retained their shape but did not exhibit significant differences after mutation. A similar observation was also reported by Vanniarajan and Chandirakala (2022), who noted that high-dose radiation is known to trigger permanent DNA damage, which does not always result in beneficial mutations, but may instead inhibit the expression of key genes or even cause neutral mutations that have no significant effect on phenotype. High-dose radiation treatments such as 300 Gy or 400 Gy may induce physiological stress in embryonic seed tissues, thereby reducing the likelihood of new phenotypic expressions.

Overall, the combination of variance, heritability, and coefficient of variation indicates that mutation treatment using gamma rays, particularly at low to moderate doses, is effective in increasing genetic variability in key traits such as hypocotyl length and diameter. These characters are highly recommended as a basis for selection due to their high heritability and prominent variability. Conversely, characters with low genotypic coefficient of variation (GCV) should be considered as complementary traits in subsequent selection or used as indicators of genetic stability, as they tend to be less affected by mutation.

4.2 Viability of Mung Bean Seeds

The assessment of seed vigor and viability is an essential step in determining the physiological quality of seeds to be used. Vigor refers to the seed's ability to grow rapidly and uniformly, even under less favorable field conditions. Meanwhile, viability refers to the seed's capacity to germinate and produce a normal seedling, which can be observed through metabolic activity or early morphological growth indicators (Sudrajat and Zanzibar, 2009).

The initial effects of induced mutation in a plant can be observed through seed germination. Low doses (such as G0: 0 Gy and G1: 100 Gy) are able to maintain the dominance of normally germinating seeds, while higher doses (such as G3: 300 Gy and G4: 400 Gy) increase the frequency of abnormal, dead, and ungerminated seeds. This indicates that radiation stress begins to damage the physiological processes of seeds when the dose exceeds the tolerance threshold. This phenomenon is presumed to occur because ionizing radiation induces DNA damage and disrupts metabolic processes, thereby inhibiting embryo development or causing abnormal seedling growth (Dewanjee and Sarkar, 2018; Mudibu et al. 2012). The ionization resulting from gamma radiation generates highly reactive hydroxyl radicals. These radicals can trigger chemical alterations and directly interact with organic molecules, both structurally and functionally, leading to disruptions in key physiological processes such as imbibition, respiration, and cell division, ultimately reducing seed germination capacity (Majeed et al. 2018; Mohammadi et al. 2024).

Moreover, the accumulation of oxidative damage caused by free radicals generated from high-dose radiation exposure may lead to the degeneration of essential seed structures, such as the radicle and plumule, which are crucial for germination (Rashid et al. 2018). As the irradiation dose increases, seeds tend to exhibit higher protein content and a reduction in both total carbohydrate levels and overall energy reserves. Low levels of carbohydrates and total energy can lead to abnormal seedlings and hinder the germination process (Sudrajat and Zanzibar, 2009). According to Amjad and Anjum (2003), in their study on irradiated *Allium cepa* L. seeds, high doses of irradiation increased the percentage of abnormal seedlings in line with the rising radiation dosage.

Both seed vigor index and germination rate exhibited a similar trend, where low-dose radiation treatments—particularly G0 (0 Gy) and G1 (100 Gy)—resulted in the highest values compared to other treatments, as shown in **Figures 3(a)** and **3(b)**. This improvement may be attributed to the stimulatory effect of low-dose mutations, which enhance metabolic activity and promote cell division during the early stages of germination (Mensah et al. 2007). As the gamma radiation dose increases to higher levels (G3: 300 Gy and G4: 400 Gy), both seed vigor and germination rate decline significantly. This reduction suggests that high doses have a damaging mutagenic effect, disrupting cellular integrity and enzymatic systems in the seed, thereby inhibiting the formation and development of healthy and uniform seedlings (Bonde et al. 2020; Vanmathi et al. 2021). The results of this study are consistent with those reported by Bonde et al. (2020), which showed that the application of high-dose gamma radiation (>200 Gy) significantly reduces the vigor index of mung bean seeds. Thus, there is a threshold dose at which the effect of radiation shifts from being stimulative to inhibitory on seed physiological quality.

According to the Indonesian National Standard (SNI), the minimum germination rate for mung bean seeds is 85%. Therefore, it can be concluded that the seeds of mung bean variety Vima 1 at radiation doses of 100 and 200 Gy, and Vima 2 at doses of 0 and 100 Gy, still meet the SNI germination standard threshold **(Figure 3(b))**. In contrast, other treatments, particularly at levels G3: 300 Gy and G4: 400 Gy, exhibited a decrease in germination rates to below 85%, with some falling within the range of 60–80%. These findings are consistent with those reported by Sagita et al. (2025) and Sivana et al. (2025), who noted that a germination rate of 68% remains below the SNI threshold for high-quality mung bean seeds.

5. Conclusions

The results of the study demonstrated that gamma irradiation had a significant effect on the seed morphological traits and viability of mung bean varieties Vima 1 and Kutilang. The traits of hypocotyl length, hypocotyl width, and hypocotyl diameter exhibited high heritability and genotypic coefficient of variation (GCV), indicating that these traits are genetically controlled and may serve as reliable selection criteria in the development of superior mutant lines. Radiation doses of 100–200 Gy were found to maintain seed germination and vigor within the standard range defined by the Indonesian National Standard (SNI), whereas higher doses (300–400 Gy) tended to reduce seed physiological quality. These findings provide a basis for determining an effective mutation dose range in irradiation-based plant breeding programs.

Author Contributions: The authors have an equal contribution. All authors have read and agreed to the published version of the manuscript

Funding: This research is supported by the Head Office of the Research and Community Service Institute (LPPM) of the University of PGRI YoGyakarta with project number 314/BAP-LPPM/I/2025.

Data Availability Statement: All data generated or analysed during this study are included in this published article.

Acknowledgments: We would like to thanks the National Research and Innovation Agency (BRIN) Yogyakarta for the facilities and technical assistance provided during the seed irradiation process. We also extend our thanks to the Head Office of the Research and Community Service Institute (LPPM) of the University of PGRI YoGyakarta for funding this research.

Conflicts of Interest: The authors declare no conflict of interest.

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