JASSU
Journal of Agrosociology and Sustainability
JASSU 2(2): 152-167
ISSN 3025-1362

Evaluating the yield potential of the mutant (M6) short stem Mentik Wangi rice varieties developed through 200-gray gamma irradiation

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Received Date: December 8, 2024 Revised Date: January 25, 2025 Accepted Date: January 29, 2025

ABSTRACT

Background: Mentik Wangi, a traditional aromatic rice variety, faces challenges such as prolonged growth duration and lodging susceptibility, limiting its productivity. The study aimed to evaluate the yield potential and identify high-performing mutant lines of Mentik Wangi rice induced by 200 Gy gamma irradiation. This study addresses the growing need for rice varieties with improved traits to enhance food security in Indonesia. **Methods:** The research was conducted at the Tegalgondo Rice Seed Garden using a randomized complete block design (RCBD) with three replications. The study included 12 M6 mutant lines of Mentik Wangi rice generated through 200 Gy gamma irradiation. Data were collected on plant growth, yield attributes, and grain quality. Statistical analyses were performed using ANOVA and Duncan's Multiple Range Test to evaluate the significance of observed traits. **Findings:** The results revealed significant variations among mutant lines for key yield components, including grains per panicle, 100-grain weight, and productivity per hectare. The line M6-MW2-G70-01-14-4-8 demonstrated the highest productivity at 7.29 tons/ha, while all mutant lines exceeded the productivity of the control (3.78 tons/ha). Gamma irradiation was effective in inducing beneficial mutations, enhancing traits such as early maturity, short stems, and higher grain density. **Conclusion:** The study successfully identified mutant lines of Mentik Wangi rice with improved yield potential and agronomic traits, demonstrating the effectiveness of gamma irradiation as a crop improvement strategy. **Novelty/Originality of this article:** This research presents innovative findings on the use of gamma irradiation to enhance the productivity and agronomic traits of a traditional rice variety, contributing to the development of high-yielding and locally adapted rice lines.

KEYWORDS: Mentik Wangi mutant rice; gamma irradiation (200 Gy); yield improvement.

1. Introduction

Rice (Oryza sativa L.) is a vital crop in Indonesia. While the country has diverse staple food sources such as corn, sago, sorghum, cassava, and sweet potato, rice remains the most demanded commodity, with increasing consumption annually. Hence, improving the quality and quantity of rice production is essential to meet food demands. With the growing population, enhancing rice productivity through crop breeding is critical for ensuring food security, particularly by developing new varieties of local rice. Indonesia is endowed with a rich diversity of local rice varieties, boasting approximately 17,000 germplasm accessions. This diversity represents a valuable genetic resource for breeding and improving rice varieties (Kodir et al., 2016).

Cite This Article:
Himawan, R., Yunus, A., Parjanto & Purwanto, E. (2025). Evaluating the yield potential of the mutant (M6) short stem Mentik Wangi rice varieties developed through 200-gray gamma irradiation. *Journal of Agrosociology and Sustainability, 2*(2), 152-167. https://doi.org/10.61511/jassu.v2i2.2025.1463

The genetic traits of local rice varieties provide specific advantages. These varieties have been cultivated for generations, resulting in genotypes that are well-adapted to specific land and climatic conditions in their regions of development. Local rice varieties are naturally resistant to pests and diseases, tolerant to abiotic stresses, and possess superior grain quality that is highly preferred by consumers in their respective areas. Therefore, these local varieties, with their unique characteristics, must be preserved as a national genetic resource and utilized in breeding programs (Sitaresmi et al., 2013). Mentik Wangi is one of the local rice varieties found in the Special Region of Yogyakarta. It is characterized by a plant height during the generative phase of 100–130 cm, a harvesting age of 121–130 days, and white panicle heads. The milling weight of Mentik Wangi ranges from 50–60 grams, and its filled grain weight and number of filled grains per panicle are key parameters for estimating yield.

Among the local rice varieties favored by Indonesian consumers is Mentik Wangi, a traditional variety originating from Magelang, Central Java. Mentik Wangi is highly regarded for its unique natural aroma and soft rice texture, making it a preferred choice for consumption. However, this variety has notable drawbacks, such as a longer harvesting time of 4 months compared to the average 3 months for other rice varieties and a high susceptibility to lodging (Wang et al., 2024). Addressing these limitations while retaining its beneficial traits requires advanced crop improvement strategies.

As Indonesia's population grows, the demand for rice continues to increase. To ensure food security, particularly for rice, various efforts have been made, including crop improvement programs. Plant breeding is both a science and an art aimed at improving plant traits that can be passed down to new individuals with desirable genetic characteristics. The primary goal of plant breeding is to develop superior varieties with high and stable yields under various environmental conditions, thereby meeting farmers' needs. Plant breeding programs are integral to the success of agricultural systems, and the resulting superior varieties can positively impact food availability (Shelton & Tracy, 2017).

Plant breeding not only increases the yield and productivity of rice but also enhances its quality. Two approaches are commonly used in plant breeding: conventional methods, such as crossing, selection, and mutation, and unconventional methods, such as gene transfer, gene cloning, and molecular markers. Typically, plant breeding begins with the collection of diverse genetic resources (germplasm), followed by identification and characterization. If using crossing or gene transfer, the process involves diversity induction, selection, testing, evaluation, release, and finally, distribution and commercialization of the variety. Genetic diversity resulting from mutations can influence various traits of a plant species in neutral, beneficial, or harmful ways (Salgotra & Chauhan, 2023).

Mutations can be induced through various techniques, including electromagnetic radiation. Electromagnetic radiation, such as gamma rays or X-rays, is used to treat specific parts of the plant at predetermined doses to induce mutations. One way to increase genetic diversity is through induced mutation, specifically irradiation. Gamma irradiation is an artificial mutation induction technique using gamma rays. Mutation serves as the primary source of genetic variation, which is the foundation of evolution. Without mutation, the evolution of living organisms would not occur. Mutations can add or modify specific traits without altering the overall superior characteristics of the original plant (Warid et al., 2017).

Gamma rays are a form of electromagnetic radiation that modifies physiological traits and acts as a mutagenic agent. Gamma radiation or electron beams can affect plasma membrane functions and proteins, inducing DNA mutations such as single-strand breaks (SSBs) and double-strand breaks (DSBs). These alterations can damage or modify essential cellular components, influencing the morpholoGy, anatomy, biochemistry, and physioloGy of plants based on the radiation dose applied (Borzouei et al., 2010). The use of gamma radiation in plants provides significant benefits in agriculture. Proper radiation doses can yield plants with desirable traits, such as high yields, early maturity, and disease resistance. The objective of mutation is to increase the variation in the treated plant population, enabling the selection of desirable traits or characteristics. Through irradiation techniques, plants with superior traits can be developed after undergoing a series of tests, selection, and certification processes (Sibarani & Hanafiah, 2015).

Modern crop improvement techniques, such as gamma irradiation, have been widely utilized. Gamma rays are a commonly employed physical mutagen in plant mutagenesis, which involves inducing genetic mutations to enhance variability. Mutations refer to modifications in genetic material that have the potential to be inherited by subsequent generations (Mullins et al., 2021). Physical mutagens can significantly enhance genetic variability for specific traits, making selection more efficient and increasing the likelihood of obtaining desired genotypes compared to conventional breeding methods (Khursheed & Khan, 2016).

This variety is appreciated for its distinctive aroma and soft texture, making it popular among consumers. However, its long harvesting time (approximately 125 days) and susceptibility to lodging reduce its attractiveness to farmers, who prefer varieties with shorter growth durations and higher yield stability. Based on these problems, this study discusses several research questions related to the potential yield of short-stemmed mutant lines of the M6 generation of the Mentik Wangi variety induced by 200 gray gamma ray irradiation. In addition, this study also explores the possibility of short-stemmed mutant lines of the Mentik Wangi variety that have high yield potential as a result of the irradiation treatment. In line with that, the purpose of this study is to evaluate the yield potential of 12 short-stemmed mutant lines of the M6 generation of the Mentik Wangi variety and to identify lines with high yield potential.

This study is expected to provide benefits to various parties. For researchers, the results of this study can provide insight into mutant lines that have superior potential, which can be the basis for further research in improving rice varieties. For farmers, the existence of mutant lines of local rice varieties with high productivity has the potential to increase their harvest yields and welfare. Meanwhile, for policy makers, the findings of this study can be used as consideration in formulating policies and strategies that support the development of local rice varieties, thereby contributing to sustainable agricultural development.

Yield testing is a critical step in the development of new varieties. It involves evaluating the yield potential of selected lines under various environmental conditions. Yield trials are conducted in three stages, namely preliminary yield trials, advanced yield trials, and multilocation trials. These stages assess the stability and adaptability of the genotypes before they are released as new varieties (Kondombo et al., 2024). Conducting advanced yield trials to minimize the loss of superior lines due to genotype-environment interactions. Additionally, Arsyad et al. (2007) emphasized that the plot size for preliminary yield trials should be smaller than that for advanced trials or multilocation trials.

The research problem addresses the limitations of the traditional Mentik Wangi rice variety, which has a long harvesting time and high susceptibility to lodging, despite its desirable aroma and texture. The primary objectives are to evaluate the yield potential of 12 short-stem mutant lines (M6 generation) developed through 200-gray gamma irradiation and identify mutant lines with high yield potential, early maturity, and short stems. By employing mutation breeding techniques, the study aims to develop improved rice varieties that can enhance rice production, provide insights for future research, and potentially contribute to sustainable agricultural development while preserving the preferred characteristics of the local Mentik Wangi variety.

This study focuses on identifying mutations that enhance desirable traits in Mentik Wangi rice while preserving its beneficial characteristics. Yield potential is a quantitative trait targeted in plant breeding. Yield testing is conducted on selected lines at specific generations. The Indica variety exhibits superior rice performance compared to other types in the studied environments, potentially attributed to its enhanced grain nitrogen use efficiency (Anila et al., 2018). The objectives are to evaluate the yield potential of short-stem mutant lines (M6 generation) of the Mentik Wangi variety and identify mutant lines with early maturity, short stems, and high yield potential.

2. Methods

This study was conducted at the Tegalgondo Rice Seed Garden, located at Jl. Solo-Jogja KM.15 Sraten, Sukoharjo, Central Java, from June to October 2020. The geographical coordinates of the site are 7°34'33.6" South Latitude and 110°43'00.4" East Longitude, at an elevation of 135 m above sea level. The experimental plot covered an area of 2500 m^2.

2.1 Tools and materials

The tools used in this study included hoes, tractors, measuring tapes, sickles, scissors, sacks, stationery, analytical scales, stakes, label boards, raffia strings, plastic bags, paper envelopes, and cameras. The study utilized wet soil, water, Urea fertilizer, NPK fertilizer, Marshall insecticide, and gamma-irradiated M5 mutant seeds (200 Gy) from 12 M5 lines, including: (1) M5-MW2-G01-02-17-14-10, (2) M5-MW2-G35-25-01-7-19, (3) M5-MW2-G35-25-01-7-38, (4) M5-MW2-G35-25-03-1-18, (5) M5-MW2-G70-01-14-19-75, (6) M5-MW2-G70-01-14-19-2, (7) M5-MW2-G70-01-14-1-18, (8) M5-MW2-G70-01-14-1-2, (9) M5-MW2-G70-01-14-1-41, (10) M5-MW2-G70-01-14-1-12, (11) M5-MW2-G70-01-14-4-51, and (12) M5-MW2-G70-01-14-4-8.

2.2 Experimental design

The experiment was conducted on the experimental farm of the Faculty of Agriculture, Universitas Sebelas Maret, located in Palur Village, Mojolaban Subdistrict, Sukoharjo Regency. It involved field trials of 51 genotypes, including 51 M5 gamma-irradiated mutant lines, using a randomized complete block design (RCBD) with three replications, including a control (non-irradiated parent plant). Each line was represented by 30 plants per block, with observations made by sampling five selected plants based on specific criteria. Data were collected through observations of the growth performance of the mutant rice plants. The collected data included yield test variables of selected lines.

2.3 Research implementation

Research implementation begins with seed preparation, seedling nursery, land preparation and soil processing, to the harvest stage and result testing. Seed preparation begins with the use of seeds from individual plants of the M5 Mentik Wangi mutant line. The seeds are then soaked in water for 24 hours to initiate absorption, which allows water absorption and enzymatic activation required for metabolic processes. After that, the seeds are incubated under controlled conditions to encourage uniform root emergence, ensuring synchronous seedling development before being transplanted. Next, seeding is carried out by sowing seeds in coded trays in the greenhouse to maintain humidity and facilitate germination. Marshall insecticide (25 g) is sprayed to prevent pest attacks. The trays are stacked and covered to improve germination. Daily watering and monitoring are carried out for 21 days before the seedlings are transplanted.

Land preparation and soil processing are carried out by cleaning the experimental plot from weeds and residues, followed by plowing and leveling the soil. Plowing aims to improve aeration and facilitate root penetration, while leveling is carried out to ensure even water distribution throughout the planting area. The main objective of this stage is to prevent nutrient competition and ensure optimal soil conditions for rice growth. After the land is ready, 21-day-old seedlings are transferred to the prepared plots with random line arrangements. Each seedling is planted individually in a prepared hole with a distance of 25 cm × 28 cm to maintain adequate root expansion and optimize light interception. To prevent interference between plots and facilitate agronomic assessment, the experimental blocks are separated by a 50 cm wide buffer zone.

Plant maintenance is carried out by watering every week or as needed to maintain the capacity of the soil during the vegetative phase. Weeding is carried out every day to remove competitive plants. Fertilization is carried out in stages, starting with the provision of Urea (100 kg/ha) and NPK (50 kg/ha) in the first week to stimulate initial vegetative growth. Fertilization is continued by providing additional doses of Urea (50 kg/ha) and NPK (150 kg/ha) in the third week to maintain nutrient availability during the tillering phase. In the fifth week, the last dose of Urea (50 kg/ha) and NPK (50 kg/ha) were given to support reproductive development and grain formation. In addition, pest and disease control measures were carried out using recommended chemical doses after detecting symptoms of pests or diseases. Harvesting was carried out when the plants reached full maturity, which was indicated by yellowing leaves, drying stems, and drooping panicles. Harvesting was done manually to ensure the separation of each line. This approach facilitated the collection of accurate data on yield performance and post-harvest quality assessment.

The post-harvest stage included drying the harvested grain for one day. The dried seeds were then carefully stored in labeled sample envelopes under optimal storage conditions to prevent damage and maintain their genetic integrity. This was done for further analysis and future planting trials. Yield testing was carried out by evaluating selected lines compared to control plants to determine whether irradiated mutants showed improved yield performance. This analysis provided important insights into the effectiveness of induced mutations in improving yield and adaptability of rice under experimental conditions.

2.4 Field observation variables

In field observations, several key variables are assessed to evaluate the yield potential of the crop are (1) grain count per panicle, (2) panicle density index, (3) weight of 100 grains, (4) grain weight per plant, and (5) total yield. Grain Count per Panicle is determined by counting the grains from three panicles per plant, providing an initial indication of productivity. Meanwhile, Panicle Density Index is calculated using the formula that relates the mean grain count per panicle to the mean panicle length, reflecting the density of panicles per unit length. Furthermore, Weight of 100 Grains (g) is measured to assess yield potential, while Grain Weight per Plant (g) records the total grain weight per plant, which is crucial for determining individual plant performance. Finally, Total Yield (kg/ha) is derived by converting the harvested grain weight to yield per hectare, offering a comprehensive overview of the productivity of the cultivated area.

2.5 Data analysis

In analysis of variance, two statistical methods were used to assess the effect of treatments on yield. ANOVA test was performed with one-way ANOVA to compare the means of different lines, testing the null hypothesis H0 that $\mu 1 = \mu 2 = \ldots = \mu k$ indicating no treatment effect against the alternative hypothesis H1 that at least one μ is different. If there is a significant difference in the means, then further analysis is required. Duncan's Multiple Range Test (DMRT) was applied after ANOVA to facilitate pairwise comparison of treatment means, ensuring that significant differences between lines are identified and reported accurately, thereby increasing the robustness of the results.

3. Results and Discussion

3.1 Number of grains per panicle

The number of grains per panicle is a key indicator of rice plant productivity. The higher the number of grains produced per panicle, the greater the overall productivity of the rice plant. The number of grains per panicle was determined by averaging the count of grains from five randomly selected panicles per plant for each line and the control group. The results of the grain count for the M6 generation of gamma-irradiated Mentik Wangi rice (200 Gy) (Fig. 1) are presented in Table 1.

Fig. 1. Number of grains in Mentik Wangi M6 rice plants resulting from 200 gray gamma ray irradiation

Based on Table 1, the line with the highest number of grains per panicle was M6-MW2-G70-01-14-4-51 with 221 grains, while the line with the lowest number was M6-MW2-G70-01-14-19-75 with 98 grains. In terms of the average number of grains per panicle, the highest was observed in M6-MW2-G35-25-03-1-18, with an average of 168.8 grains (range: 125–200). Conversely, the lowest average was recorded in M6-MW2-G35-25-01-7-19, with 145.4 grains (range: 108–185). The average number of grains per panicle in the control plants (M5 generation) was 133.4 grains, indicating that all mutant lines had a higher number of grains compared to the control.

Table 1. Number of grains per panicle of Mentik Wangi rice (M6) resulting from 200 Gy gamma-ray irradiation

No.	Line ID	Lowest	Highest	Range	Average	
1	M6-MW2-G01-02-17-14-10	111.0	201.0	111-201	165.0	ab
2	M6-MW2-G35-25-01-7-19	108.0	185.0	108-185	145.4	c
3	M6-MW2-G35-25-01-7-38	130.0	207.0	130-207	165.6	ab
4	M6-MW2-G35-25-03-1-18	125.0	200.0	125-200	168.8	a
5	M6-MW2-G70-01-14-19-2	121.0	206.0	121-206	165.2	ab
6	M6-MW2-G70-01-14-19-75	98	199.0	82-199	155.3	bc
7	M6-MW2-G70-01-14-1-2	139.0	208.0	139-208	166.3	ab
8	M6-MW2-G70-01-14-1-12	107.0	197.0	107-197	153.9	bc
9	M6-MW2-G70-01-14-1-18	139.0	206.0	139-206	161.3	ab
10	M6-MW2-G70-01-14-1-41	113.0	201.0	113-201	166.1	ab
11	M6-MW2-G70-01-14-4-8	119.0	193.0	119-193	160.8	ab
12	M6-MW2-G70-01-14-4-51	107.0	221.0	107-221	164.3	ab

Notes: Values followed by the same letter are not significantly different based on Duncan's Multiple Range Test at a 5% significance level

The results of the F-test with a confidence level of 0.05 indicate a value of 0.009. Based on this value, the number of grains per panicle shows no significant effect between the lines and panicle length. However, the results of the Duncan multiple range test (Table 1) reveal that the number of grains per panicle differs significantly among the tested lines. This indicates that the effect of gamma irradiation at 200 gray and the genetic lines, individually, has a significant impact on the number of grains per panicle.

The higher the number of productive tillers per unit area, the greater the number of panicles per unit area, which results in more grains emerging on each panicle. This aligns with the statement of Li et al. (2021) that an ideal rice plant has long and dense panicles with a high number of grains. Both genetic and environmental factors greatly influence the number of grains per panicle. Unfavorable factors may occur during growth, panicle formation, or grain filling, which means that a high number of grains per panicle does not always correspond to a high yield. This is consistent with the statement of Makarim & Suhartatik (2009) which emphasizes that the number of grains produced on a panicle in a clump does not fully represent the total yield obtained.

Based on the character of the number of grains per panicle, the lines M6-MW2-G35-25-03-1-18, M6-MW2-G70-01-14-1-41, M6-MW2-G35-25-01-7-38, and M6-MW2-G01-02-17-14-10 exhibited the highest number of grains per panicle. These lines are expected to have high yield potential and could serve as a new source of genetic diversity. Further multilocation trials are recommended to evaluate their performance before release as new varieties.

3.2 Panicle density index

The panicle density index is an important indicator of the yield potential of rice plants. Wu et al. (2025) stated that panicle density is determined by the total number of grains and the length of the panicle. The index is calculated as the ratio of the total number of grains per panicle to the panicle length, providing an estimate of grain density on the panicle. The results for the panicle density index of the M6 generation of Mentik Wangi rice irradiated with 200 Gy gamma rays are shown in Table 2.

Table 2. Panicle density index of Mentik Wangi rice (M6) resulting from 200 Gy gamma-ray irradiation

No.	Line ID	Avg. grains per panicle	Avg. panicle length (cm)	Density index	
1	M6-MW2-G01-02-17-14-10	165.0	26	6.2	a
2	M6-MW2-G35-25-01-7-19	145.4	26.9	5.5	b
3	M6-MW2-G35-25-01-7-38	165.6	27.3	6.1	a
4	M6-MW2-G35-25-03-1-18	168.8	26.5	6.4	a
5	M6-MW2-G70-01-14-19-2	165.2	26	6.5	a
6	M6-MW2-G70-01-14-19-75	155.3	24.7	6.2	a
7	M6-MW2-G70-01-14-1-2	166.3	26.7	6.2	a
8	M6-MW2-G70-01-14-1-12	153.9	25.8	6.0	ab
9	M6-MW2-G70-01-14-1-18	161.3	26.2	6.3	a
10	M6-MW2-G70-01-14-1-41	166.1	26.3	6.2	a
11	M6-MW2-G70-01-14-4-8	160.8	26.1	6.2	a
12	M6-MW2-G70-01-14-4-51	164.3	25.8	6.4	a

Notes: Values followed by the same letter are not significantly different based on Duncan's Multiple Range Test at a 5% significance level

Based on Table 2, the line with the highest panicle density index was M6-MW2-G70-01-14-19-2, with an index value of 6.5. This line had an average of 165.2 grains per panicle and an average panicle length of 26 cm. The line with the lowest index was M6-MW2-G35-25-01-7-19, with a density index of 5.5, 145.4 grains per panicle, and a panicle length of 26.9 cm. According to Las et al. (2003), a higher number of grains per panicle results in a higher panicle density index. The average panicle density index of the control plants in the M5 generation was 5.47, indicating that the mutant lines achieved better results.

The F-test results at a 0.05 confidence level yielded a value of 0.110. This indicates that there was no significant effect of the lines on panicle density index and panicle length. However, Duncan’s Multiple Range Test (Table 2) revealed significant differences in the panicle density index among the tested lines. This demonstrates that the 200 Gy gamma irradiation and the lines individually had a significant effect on the panicle density index. According to Viana (2019), mutations can induce changes in genetic material at the gene or chromosomal level, which can subsequently lead to phenotypic or trait alterations in plants. The lines M6-MW2-G70-01-14-19-2, M6-MW2-G35-25-03-1-18, M6-MW2-G70-01-14-4-

51, and M6-MW2-G70-01-14-1-18 demonstrated high panicle density indices, indicating their potential as sources of genetic variation for developing high-yield rice varieties.

3.3 Weight of 100 grains

The weight of 100 grains is an estimate of the total weight of grains harvested per plant and serves as an indicator of grain quality. According to Gasparis et al. (2023), measuring the weight of 100 grains is essential for determining grain size, with heavier grains indicating larger and denser kernels. This parameter is a crucial indicator of the quality and marketability of rice varieties. The results for the weight of 100 grains in the M6 generation of gamma-irradiated Mentik Wangi rice (200 Gy) are presented in Table 3.

Table 3. Weight of 100 grains of Mentik Wangi Rice (M6) resulting from 200 Gy gamma-ray irradiation

No.	Line ID	Lowest (g)	Highest (g)	Range (g)	Average (g)	
1	M6-MW2-G01-02-17-14-10	2.6	3.8	2.6-3.8	3.1	ab
2	M6-MW2-G35-25-01-7-19	2.8	3.8	2.8-3.8	3.3	ab
3	M6-MW2-G35-25-01-7-38	2.9	3.9	2.9-3.9	3.5	ab
4	M6-MW2-G35-25-03-1-18	2.7	3.2	2.7-3.2	2.9	b
5	M6-MW2-G70-01-14-19-2	2.7	3.7	2.7-3.7	3.2	ab
6	M6-MW2-G70-01-14-19-75	2.8	4.1	2.8-4.1	3.3	ab
7	M6-MW2-G70-01-14-1-2	3.2	4.4	3.2-4.4	3.8	a
8	M6-MW2-G70-01-14-1-12	2.7	3.9	2.7-3.9	3.4	ab
9	M6-MW2-G70-01-14-1-18	3.0	4.2	3-4.2	3.5	ab
10	M6-MW2-G70-01-14-1-41	2.6	3.8	2.6-3.8	3.1	ab
11	M6-MW2-G70-01-14-4-8	2.8	4.1	2.8-4.1	3.2	ab
12	M6-MW2-G70-01-14-4-51	2.6	3.7	2.6-3.7	3.0	b

Notes: Values followed by the same letter are not significantly different based on Duncan's Multiple Range Test at a 5% significance level

Based on the results in Table 3, the line with the highest 100-grain weight was M6-MW2-G70-01-14-1-2, with a weight of 4.4 grams, while the lines with the lowest 100-grain weight were M6-MW2-G01-02-17-14-10, M6-MW2-G70-01-14-1-41, and M6-MW2-G70-01-14-4-51, each weighing 2.6 grams. When examining the average 100-grain weight, the highest value was recorded for the line M6-MW2-G70-01-14-1-2, with an average weight of 3.8 grams, ranging from 3.2 to 4.4 grams. In contrast, the lowest average 100-grain weight was observed in the line M6-MW2-G35-25-03-1-18, with an average of 2.9 grams and a range of 2.7 to 3.2 grams (Fig. 2). Masdar (2007) stated that the weight of seeds is influenced by the amount of dry matter contained within the seeds.

Fig. 2. Weight of 100 grains in Mentik Wangi M6 rice plants resulting from 200 Gray gamma ray irradiation

The F-test results at a 0.05 confidence level showed a value of 0.304. Based on this result, there was no significant effect between the lines and panicle length in relation to the 100-grain weight. However, Duncan's multiple range test (Table 3) indicated that the 100-grain weight of rice plants showed significant differences among the lines tested. This demonstrates that gamma irradiation at 200 gray and the individual lines tested had significantly different effects on the 100-grain weight.

The variation in the 100-grain weight is presumed to result from genetic changes in the mutated plants, which can exhibit distinct traits even within the same variety. This is consistent with the statement of Daeli et al. (2013), who noted that changes in genetic material can result in each plant possessing unique traits, even within the same species, thereby demonstrating phenotypic variability.

The average 100-grain weight of the control plants in the fifth generation (M5) was 1.91 grams. Gamma-ray irradiation treatment proved to be effective in influencing the 100-grain weight character in rice plants, resulting in higher weights compared to the control plants. This aligns with Sibarani & Hanafiah (2015), who reported that gamma irradiation has a positive effect, producing better 100-grain weights than the control. Dewi et al. (2014) stated that sunlight affects physiological processes related to seed production from the vegetative phase to the seed-filling phase. Additionally, Donggulo et al. (2017) emphasized that the photosynthesis process significantly influences the seed weight formed. Based on the 100-grain weight characteristic, lines M6-MW2-G70-01-14-1-2, M6-MW2-G35-25-01-7-38, M6-MW2-G70-01-14-1-18, and M6-MW2-G70-01-14-1-12 exhibited high 100-grain weights. These lines are expected to serve as a new source of genetic variation for further multilocation testing and potential release as new early-maturing varieties.

3.4 Grain weight per clump

Grain weight per clump refers to the total weight of grains produced by a single clump, including grains from both the main panicle and secondary panicles. Bahuguna et al. (2017) noted that grain weight is influenced by post-flowering conditions, this phase is crucial for grain filling, which directly determines grain weight, and in the context of the study, high night temperature (HNT) during the post-flowering phase increases night respiration (Rn), leading to greater carbon losses.. The results for grain weight per clump in the M6 generation of gamma-irradiated Mentik Wangi rice (200 Gy) are presented in Table 4.

Table 4. Grain weight per clump of Mentik Wangi Rice (M6) resulting from 200 Gy gamma-ray irradiation

No.	Line ID	Lowest (g)	Highest (g)	Range (g)	Average (g)	
1	M6-MW2-G01-02-17-14-10	51.3	74.6	51.3-74.6	68.5	a
2	M6-MW2-G35-25-01-7-19	50.0	78.1	50-78.1	66.4	ab
3	M6-MW2-G35-25-01-7-38	50.0	60.6	50-60.6	59.6	ab
4	M6-MW2-G35-25-03-1-18	48.3	61.5	48.3-61.5	59.7	ab
5	M6-MW2-G70-01-14-19-2	48.6	58.2	48.6-58.2	57.4	b
6	M6-MW2-G70-01-14-19-75	42.8	59.9	42.8-59.9	57.0	b
7	M6-MW2-G70-01-14-1-2	48.8	62.8	48.8-62.8	61.7	ab
8	M6-MW2-G70-01-14-1-12	51.6	69.1	51.6-69.1	66.2	ab
9	M6-MW2-G70-01-14-1-18	41.3	58.9	41.3-58.9	57.1	b
10	M6-MW2-G70-01-14-1-41	51.7	61.3	51.7-61.3	58.8	ab
11	M6-MW2-G70-01-14-4-8	48.9	66.2	48.9-66.2	65.1	ab
12	M6-MW2-G70-01-14-4-51	51.6	60.5	51.6-60.5	58.9	ab

Notes: Values followed by the same letter are not significantly different based on Duncan's Multiple Range Test at a 5% significance level

Based on the data presented in Table 4, the line with the highest grain weight per clump was M6-MW2-G35-25-01-7-19, with a grain weight of 78.1 grams. Conversely, the line with the lowest grain weight per clump was M6-MW2-G70-01-14-1-18, with a grain weight of

41.3 grams. Considering the average grain weight per clump, the highest value was observed in line M6-MW2-G01-02-17-14-10, with an average grain weight of 68.5 grams, ranging from 51.3 to 74.6 grams. In contrast, the lowest average grain weight per clump was found in line M6-MW2-G70-01-14-19-75, with an average weight of 57 grams, ranging from 42.8 to 59.9 grams. Makarim & Suhartatik (2009) suggested that the weight of 1,000 grains, considered to be "heavy" grain weight, typically ranges from 22.0 to 28.0 grams. Furthermore, they emphasized that heavier grain weights correspond to higher yields, while lighter grain weights are associated with lower yields in crops.

The F-test results at a 0.05 significance level indicated an F-value of 0.126. This result suggests that grain weight per clump did not show a significant effect of interaction between lines and panicle length. However, the results of Duncan's Multiple Range Test (Table 4) indicated significant differences in grain weight per clump among the tested lines. These findings demonstrate that the effect of 200 Gy gamma irradiation and the lines, when considered individually, had a significant impact on grain weight per clump. The variation in grain weight per clump reflects the yield potential of rice plants, which is influenced by the accumulation of dry matter during the photosynthesis process. This is consistent with the findings of Chen et al. (2018), who stated that the dry grain weight is indicative of the yield potential of rice crops.

The average weight of 100 grains from the control plants in the fifth generation (M5) was 23.080 grams. According to Kim & Lee (2023), elevated temperatures, especially during the reproductive growth stage, are linked to yield reductions caused by a decrease in both grain number and grain weight. Katsura et al. (2008) further emphasized that a well-executed panicle initiation process increases the likelihood of grain formation. Based on the grain weight per clump, the lines M6-MW2-G01-02-17-14-10, M6-MW2-G35-25-01-7-19, M6-MW2-G70-01-14-1-12, and M6-MW2-G70-01-14-4-8 exhibited high 100-grain weights. These lines are expected to serve as new sources of genetic variation and should be subjected to multilocation trials before being released as new rice varieties.

3.5 Productivity (Ton Ha^{-1})

Productivity is defined as the total grain yield per hectare, expressed in tons per hectare (Ton Ha^{-1}). The productivity of rice is determined by the interaction between genetic factors and environmental conditions. Key components influencing rice yield include the number of grains per panicle, the number of panicles per clump, the weight of 1,000 grains, and the percentage of filled grains (Ma'sum et al., 2016). Zhai et al. (2023) stated that *Oryza sativa* NIL-LVPA4LT exhibited a yield increase of 7.6% to 9.6%, primarily attributed to a significantly higher number of filled grains per panicle.. The results for productivity in the M6 generation of gamma-irradiated Mentik Wangi rice (200 Gy) are presented in Table 5.

Table 5. Productivity of Mentik Wangi rice (M6) resulting from 200 Gy gamma-ray irradiation

No.	Line ID	Productivity (Ton Ha^{-1})	
1	M6-MW2-G01-02-17-14-10	6.59	ab
2	M6-MW2-G35-25-01-7-19	6.82	ab
3	M6-MW2-G35-25-01-7-38	6.58	ab
4	M6-MW2-G35-25-03-1-18	6.30	ab
5	M6-MW2-G70-01-14-19-2	7.02	ab
6	M6-MW2-G70-01-14-19-75	6.81	ab
7	M6-MW2-G70-01-14-1-2	6.29	ab
8	M6-MW2-G70-01-14-1-12	6.57	a
9	M6-MW2-G70-01-14-1-18	6.27	a
10	M6-MW2-G70-01-14-1-41	6.62	ab
11	M6-MW2-G70-01-14-4-8	7.29	b
12	M6-MW2-G70-01-14-4-51	6.80	ab

Notes: Values followed by the same letter are not significantly different based on Duncan's Multiple Range Test at a 5% significance level

The line with the highest productivity was M6-MW2-G70-01-14-4-8, with an average of 7.29 Ton Ha^{-1}. The lowest productivity was observed in M6-MW2-G70-01-14-1-18, with an average of 6.27 Ton Ha^{-1}. All mutant lines demonstrated productivity levels exceeding the average productivity of existing rice varieties, which is typically 4 Ton Ha^{-1}.

The productivity of Mentik Wangi rice irradiated with 200 Gy gamma rays was influenced by the interaction of genetic traits with environmental conditions during the growth phases (Fig. 3). This is consistent with the findings of Fatimaturrahma et al. (2016), who stated that productivity variation among lines is influenced by the ability of plants to tolerate environmental conditions during their growth phases. Duncan's Multiple Range Test revealed significant differences among the lines, indicating the genetic potential of individual lines for productivity. The lines M6-MW2-G70-01-14-4-8, M6-MW2-G70-01-14-19-2, M6-MW2-G35-25-01-7-19, and M6-MW2-G70-01-14-4-51 demonstrated high productivity and are expected to serve as sources of genetic variation for further multilocation trials and potential release as high-yielding rice varieties.

Fig. 3. Productivity per clump of Mentik Wangi M6 rice plants irradiated with 200 gray gamma rays

The F-test results at a confidence level of 0.05 indicated a value of 0.439. Based on this value, the grain weight per clump showed no significant effect between lines and panicle length. However, the Duncan’s multiple range test (Table 5) revealed significant differences in grain weight per clump among the tested lines. This suggests that the effect of 200 Gray gamma irradiation and the lines individually exhibited significant differences in grain weight per clump.

The productivity of all mutant lines was categorized as high, as it exceeded the average production of the variety, which is 4 tons per hectare. The increase in rice plant productivity can be attributed to the generative phase occurring during the dry season in September. This aligns with Tu et al. (2022) statement that global warming significantly impacts rice development across various growth stages, leading to a decline in its quality. According to Oo et al. (2013), understanding the breeding for drought tolerance, priority should be given to selecting lines with superior tolerance rather than focusing solely on yield potential. This variation in productivity is likely due to genetic differences among the tested lines, which can lead to varying results. Based on productivity characteristics, the lines M6-MW2-G70-01-14-4-8, M6-MW2-G70-01-14-19-2, M6-MW2-G35-25-01-7-19, and M6-MW2-G70-01-14-4-51 demonstrated high productivity. These lines are expected to serve as a new source of genetic diversity, warranting further multilocation testing and potential release as new varieties.

The potential of gamm—ray irradiation in enhancing rice productivity is underscored by the genetic plasticity observed in this study. By targeting specific genetic mutations through 200 Gy gamma radiation, researchers created a diverse pool of rice lines with improved yield potential. The substantial increase in productivity compared to traditional varieties (from 4 to over 6 Ton Ha^{-1}) demonstrates the efficacy of mutation breeding techniques in developing resilient and high-yielding rice cultivars. This approach not only addresses food security challenges but also provides a promising pathway for developing rice varieties adaptable to varying environmental conditions.

3.6 Results of mutant line selection

Selection is a crucial process in plant breeding, involving the separation of individual plants or plant groups from a mixed population. The ultimate goal of plant breeding is to improve traits and enhance yield potential. According to Wirnas et al. (2006), positive correlation values and high heritability values of certain traits can be utilized in the selection process for yield potential, ensuring that these traits can be inherited by subsequent generations. The results of selection in the M6 generation of Mentik Wangi rice lines, derived from gamma irradiation at 200 Gray, are presented in Table 6.

Hamdan et al. (2024) states that mutation induction is a human-mediated approach to altering plant genetics, contributing to improved traits compared to the original genetic characteristics of the plant. The selection activities conducted aim to identify rice plants with higher yield potential. Plant selection is carried out to identify the best-performing plants based on the research objectives. The results of selecting M6 mutant Mentik Wangi rice lines irradiated with 200 Gy gamma rays, as shown in Table 6, indicate that the M6-MW2-G35-25-03-1-18, M6-MW2-G70-01-14-19-2, M6-MW2-G70-01-14-1-2, and M6-MW2-G70-01-14-1-18 lines were not among the selected M6 Mentik Wangi rice lines.

Table 6. Selected lines of Mentik Wangi rice (M6) resulting from 200 Gy gamma-ray irradiation

No	Line ID	Plant height (cm)	Harvest age (DAP)	Productivity (Ton Ha^{-1})
1	M6-MW2-G70-01-14-4-8	121.20	92.33	7.29
2	M6-MW2-G01-02-17-14-10	114.30	93.67	6.59
3	M6-MW2-G35-25-01-7-19	113.90	96.00	6.82
4	M6-MW2-G70-01-14-19-75	121.70	94.33	6.81
5	M6-MW2-G35-25-01-7-38	117.70	96.00	6.58
6	M6-MW2-G70-01-14-4-51	114.13	94.33	6.80
7	M6-MW2-G70-01-14-1-41	117.20	94.00	6.62
8	M6-MW2-G70-01-14-1-12	122.80	93.33	6.57
9	Control (*)	139.80	123.00	3.78

Notes: (*) Control (M5 generation) was planted during a different planting season (November 2018 to April 2019)

The breeding process to develop superior varieties involves several stages: the formation of a base population for material selection, the development of pure lines, selection, and yield testing. Phillips & Wolfe (2009) assert that selection involves the identification of the best individual plants based on desired traits. Selected plants exhibit better performance in observed variables compared to control plants (non-irradiated) as well as mutant plants from other lines.

Prabhandaru & Saputro (2017) stated that gamma rays at an appropriate dose exert beneficial effects in agriculture, such as inducing favorable traits like early maturity, resistance, and high productivity. According to Mangoendidjojo (2003), selection reduces heterogeneity and increases homogeneity, with high homogeneity indicating the culmination of the selection process. To achieve selection objectives and optimize the identification of one or more plant traits, it is essential to understand the relationships between agronomic traits, yield components, and overall yield. Selected mutant lines are those with superior characteristics compared to other mutant lines. The results of the M6 mutant selection showed plant heights ranging from 110.6 to 122.80 cm. The selected lines included M6-MW2-G70-01-14-4-8, M6-MW2-G01-02-17-14-10, M6-MW2-G35-25-01-7-19, M6-MW2-G70-01-14-19-75, M6-MW2-G35-25-01-7-38, M6-MW2-G70-01-14-4-51, M6-MW2-G70-01-14-1-41, and M6-MW2-G70-01-14-1-12.

4. Conclusions

Rice productivity in Indonesia remains a critical issue due to increasing population pressure and limited agricultural land. Traditional rice varieties like Mentik Wangi possess unique characteristics, including aromatic quality and soft texture, making them highly valued by consumers. However, their limitations necessitate advanced breeding strategies to ensure their sustainability in modern agricultural systems. The use of gamma irradiation in this study provided a novel approach to enhancing the genetic variability of Mentik Wangi rice, enabling the identification of lines with superior traits. The research findings demonstrated significant improvements in yield attributes among the 12 mutant lines evaluated. Key parameters such as plant height, flowering time, productive tillers, grains per panicle, and grain weight per clump showed positive responses to gamma irradiation. Notably, the line M6-MW2-G70-01-14-4-8 emerged as the most promising candidate, with a productivity of 7.29 tons/ha. This represents a substantial improvement compared to the control line, which yielded 3.78 tons/ha. The enhanced productivity of the mutant lines can be attributed to genetic modifications induced by gamma irradiation, which improved traits such as grain density, panicle length, and harvest index.

Future research should focus on conducting multilocation trials for the most promising mutant lines (M6-MW2-G70-01-14-4-8, M6-MW2-G70-01-14-19-2, M6-MW2-G35-25-01-7-19, and M6-MW2-G70-01-14-4-51) across different environmental conditions to validate their yield potential and stability. Researchers should systematically evaluate these lines for agronomic performance, disease resistance, grain quality, and adaptability to various climatic zones. Additionally, advanced molecular characterization techniques, such as genomic sequencing and marker-assisted selection, could be employed to further understand the genetic mechanisms.

Acknowledgement

The authors sincerely thank the Tegalgondo Rice Seed Garden for providing research facilities. Special appreciation goes to colleagues and advisors for their invaluable support.

Author Contribution

The study was conceptualized and designed collaboratively. Data collection, analysis, and interpretation were carried out jointly. Manuscript writing and revisions were conducted with equal contributions. All authors approved the final version.

Funding

This research received no external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

Not available.

Conflicts of Interest

The authors declare no conflict of interest.

Open Access

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