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Impact of gamma irradiation in different doses on earliness, morpho-physiological characteristics, and yield traits of diverse bread wheat genotypes

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MUTATION is a powerful tool for introducing novel variations into crop genomes and for directly developing high-yielding and well-adapted genotypes. This study aimed to assess the mutagenic effects of gamma irradiation applied in three doses (250 Gy, 350 Gy, and 450 Gy) on earliness traits, morpho-physiological characteristics, spike properties, and yield components of diverse bread wheat genotypes across the first (M1) and second (M2) mutant generations. Seeds of six wheat genotypes (Misr-2, Giza-171, Line-1, Line-3, Gemmeiza-12, and Shandweel-1) were exposed to four gamma irradiation doses. The results demonstrated that gamma irradiation at 250–450Gy caused delaying in earliness traits ranging from 0 to 14 days, depending on genotype and dose. Misr-2 exhibited the greatest delaying in heading in the M1 generation (up to 12 days at 250Gy), while Gemmeiza-12 showed 2.33-day advancement in the M2 generation under the same dose. Gamma irradiation generally promoted vegetative growth and prolonged the reproductive phases. In contrast, the grain filling period showed no significant change in M1 and was insignificantly shortened in M2. Significant genotypic variation was observed for earliness traits, with Misr-2 and Shandweel-1 being among the earliest and latest genotypes in terms of days to heading, flowering, and maturity. Gamma irradiation significantly influenced morpho-physiological traits, such as plant height, flag leaf area, chlorophyll content, and flag leaf efficiency. Gamma irradiation improved physiological characteristics associated with photosynthetic efficiency, such as increased flag leaf chlorophyll content and flag leaf efficiency, which contributed to improved grain yield performance. The results also showed significant effects on spike characteristics, specifically, the 250 Gy enhanced spike length, grain weight per spike, and the number of fertile spikelets, while higher doses reduced these traits. Regarding yield components, the 250 Gy dose significantly increased number of spikes per plant, grains per spike, 1000-grain weight, and grain yield per plant. Conversely, higher doses (350 and 450 Gy) caused a decline in these traits. Genotypic variation was observed in yield components, with Misr-2, Gemmeiza-12, and Shandweel-1 exhibiting superior performance in terms of grain yield. Moreover, the findings revealed significant associations between several characters and grain yield, providing key insights for optimizing wheat breeding programs under stress conditions. Overall, this study highlights the significant impact of gamma irradiation on the genetic makeup of wheat genotypes, influencing key agronomic traits and suggesting its potential use in wheat breeding to improve yield and stress resilience.

Keywords: Wheat, gamma irradiation, mutation breeding, genetic variability, yield traits.

Introduction

Wheat (*Triticum aestivum* L.) is one of the most widely cultivated cereals globally, serving as a staple food crop (Yuan and Sun 2022) . It accounts for a substantial portion of the world cereal production, with a total output of 798.98 million tons cultivated across 220.41 million hectares (FAOSTAT 2025). In Egypt, wheat is grown on approximately 1.35 million hectares, yielding an annual production of 9.70 million tons (FAOSTAT 2025). However, wheat production in Egypt remains insufficient to meet the country's consumption needs, necessitating the importation of more than 50% of the nation wheat requirements (Abdalla *et al.*, 2022). Therefore, increasing wheat

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production is essential to bridge the gap between supply and demand. This can be achieved by expanding the cultivated area and improving productivity per unit area (Gracia *et al.,* 2012, Zubair *et al.,* 2021).

In recent years, the accelerating challenges posed by climate change, including increasing temperatures, fluctuating precipitation patterns, and expanding areas of arid and semi-arid lands, have intensified the urgency to develop wheat genotypes with enhanced adaptability and resilience (Galal *et al.,* 2023, Ezzat *et al.,* 2024). These environmental stresses adversely affect wheat growth and yield, threatening food security, particularly in regions like Egypt that are highly dependent on wheat imports (Megahed *et al.,* 2022, Awaad *et al.,* 2023, Fazaa *et al.,* 2025). Consequently, breeding strategies must not only target higher yield potential but also improve physiological traits linked to stress tolerance, such as photosynthetic efficiency, early maturity, and spike development (Elgharbawy *et al.,* 2021, Kamara *et al.,* 2022).

Enhancing wheat production in Egypt continue to escalate as a topic of interest for agronomists and plant breeders (Mansour *et al.,* 2017, Abdelmageed *et al.,* 2019). One promising approach to achieving this goal from plant breeding perspective is mutation breeding. Mutation breeding can supplement existing germplasm and improve cultivars for specific traits (El-Degwy 2013, Mohanta *et al.,* 2025). Mutant plants, created through mutagenesis, are increasingly recognized for their potential to enhance crop varieties (Pandit *et al.,* 2021, Mohsen *et al.,* 2023). To date, wheat, a total of 276 mutant varieties have been released worldwide, with 195 developed using physical mutagens, such as gamma rays, 40 using chemical mutagens, and two using a combination of both (FAO/IAEA 2025). The widespread adoption of physical mutagens like gamma rays has contributed to the development of a significant number of mutant varieties, with over 64% of these mutants being generated through the application of physical mutagens (El-Degwy and Hathout 2014, Bharat *et al.,* 2024). Gamma rays have proven to be particularly effective in inducing biological, physiological, biochemical, and agronomic changes in plants, leading to improvements in yield and quality (Hamad *et al.,* 2022, Katiyar *et al.,* 2022).

Wheat is a polyploid plant; the doubling of its genes ensures that induced genetic changes are more likely to be preserved and passed on to future generations (Borisjuk *et al.,* 2019). The extent of genetic variation in quantitative traits, such as yield and other agronomic characteristics, is influenced by several factors, including the mutagenic agent used, the genotype, and the specific traits being investigated (Ponce-Molina *et al.,* 2012, Prasad *et al.,* 2024).

There remains limited comprehensive understanding of the precise effects of different gamma irradiation doses on the earliness, morpho-physiological traits, and yield components of diverse bread wheat genotypes, particularly under the environmental conditions of Egypt (Ahmed *et al.,* 2020). This study hypothesized that different doses of gamma irradiation could induce significant genetic variability in bread wheat genotypes, resulting in alterations in earliness, morphophysiological characteristics, and yield traits across generations. Therefore, the present study aimed to assess the mean performance of M1 and M2 generations in terms of earliness, morpho-physiological traits, spike characteristics, and yield components. Additionally, the effects of different gamma ray doses on the stimulation or reduction of these traits were evaluated. The relationships among traits were further examined using correlation and factor analyses.

Materials and Methods

Experimental site

Field experiments were conducted at a research field in Awlad Saqr Center, Sharkia Governorate, Egypt (30.93° N, 31.69° E) during the 2017/2018 and 2018/2019 growing seasons. The soil was predominantly sandy, with a sand content of 97.2%, 1.8% silt, and 1.0% clay. The climate of the experimental site exhibited average minimum temperatures ranging from 10.72°C (January) to 22.50°C (October) and an average maximum temperature of 34.81°C (February). Relative humidity (RH) varied from 60.90% (May) to 70.32% (February). RH varied from 60.90% in May to 70.32% in February. Overall, the climate at the experimental site showed mild to warm temperatures, with fluctuations in humidity and rainfall.

Plant material and field trials

Six bread wheat genotypes were used: four commercial cultivars (Misr-2, Gemmeiza-12, Giza-171, and Shandweel-1) and two promising lines (Line-1 and Line-3). The name and pedigree of each genotype are provided in Table S1. In the first season, wheat seeds were irradiated with 250, 350, and 450 Gy gamma rays, in addition to a control group. The seeds were irradiated with gamma rays from Cobalt-60 (60Co) at the Nuclear Research Center, Atomic Energy Authority, Inchas, Egypt, and were immediately sown in the field on November 25. Each seed was sown individually in rows 2 meters long and 20 cm apart, with a plant spacing of 10 cm. The experiment was implemented followed a factorial in a randomized complete block design in three replicates. For the second season, seeds from the M1 generation were sown on November 25 in plots to obtain the M2 generation. Each plot consisted of 5 rows, with each row being 2 meters in length and spaced 20 cm apart, and seeds were spaced 10 cm apart within each row.

Recorded traits

In both seasons, data were recorded on individual guarded plants to assess various traits for the studied generations, including earliness, morpho-physiological characteristics, spike characteristics, and yield and its components. The following parameters were measured: For earliness characteristics, data were collected on days to heading, days to flowering, days to maturity, and the grain filling period. For morpho-physiological characteristics, measurements included plant height (measured from the soil surface to the tip of the highest spike, excluding awns), flag leaf area (calculated using the formula: maximum length × maximum width × 0.72), flag leaf chlorophyll content (assessed using a SPAD-502 chlorophyll meter by Minolta Camera Co., Osaka, Japan). Flag leaf efficiency (g/cm^2) was calculated by dividing grain weight of the main stem (g) by flag leaf area (cm^2) then multiplied by 100. For spike characteristics, spike length (cm), the number of fertile and sterile spikelets per spike, and grain weight per spike (g) were recorded. Lastly, for yield and its components, the number of spikes per plant, the number of grains per spike, 1000-grain weight (g), and grain yield per plant (g/plant) were measured.

Statistical analysis

The data were statistically analyzed using GenStat version 18. The means were compared using the Least Significant Difference (LSD) test at the 5% level. Reduction or stimulation of the studied traits was estimated according to Rybinski *et al.*, (2003). Correlation was measured as the method described by Singh and Chaudhary (1985). Factor analysis was estimated according to and Walton (1972).

Results

Mean performance

Earliness characters

The performance of M1 and M2 generations for six bread wheat genotypes for earliness characteristics using different doses is presented in Table 1. Gamma irradiation doses resulted in significant delays for all studied earliness characteristics compared to the untreated control, except for the grain filling period, which was not statistically significant. In most cases, the grain filling period tended to shorten with increasing gamma irradiation doses. These results suggest that gamma irradiation significantly influenced the genetic makeup of wheat cultivars concerning earliness characters, with gamma rays promoting vegetative growth and cell elongation, thereby delaying heading, flowering, and maturity.

Additionally, significant differences were observed among wheat genotypes for earliness traits. In M1, the earliest and latest genotypes were Gemmeiza-12 (91.17 day) and Giza-171 (97.17 day) for days to heading; Gemmeiza-12 (99.67 day) and Giza-171 (107.9 day) for days to flowering; Gemmeiza-12 (148.58 day) and Line 3 (155.92 day) for days to maturity; Shandweel-1 (45.00 day) and Line-3 (51.42 day) for grain filling period (Table 1). These significant differences highlight the presence of considerable genetic variability among the wheat cultivars, which is valuable for further biometric assessments. Furthermore, significant differences were observed among wheat genotypes for earliness traits in M2. Misr-2 (91.25 days) was the earliest, while Giza-171 (94.50 days) was the latest for days to heading. Misr-2 (103.50 days) and Giza-171 (105.33 days) were the earliest and latest, respectively, for days to flowering. Misr-2 (147.17 days) and Line-3 (150.58 days) exhibited the earliest and latest days to maturity, while Shandweel-1 (43.67 days) and Line-3 (46.08 days) showed the shortest and longest grain filling periods, respectively. These significant differences suggest considerable genetic variability among wheat cultivars, providing valuable resources for further biometric assessments.

The interaction effect between gamma-ray dose and assessed genotypes was significant for all earliness characters. In M1, the best earliness values for days to heading (87.00 days), days to flowering (92.67 days), days to maturity (143.33 days) with control and Misr-2, as well as grain filling period (43.67 days) with 350 Gy and Shandweel-1. These findings indicated the impact of gamma irradiation on the behavior of wheat genotypes. In M2, the best earliness values were observed for days to heading (88.00 days) with control and Line-3, days to flowering (101.67 days) and days to maturity (146.33 days) with 250 Gy and Misr-2, and grain filling period (40.67 days) with control and Shandweel-1. This indicates that the performance of wheat genotypes was influenced by gamma irradiation.

Morpho-physiological characters

The mean performance of morpho-physiological characteristics, including plant height, flag leaf area, flag leaf chlorophyll content, and flag leaf efficiency, as influenced by gamma irradiation in the M1 and M2 generations for six bread wheat genotypes, is presented in Table 2. In M1, Line-3 and Line-1 exhibited the shortest plants, measuring 72.24 cm and 76.20 cm, respectively. For flag leaf area, Giza-171, Line-1, and Line-3 recorded the best values (36.77 cm², 35.27 cm², and 35.15 cm², respectively). Shandweel-1, Misr-2, and Line-1, and outperformed all other genotypes in flag leaf chlorophyll content (49.42, 47.75, and 47.28, respectively) and Misr-2, Gemmeiza-12, and Shandweel-1 had the highest flag leaf efficiency (5.44 g/cm², 5.17 g/cm², and 4.98 g/cm², respectively). Conversely, Gemmeiza-12 and Misr-2 produced the tallest plants (84.48 cm and 84.03 cm), while Misr-2 and Shandweel-1 had the smallest flag leaf area (29.81 cm² and 31.37 cm²), and Line-3 and Giza-171 recorded the lowest flag leaf chlorophyll content (44.82 and 46.15, respectively). These results indicate significant variation among wheat genotypes for morpho-physiological traits. In M2, Line-3 and Giza-171 exhibited the shortest plants (78.12 cm and 77.79 cm, respectively). Giza-171, Misr-2, and Line-1 displayed the largest flag leaf areas, with values of 33.65 cm², 33.45 cm², and 32.20 cm², respectively.

Misr-2, Gemmeiza-12, and Shandweel-1 had the highest flag leaf chlorophyll content (50.22, 47.77, and 47.46) and Gemmmeiza-12, Shandweel-1 and Misr-2 had the highest flag leaf efficiency (5.03 g/cm², 4.88 g/cm², 4.47 g/cm², respectively).

In contrast, Shandweel-1 and Misr-2 exhibited the tallest plants (82.53 cm and 82.70 cm), while Line-3 and Shandweel-1 had the smallest flag leaf areas (30.93 cm² and 31.32 cm²), and Line-3 and Giza-171 recorded the lowest flag leaf chlorophyll content (46.32 and 46.85, respectively).

Table 1. Mean performance of earliness characters in six bread wheat genotypes exposed to different gamma ray doses in M1 and M2 generations.

Genotypes	Control		250 Gy		350 Gy		450 Gy		Mean	
	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2
	Days to heading (days)									
Misr-2	87.00	89.00	99.33	89.00	94.33	92.33	96.33	94.67	94.25	91.25
Gemmeiza-12	87.33	92.33	92.67	90.00	90.00	92.67	94.67	92.00	91.17	91.75
Giza-171	93.00	91.67	94.00	92.67	100.00	97.00	101.67	96.67	97.17	94.50
Shandweel-1	90.67	90.00	94.67	89.33	98.00	92.00	98.67	94.33	95.50	91.42
Line-1	91.00	91.33	95.00	93.67	97.00	94.67	98.67	95.33	95.42	93.75
Line-3	92.67	88.00	94.67	90.00	97.67	92.67	98.67	94.67	95.92	91.33
Mean	90.27	90.39	95.05	90.78	96.16	93.56	98.11	94.61	94.90	92.33
$LSD_{0.05}$	M1	M2								
Genotypes (G)	1.67	1.34								
Treatments (T)	1.69	1.13								
GxT	4.14	2.78								
					Days to flowering (days)					
Misr-2	92.67	103.33	99.00	101.67	103.00	105.67	105.33	103.33	100.00	103.50
Gemmeiza-12	95.00	105.67	99.67	105.33	100.00	104.67	104.00	102.33	99.67	104.50
Giza-171	102.00	105.33	104.00	104.00	109.67	106.00	112.67	106.00	107.09	105.33
Shandweel-1	101.00	104.67	103.67	103.33	108.33	106.33	109.33	104.00	105.58	104.58
Line-1	102.67	107.00	106.33	106.00	107.67	102.33	110.00	103.00	106.67	104.58
Line-3	100.67	105.00	102.33	102.67	106.00	104.33	109.00	106.33	104.50	104.60
Mean	99.00	105.17	102.50	103.83	105.77	104.89	108.38	104.17	103.91	104.51
$LSD_{0.05}$	M1	M2								
Genotypes (G)	2.15	1.61								
Treatments (T)	0.89	1.31								
GxT	2.17	3.21								
					Days to maturity (days)					
Misr-2	143.33	148.33	147.67	146.33	150.67	147.00	155.00	147.00	149.17	147.17
Gemmeiza-12	143.67	151.67	147.33	150.67	150.00	148.67	153.33	147.33	148.58	149.58
Giza-171	150.00	148.67	152.00	146.67	156.67	150.33	160.67	151.33	154.84	149.25
Shandweel-1	147.33	149.00	149.33	147.00	152.00	151.67	153.67	148.33	150.58	149.00
Line-1	150.00	151.33	153.67	152.00	155.33	148.33	155.33	146.67	153.58	149.85
Line-3	153.00	151.00	154.67	147.67	157.33	150.00	158.67	153.67	155.92	150.58
Mean	147.88	150.00	150.77	148.39	153.66	149.33	156.11	149.06	152.11	149.19
$LSD_{0.05}$	M1	M2								
Genotypes (G)	2.71	1.61								
Treatments (T)	4.14	1.31								
GxT	5.49	3.22								
					Grain filling period (days)					
Misr-2	50.67	44.67	48.67	44.00	47.67	43.00	49.67	44.67	49.17	44.08
Gemmeiza-12	48.67	44.67	47.67	42.00	50.00	43.00	49.33	45.67	48.92	43.83
Giza-171	48.00	41.33	48.00	41.33	47.00	45.00	48.00	47.67	47.75	43.83
Shandweel-1	46.33	40.67	45.67	43.33	43.67	45.67	44.33	45.00	45.00	43.67
Line-1	47.33	43.67	47.33	44.33	47.67	45.33	45.33	45.33	46.92	44.67
Line-3	52.33	42.67	52.33	46.33	51.33	46.67	49.67	48.67	51.42	46.08
Mean	48.88	42.94	48.27	43.56	47.89	44.78	47.72	46.17	48.19	48.36
$LSD_{0.05}$	M1	M2								
Genotypes (G)	1.97	1.70								
Treatments (T)	1.67	1.40								

LSD (Least Significant Difference) values indicate the minimum difference required between means to be considered statistically significant at the specified probability level. Means differing by more than the LSD value are significantly different.

The interaction effect between gamma-ray dose and cultivar was significant for morpho-physiological characters. In M1, the best results for short plants (70.41 cm) were observed for Line-3 under the 350 Gy dose, while the highest values of flag leaf chlorophyll content (51.17) were recorded at 450 Gy with Shandweel-1. For flag leaf area (40.59 cm²), the best results were obtained at control with Line-3, and for flag leaf efficiency (6.11 g/cm²), the highest value was recorded at 250 Gy with Misr-2. These findings emphasize that gamma irradiation doses influenced the morpho-physiological traits of wheat genotypes. In M2, the best results for short plants (73.43 cm) were obtained with 450 Gy and Giza-171, while the highest flag leaf chlorophyll content (50.95) was recorded at 450 Gy with Gemmeiza-12.

The highest values for flag leaf area (39.22 cm²) and flag leaf efficiency (5.62 g/cm²) were observed at control and 250 Gy with Misr-2 and Gemmeiza-12, respectively.

Table 2. Mean performance of the morpho-physiological characters in six bread wheat genotypes exposed to different gamma ray doses in M1 and M2 generations.

Genotypes	Control		250 Gy		350 Gy		450 Gy		Mean	
	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2
					Plant height (cm)					
Misr-2	85.13	83.18	85.57	83.07	82.63	82.69	82.80	81.85	84.03	82.70
Gemmeiza-12	84.67	78.20	84.40	75.90	84.83	85.65	84.00	84.83	84.48	81.14
Giza-171	81.63	79.72	83.57	80.06	80.67	77.94	76.70	73.43	80.64	77.79
Shandweel-1	78.90	82.83	80.67	84.51	79.87	81.41	76.73	81.35	79.04	82.53
Line-1	77.17	75.57	77.80	73.69	74.27	83.30	75.57	81.41	76.20	78.49
Line-3	72.81	81.23	74.13	79.81	70.41	75.84	71.60	75.62	72.24	78.12
Mean	80.05	80.12	81.02	79.50	78.78	81.14	77.90	79.75	79.44	80.13
$LSD_{0.05}$	M1	M2								
Genotype (G)	2.21	2.42								
Treatment (T)	1.96	1.98								
G×T	4.79	4.85								
					Flag leaf chlorophyll content					
Misr-2	47.84	50.05	45.34	50.63	49.19	49.87	48.61	50.33	47.75	50.22
Gemmeiza-12	46.98	48.32	48.26	45.64	45.44	46.18	48.07	50.95	47.19	47.77
Giza-171	43.62	47.08	43.93	47.18	47.96	47.62	49.07	45.52	46.15	46.85
Shandweel-1	47.77	47.60	50.58	48.84	48.16	47.08	51.17	46.33	49.42	47.46
Line-1	47.70	47.24	46.26	45.45	47.07	46.57	48.08	48.73	47.28	47.00
Line-3	42.32	45.66	47.14	48.25	42.80	46.90	47.00	44.47	44.82	46.32
Mean	46.03	47.66	46.91	47.66	46.77	47.37	48.61	47.72	47.09	47.60
$LSD_{0.05}$	M1	M2								
Genotype (G)	2.10	2.07								
Treatment (T)	1.48	1.69								
G×T	3.35	4.14								
					Flag leaf area (cm^2)					
Misr-2	30.61	39.22	28.23	33.65	30.49	31.26	29.91	29.67	29.81	33.45
Gemmeiza-12	31.61	31.84	32.17	26.92	35.04	36.66	28.15	31.60	31.74	31.75
Giza-171	40.53	35.04	31.12	29.44	37.41	35.90	38.02	34.22	36.77	33.65
Shandweel-1	39.06	36.62	33.67	31.33	28.05	29.55	24.68	27.77	31.37	31.32
Line-1	38.13	32.62	37.30	25.99	32.84	37.20	32.81	32.98	35.27	32.20
Line-3	40.59	32.62	36.35	25.99	31.76	37.20	31.88	32.98	35.15	30.93
Mean	36.75	33.31	33.14	28.89	32.59	34.63	30.90	27.09	33.35	32.22
$LSD_{0.05}$	M1	M2								
Genotype (G)	3.50	2.88								
Treatment (T)	3.35	2.35								
G×T	8.19	5.77								
					Flag leaf efficiency (g/cm^2)					
Misr-2	5.49	4.21	6.11	4.84	5.30	5.11	4.86	5.35	5.44	4.88
Gemmeiza-12	5.00	4.63	5.41	5.62	4.91	4.29	5.36	4.95	5.17	4.87
Giza-171	3.65	4.27	5.07	5.09	3.81	3.94	3.62	4.07	4.04	4.34
Shandweel-1	3.80	4.21	4.89	4.97	5.42	5.56	5.80	5.39	4.98	5.03
Line-1	3.68	4.39	4.06	5.24	4.07	4.16	3.98	4.53	3.95	4.58
Line-3	3.45	4.57	4.01	5.24	4.73	3.74	4.27	5.00	4.12	4.64
Mean	4.17	4.38	4.93	5.17	4.70	4.47	4.64	4.88	4.61	4.72
$LSD_{0.05}$	M1	M2								
Genotype (G)	0.58	0.50								
Treatment (T)	0.58	0.41								
G×T	1.43	1.01								

LSD (Least Significant Difference) values indicate the minimum difference required between means to be considered statistically significant at the specified probability level. Means differing by more than the LSD value are significantly different.

Spike characteristics

The mean performance of spike characteristics, such as spike length, grain weight per spike, number of fertile spikelets per spike, and number of sterile spikelets per spike, as affected by gamma irradiation in the M1 and M2 generations for six bread wheat genotypes, is presented in Table 3. Gamma irradiation treatments significantly affected spike characteristics. The 250 Gy dose resulted in an increase in spike length, grain weight per spike, and the number of fertile spikelets per spike compared to the control, while these traits decreased with higher gamma irradiation doses (350 and 450 Gy). In M1, the mean performance for spike length was 10.80 cm, 10.31 cm, and 8.95 cm for 250, 350, and 450 Gy, respectively, compared to 10.34 cm for the control. For grain weight per spike, the values were 1.53 g, 1.46 g, and 1.35 g for 250, 350, and 450 Gy, respectively, compared to 1.49 g for the control. Similarly, the number of fertile spikelets per spike increased under the 250 Gy dose (15.80) but decreased under higher doses (14.43 and 12.18 for 350 and 450 Gy, respectively). In contrast, the number of sterile spikelets per spike decreased under the 250 Gy dose but increased with higher doses (3.50, 3.96, and 4.89 for 250, 350, and 450 Gy, respectively, compared to 3.64 for the control). In M2, the mean performance for spike length was 10.88 cm, 10.44 cm, and 9.33 cm for 250, 350, and 450 Gy, respectively, compared to 9.92 cm for the control. Similarly, the number of sterile spikelets per spike increased with higher doses (350 and 450 Gy), with mean values of 3.97, and 4.27, compared to 3.67 for the control. In contrast, a decrease in the number of fertile spikelets per spike and grain weight per spike was detected as the gamma-ray dose increased. The mean values for the number of fertile spikelets were 14.25, 14.86, and 14.35 under 250, 350, and 450 Gy, respectively, compared to 15.23 for the control. For grain weight per spike, the values were 1.49 g, 1.50 g, and 1.47 g for 250, 350, and 450 Gy, respectively, compared to 1.51 g for the control. These findings indicate that gamma irradiation doses had a significant impact on spike characteristics in wheat genotypes.

In M1, Gemmeiza-12, Giza-171, and Shandweel-1 exhibited superior spike lengths, with mean values of 11.54 cm, 10.66 cm, and 11.07 cm, respectively. Misr-2, Gemmeiza-12, and Shandweel-1 were the best performers in grain weight per spike (1.61 g, 1.55 g, and 1.47 g, respectively) and the number of fertile spikelets per spike (16.51, 15.4, and 14.94, respectively). Conversely, Line-3 showed the shortest spike length (8.60 cm), the lightest grain weight per spike (1.33 g), the lowest number of fertile spikelets per spike (12.06), and the highest number of sterile spikelets per spike (4.59). Likewise, in M2, significant differences were observed among wheat genotypes for spike characteristics. Gemmeiza-12, Giza-171, and Shandweel-1 exhibited the longest spikes, with mean values of 11.57 cm, 10.90 cm, and 11.20 cm, respectively. Misr-2, Gemmeiza-12, and Shandweel-1 outperformed other genotypes in grain weight per spike and the number of fertile spikelets per spike, with values of 1.60 g, 1.51 g, and 1.55 g for grain weight, and 15.56, 15.07, and 14.87 for fertile spikelets per spike, respectively. Line-3 exhibited the shortest spike length (8.59 cm), the lightest grain weight per spike (1.40 g), the lowest number of fertile spikelets per spike (14.0), and the highest number of sterile spikelets per spike (4.26).

The interaction effect between gamma-ray dose and cultivar was significant for spike characteristics. In M1, the best results for spike length (12.67 cm) were obtained for Gemmeiza-12 under the 350 Gy dose. The highest grain weight per spike (1.69 g) and the number of fertile spikelets per spike (17.78) were recorded under the 250 Gy dose with Misr-2. In contrast, the lowest number of sterile spikelets per spike (2.83) was recorded under the 250 Gy dose with Gemmeiza-12. In M2, the highest spike length (12.70 cm) was recorded under the 350 Gy dose with Gemmeiza-12, while the highest grain weight per spike (1.65 g) was observed at the control with Misr-2. The highest number of fertile spikelets per spike (17.17) was recorded under control with Misr-2, and the lowest number of sterile spikelets per spike (2.70) was recorded under control with Shandweel-1

Table 3. Mean performance of spike characteristics in six bread wheat genotypes exposed to different gamma ray doses in M1 and M2 generations.

Genotypes	Control		250 Gy		350 Gy		450 Gy		Mean	
	M1	**M2**	**M1**	**M2**	**M1**	**M2**	**M1**	**M2**	**M1**	**M2**
Spike length (cm)										
Misr-2	10.20	7.22	10.68	10.86	9.70	10.00	9.00	9.40	9.90	9.37
Gemmeiza-12	11.10	10.98	11.78	11.78	12.67	12.70	10.60	10.80	11.54	11.57
Giza-171	11.40	11.58	11.75	11.99	10.27	10.20	9.23	9.83	10.66	10.90
Shandweel-1	10.80	10.90	12.27	12.28	12.03	12.05	9.16	9.55	11.07	11.20
Line-1	9.25	9.60	9.67	9.80	8.47	9.00	7.97	8.53	8.84	9.23
Line-3	9.30	9.25	8.65	8.54	8.73	8.70	7.73	7.86	8.60	8.59
Mean	10.34	9.92	10.80	10.88	10.31	10.44	8.95	9.33	10.10	10.14
$LSD_{0.05}$	M1	M2								
Genotype (G)	0.38	0.73								
Treatment (T)	0.40	0.60								
G×T	0.98	1.46								
Grain weight/spike (g)										
Misr-2	1.68	1.65	1.69	1.62	1.61	1.58	1.44	1.56	1.61	1.60
Gemmeiza-12	1.58	1.47	1.64	1.45	1.58	1.57	1.41	1.56	1.55	1.51
Giza-171	1.49	1.47	1.56	1.47	1.43	1.41	1.37	1.39	1.46	1.44
Shandweel-1	1.47	1.54	1.56	1.55	1.50	1.62	1.36	1.46	1.47	1.55
Line-1	1.38	1.43	1.38	1.36	1.31	1.55	1.24	1.49	1.33	1.46
Line-3	1.37	1.50	1.38	1.51	1.33	1.28	1.30	1.32	1.35	1.40
Mean	1.49	1.51	1.53	1.49	1.46	1.50	1.35	1.47	1.46	1.49
$LSD_{0.05}$	M1	M2								
Genotype (G)	0.07	0.07								
Treatment (T)	0.05	0.06								
G×T	0.13	0.15								
Number of fertile spikelets/spike										
Misr-2	17.63	17.17	17.78	16.02	16.80	13.56	13.83	15.51	16.51	15.56
Gemmeiza-12	16.00	15.00	16.87	13.14	15.40	16.57	13.33	15.57	15.40	15.07
Giza-171	14.10	13.78	14.33	15.00	12.67	14.69	11.47	12.52	13.14	14.00
Shandweel-1	15.53	16.33	16.26	15.20	15.54	13.27	12.43	14.66	14.94	14.87
Line-1	15.53	15.61	15.98	10.75	14.71	16.27	12.33	15.55	14.64	14.54
Line-3	13.40	13.50	13.60	15.40	11.50	14.79	9.73	12.31	12.06	14.00
Mean	15.36	15.23	15.80	14.25	14.43	14.86	12.18	14.35	14.44	14.67
$LSD_{0.05}$	M1	M2								
Genotype (G)	0.86	1.03								
Treatment (T)	0.69	0.84								
G×T	1.69	2.06								
Number of sterile spikelets/ spike										
Misr-2	3.27	3.27	2.70	2.87	3.27	4.10	4.63	4.36	3.47	3.65
Gemmeiza-12	3.27	3.88	2.83	3.83	3.20	3.24	4.14	3.73	3.36	3.67
Giza-171	3.57	3.90	3.47	3.83	3.92	4.61	4.77	4.71	3.93	4.26
Shandweel-1	4.33	2.70	4.21	3.69	4.20	4.10	5.13	4.63	4.47	3.78
Line-1	3.41	4.70	3.87	4.70	4.33	3.28	5.20	3.82	4.20	4.13
Line-3	4.00	3.57	4.03	4.18	4.87	4.47	5.47	4.40	4.59	4.16
Mean	3.64	3.67	3.50	3.85	3.96	3.97	4.89	4.27	4.00	3.94
$LSD_{0.05}$	M1	M2								
Genotype (G)	0.40	0.46								
Treatment (T)	0.34	0.38								
G×T	0.84	0.92								

LSD (Least Significant Difference) values indicate the minimum difference required between means to be considered statistically significant at the specified probability level. Means differing by more than the LSD value are significantly different.

Grain yield and its components

The mean performance of yield and its components, number of spikes per plant, number of grains per spike, 1000-grain weight, and grain yield per plant under the influence of gamma irradiation in the M1 and M2 generations for six bread wheat genotypes is shown in Table 4. Gamma irradiation treatments resulted in significant differences in yield and its components. In M1, a significant increase in the number of spikes per plant, number of grains per spike, 1000-grain weight, and grain yield per plant was observed under the 250 Gy dose compared to the control. However, these traits decreased when the gamma-ray dose increased from 350 to 450 Gy. Specifically, the mean values were as follows: number of spikes per plant: 8.13, 7.34, 6.26, and 7.96 for 250, 350, 450 Gy, and control, respectively; number of grains per spike: 51.93, 49.03, 41.73, and 50.52; 1000-grain weight: 41.69 g, 40.0 g, 35.71 g, and 40.47 g; and grain yield per plant: 12.19 g, 11.54 g, 9.88 g, and 11.44 g under 250, 350, 450 Gy, and control, respectively. Interestingly, gamma irradiation significantly affected all yield and its components in all cases (Table 4). Similarly, in M2, a significant increase in the number of spikes per plant and the number of grains per spike was observed under the 250 Gy dose of gamma irradiation, whereas the 350 Gy dose resulted in higher 1000-grain weight and grain yield per plant compared to the control. However, when the gamma-ray dose increased from 350 to 450 Gy, these characters declined. Specifically, the mean values were as follows: number of spikes per plant: 8.23, 7.67, 6.81, and 8.05 for 250, 350, 450 Gy, and control, respectively; number of grains per spike: 51.82, 49.94, 43.07, and 50.74; 1000-grain weight: 39.86 g, 40.36 g, 39.70 g, and 41.28 g; and grain yield per plant: 11.10 g, 12.03 g, 10.96 g, and 11.49 g for the respective treatments. These results emphasize the significant impact of gamma irradiation doses on the performance of wheat genotypes with respect to yield and its components.

In M1, Misr-2, Gemmeiza-12, and Shandweel-1 excelled in both the number of spikes per plant and grain yield per plant. The mean values for number of spikes per plant were 9.054, 7.84, and 7.21, while the mean grain yield per plant was 12.54 g, 12.40 g, and 11.53 g, respectively. Misr-2, Gemmeiza-12, and Giza-171 also outperformed other genotypes in terms of number of grains per spike and 1000-grain weight, with values of 53.70, 53.41, and 48.0 for grains per spike, and 45.58 g, 42.28 g, and 38.96 g for 1000-grain weight, respectively. In contrast, Line-3 recorded the lowest number of spikes per plant (6.57), Line-1 had the lightest 1000-grain weight (34.99 g), and Line-3 showed the lowest number of grains per spike (42.54) and grain yield per plant (10.22 g). In M2, Misr-2, Gemmeiza-12, and Shandweel-1 excelled in both the number of spikes per plant and grain yield per plant. The mean values for number of spikes per plant were 9.29, 8.35, and 7.39, while the mean grain yield per plant was 13.47 g, 11.97 g, and 11.67 g, respectively. Misr-2, Gemmeiza-12, and Giza-171 also performed best in the number of grains per spike, with values of 54.97, 53.81, and 49.30 for grains per spike. Misr-2, Gemmeiza-12, and Shandweel-1 also performed best in1000-grain weight with values 43.28 g, 40.65 g, and 42.09 g, respectively. In contrast, Line-3 recorded the lowest number of spikes per plant (6.68), the lowest grain weight per spike (42.39 g), the lightest 1000-grain weight (37.38 g), and the lowest grain yield per plant (10.07 g).

The interaction between gamma-ray dose and cultivar was significant for yield characters. In M1, the highest values were recorded for number of spikes per plant (9.67), number of grains per spike (59.93), 1000-grain weight (51.3 g), and grain yield per plant (13.87 g) at 250 Gy with Misr-2. These findings confirm that the mean performance of wheat genotypes was influenced by gamma irradiation. In M2, the highest values for number of spikes per plant (9.80) and number of grains per spike (59.41) were recorded at 250 Gy with Misr-2, while the highest 1000-grain weight (48.83 g) and grain yield per plant (15.37 g) were observed under the control with Misr-2.

Table 4. Mean performance of grain yield and its components in six bread wheat genotypes exposed to different gamma ray doses in M1 and M2 generations.

Genotypes	Control		250 Gy		350 Gy		450 Gy		Mean	
	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2
Number of spikes/plant										
Misr-2	9.53	9.56	9.67	9.80	9.11	9.36	7.87	8.43	9.05	9.29
Gemmeiza-12	8.57	9.01	8.97	9.05	7.17	8.07	6.63	7.25	7.84	8.35
Giza-171	7.43	7.48	7.8	8.21	6.87	7.17	5.43	6.03	6.88	7.23
Shandweel-1	7.63	7.6	7.93	7.73	7.33	7.57	5.93	6.67	7.21	7.39
Line-1	7.73	7.93	7.47	7.43	7.03	7.30	5.83	6.27	7.02	7.23
Line-3	6.87	6.74	6.93	7.17	6.57	6.57	5.9	6.23	6.57	6.68
Mean	7.96	8.05	8.13	8.23	7.34	7.67	6.26	6.81	7.42	7.69
$LSD_{0.05}$	M1	M2								
Genotype (G)	0.53	0.54								
Treatment (T)	0.42	0.44								
G×T	1.02	1.07								
Number of grains/spike										
Misr-2	56.67	58.59	59.93	59.41	55.65	56.64	42.53	45.25	53.7	54.97
Gemmeiza-12	52.23	52.96	57.07	56.93	55.93	57.22	48.39	48.11	53.41	53.81
Giza-171	51.33	51.03	52.30	52.04	47.07	49.47	41.30	44.65	48.00	49.30
Shandweel-1	49.44	50.59	49.90	51.37	49.31	50.00	42.03	44.45	47.67	49.10
Line-1	48.00	46.25	47.28	46.17	44.87	44.95	37.93	37.75	44.52	43.78
Line-3	45.47	45.03	45.13	44.99	41.37	41.37	38.2	38.18	42.54	42.39
Mean	50.52	50.74	51.93	51.82	49.03	49.94	41.73	43.07	48.3	48.89
$LSD_{0.05}$	M1	M2								
Genotype (G)	3.00	3.58								
Treatment (T)	2.34	2.92								
G×T	5.73	7.16								
1000-grain weight (g)										
Misr-2	45.80	48.83	51.3	44.25	47.65	39.12	37.57	40.9	45.58	43.28
Gemmeiza-12	41.50	36.06	45.23	38.24	43.07	46.61	39.3	41.71	42.28	40.65
Giza-171	41.07	40.46	39.92	38.52	38.42	35.01	36.43	38.39	38.96	38.1
Shandweel-1	39.10	46.57	39.87	43.89	39.47	39.97	36.1	37.93	38.64	42.09
Line-1	37.43	36.61	36	35.55	34.77	45.83	31.74	43.15	34.99	40.29
Line-3	37.97	39.13	37.83	38.68	36.65	35.64	33.17	36.09	36.41	37.38
Mean	40.47	41.28	41.69	39.86	40	40.36	35.71	39.7	39.47	40.3
$LSD_{0.05}$	M1	M2								
Genotype (G)	1.54	2.11								
Treatment (T)	1.24	1.72								
G×T	3.03	4.21								
Grain yield/ plant (g)										
Misr-2	12.80	15.37	13.87	14.68	12.70	12.29	10.8	11.52	12.54	13.47
Gemmeiza-12	12.27	11.01	13.67	9.74	13.31	14.44	10.33	12.69	12.40	11.97
Giza-171	10.27	10.39	11.73	11.06	10.80	10.34	9.91	9.25	10.68	10.26
Shandweel-1	11.96	11.76	12.55	11.91	11.84	12.02	9.77	11.01	11.53	11.67
Line-1	10.73	9.49	10.74	9.06	10.25	12.76	9.18	12.40	10.23	10.93
Line-3	10.64	10.90	10.60	10.13	10.34	10.36	9.30	8.90	10.22	10.07
Mean	11.44	11.49	12.19	11.10	11.54	12.03	9.88	10.96	11.26	11.39
$LSD_{0.05}$	M1	M2								
Genotype (G)	0.58	1.32								
Treatment (T)	0.51	1.08								
G×T	1.24	2.63								

LSD (Least Significant Difference) values indicate the minimum difference required between means to be considered statistically significant at the specified probability level. Means differing by more than the LSD value are significantly different.

Table 5. Reduction (negative values) or stimulation (positive values) of earliness characters for six bread wheat genotypes as influenced by gamma ray in M1 and M2 generations.

Genotypes	Cont. versus 250 Gy		Cont. versus 350 Gy		Cont. versus 450 Gy	
	M1	**M2**	**M1**	**M2**	**M1**	**M2**
Days to heading (days)						
Misr-2	14.17	0.00	8.42	3.74	10.72	6.37
Gemmeiza-12	6.11	-2.52	3.05	0.37	8.40	-0.36
Giza-171	1.07	1.09	7.52	5.81	9.32	5.45
Shandweel-1	4.41	-0.74	8.08	2.22	8.82	4.81
Line-1	4.39	2.56	6.59	3.66	8.42	4.38
Line-3	2.15	2.27	5.39	5.31	6.47	7.58
Days to flowering (days)						
Misr-2	6.83	-1.61	11.14	2.26	13.66	0.00
Gemmeiza-12	4.91	-0.32	5.26	-0.95	9.47	-3.16
Giza-171	1.96	-1.26	7.51	0.64	10.46	0.64
Shandweel-1	2.64	-1.28	7.25	1.59	8.24	-0.64
Line-1	3.56	-0.93	4.86	-4.36	7.13	-3.74
Line-3	1.64	-2.22	5.29	-0.64	8.27	1.27
Days to maturity (days)						
Misr-2	3.02	-1.35	5.12	-0.90	8.14	-0.90
Gemmeiza-12	2.54	-0.66	4.40	-1.98	6.72	-2.86
Giza-171	1.33	-1.35	4.44	1.12	7.11	1.79
Shandweel-1	1.35	-1.34	3.16	1.79	4.30	-0.45
Line-1	2.44	0.44	3.55	-1.98	3.55	-3.08
Line-3	1.09	-2.21	2.83	-0.66	3.70	1.77
Grain filling period (days)						
Misr-2	-3.94	-1.50	-5.92	-3.74	-1.97	0.00
Gemmeiza-12	-2.05	-5.98	2.73	-3.74	1.35	2.24
Giza-171	0.00	0.00	-2.08	8.88	0.00	15.34
Shandweel-1	-1.42	6.54	-5.74	12.29	-4.31	10.65
Line-1	0.00	1.51	0.71	3.80	-4.22	3.80
Line-3	0.00	8.58	-1.91	9.37	-5.08	14.06

Reduction or stimulation of studied traits

Earliness characters

The reduction or stimulation of earliness characters in M1 and M2 generations, expressed as a percentage of the control value relative to the gamma irradiation doses, is summarized in Table 5. The results of M1 showed that the maximum stimulation levels for earliness characters were +14.17% (control vs. 250 Gy for Misr-2) for days to heading, +13.66% (control vs. 450 Gy for Misr-2) for days to flowering, and +8.14% (control vs. 450 Gy for Misr-2) for days to maturity. In contrast, the minimum stimulation levels were +1.07% (control vs. 250 Gy for Giza-171) for days to heading, +1.64% (control vs. 250 Gy for Line-3) for days to flowering, +1.09% (control vs. 250 Gy for Line-3) for days to maturity, and +1.35% (control vs. 450 Gy for Gemmeiza-12) for grain filling period. The maximum stimulation for a shortened grain filling period was -5.92% (control vs. 350 Gy for Misr-2), while the largest delay was +2.73% (control vs. 350 Gy for Gemmeiza-12). In M2, the maximum stimulation levels towards earliness were -2.52% (control vs. 250 Gy for Gemmeiza-12) for days to heading, -4.36% (control vs. 350 Gy for Line-1) for days to flowering, -3.08% (control vs. 450 Gy for Line-1) for days to maturity, and -5.98% (control vs. 250 Gy for Gemmeiza-12) for grain filling period .

Morpho-physiological characters

The results of M1 showed that the maximum desirable stimulation for plant height was +2.37% (control vs. 250 Gy for Giza-171), while the shortest plant height was observed at -6.03% (control vs. 450 Gy for Giza-171) (Table 6). This reduction in plant height is important for improving lodging resistance in wheat breeding programs, as shorter plants tend to be more resistant to lodging. Similarly, gamma irradiation led to significant increases in flag leaf area (+10.85% at 350 Gy for Gemmeiza-12), flag leaf chlorophyll content (+12.49% at 450 Gy for Giza-171), and flag leaf efficiency (+52.63% at 450 Gy for Shandweel-1). These traits play a crucial role in photosynthetic efficiency and grain yield. In M2, the maximum stimulation for plant height was +10.23% (control vs. 350 Gy for Line-1), while maximum decrease observed at -7.89% (control vs. 450 Gy for Giza-171). The increase in plant height due to gamma irradiation is associated with enhanced gibberellic acid secretion, promoting shoot growth. Additionally, the highest stimulation was observed for flag leaf chlorophyll content (+5.67% at 250 Gy for Line-3) and flag leaf efficiency (+32.07% at 350 Gy for Shandweel-1), emphasizing the impact of gamma irradiation on photosynthesis and grain yiel

Table 6. Reduction (negative values) or stimulation (positive values) of morpho-physiological characters for six bread wheat genotypes as influenced by gamma ray in M1 and M2 generations.

Genotypes	Cont. versus 250 Gy		Cont. versus 350 Gy		Cont. versus 450 Gy	
	M1	M2	M1	M2	M1	M2
			Plant height (cm)			
Misr-2	0.51	-0.13	-2.93	-0.59	-2.73	-1.60
Gemmeiza-12	-0.31	-2.94	0.18	9.53	-0.79	8.48
Giza-171	2.37	0.43	-1.17	-2.23	-6.03	-7.89
Shandweel-1	2.24	2.03	1.22	-1.71	-2.75	-1.79
Line-1	0.81	-2.49	-3.75	10.23	-2.07	7.73
Line-3	1.81	-1.75	-3.29	-6.64	-1.66	-6.91
			Flag leaf chlorophyll content			
Misr-2	-5.22	1.16	2.82	-0.36	1.60	0.56
Gemmeiza-12	2.72	-5.55	-3.27	-4.43	2.32	5.44
Giza-171	0.71	0.21	9.94	1.15	12.49	-3.31
Shandweel-1	5.88	2.61	0.81	-1.09	7.11	-2.67
Line-1	-3.01	-3.79	-1.32	-1.42	0.79	3.15
Line-3	11.38	5.67	1.13	2.72	11.05	-2.61
			Flag leaf area (cm^2)			
Misr-2	-7.78	-14.20	-0.39	-20.30	-2.29	-24.35
Gemmeiza-12	1.77	-15.45	10.85	15.14	-10.95	-0.75
Giza-171	-23.22	-15.98	-7.70	2.45	-6.19	-2.34
Shandweel-1	-13.8	-14.45	-28.19	-19.31	-36.82	-24.17
Line-1	-2.18	-20.32	-13.87	14.04	-13.95	1.10
Line-3	-10.45	-20.32	-21.75	14.04	-21.46	1.10
			Flag leaf efficiency (g/cm^2)			
Misr-2	11.29	14.96	-3.46	21.38	-11.47	27.08
Gemmeiza-12	8.21	21.38	-1.80	-7.34	7.20	6.91
Giza-171	38.9	19.20	4.38	-7.73	-0.82	-4.68
Shandweel-1	28.68	18.05	42.63	32.07	52.63	28.03
Line-1	10.32	19.36	10.59	-5.24	8.15	3.19
Line-3	16.23	14.66	37.10	-18.16	23.76	9.41

Spike characteristics

The reduction or stimulation of spike characteristics, expressed as a percentage of the control value relative to the gamma irradiation doses, is shown in Table 7. In M1, the most desirable stimulation for spike characteristics was observed at +14.14% for spike length (control vs. 350 Gy for Gemmeiza-12), +6.12 for the grain weight per spike (control vs. 250 Gy for Shandweel-1), and +5.43% for the number of fertile spikelets per spike (control vs. 250 Gy for Gemmeiza-12). On the other hand, the maximum reduction was observed for the number of sterile spikelets per spike at -17.43% (control vs. 250 Gy for Misr 1). In M2, the maximum stimulation for spike characteristics was observed at +50.42% (control vs. 250 Gy for Misr-2) for spike length, +8.39% (control vs. 350 Gy for Line-1) for grain weight per spike, and +14.07% (control vs. 250 Gy for Line-3) for the number of fertile spikelets per spike. On the other hand, the maximum reduction was observed for the number of sterile spikelets per spike at -30.21% (control vs. 350 Gy for Line-1)

Table 7. Reduction (negative values) or stimulation (positive values) of spike characters for six bread wheat genotypes as influenced by gamma ray in M1 and M2 generations.

Genotypes	Cont. versus 250 Gy		Cont. versus 350 Gy		Cont. versus 450 Gy	
	M1	M2	M1	M2	M1	M2
			Spike length (cm)			
Misr-2	4.70	50.42	-4.90	38.50	-11.76	30.19
Gemmeiza-12	6.12	7.29	14.14	15.66	-4.50	-1.64
Giza-171	3.07	3.54	-9.91	-11.92	-19.03	-15.11
Shandweel-1	13.61	12.66	11.38	10.55	-15.18	-12.39
Line-1	4.54	2.08	-8.43	-6.25	-13.83	-11.15
Line-3	-6.98	-7.68	-6.12	-5.95	-16.88	-15.03
			Grain weight/ spike (g)			
Misr-2	0.59	-1.82	-4.16	-4.24	-14.28	-5.45
Gemmeiza-12	3.79	-1.36	0.00	6.80	-10.75	6.12
Giza-171	4.69	0.00	-4.02	-4.08	-8.05	-5.44
Shandweel-1	6.12	0.65	2.04	5.19	-7.48	-5.19
Line-1	0.00	-4.90	-5.07	8.39	-10.14	4.20
Line-3	0.72	0.67	-2.91	-14.67	-5.10	-12.00
			Number of fertile spikelets/spike			
Misr-2	0.85	-6.70	-4.70	-21.03	-21.55	-9.67
Gemmeiza-12	5.43	-12.40	-3.75	10.47	-16.68	3.80
Giza-171	1.63	8.85	-10.14	6.60	-18.65	-9.14
Shandweel-1	4.70	-6.92	0.06	-18.74	-19.96	-10.23
Line-1	2.89	-31.13	-5.28	4.23	-20.60	-0.38
Line-3	1.49	14.07	-14.17	9.56	-27.38	-8.81
			Number of sterile spikelets/spike			
Misr-2	-17.43	-12.23	0.00	25.38	41.59	33.33
Gemmeiza-12	-13.45	-1.29	-2.14	-16.49	26.60	-3.87
Giza-171	-2.80	-1.79	9.80	18.21	33.61	20.77
Shandweel-1	-2.77	36.67	-3.00	51.85	18.47	71.48
Line-1	13.48	0.00	26.97	-30.21	52.49	-18.72
Line-3	0.75	17.09	21.75	25.21	36.75	23.25

Grain yield and its components

In M1, the highest stimulation for yield and its components occurred at +4.97% (control vs. 250 Gy for Giza-171) for the number of spikes per plant, +9.26% (control vs. 250 Gy for Gemmeiza-12) for the number of grains per spike, and +12.00% (control vs. 250 Gy for Misr-2) for 1000-grain weight (Table 8). Grain yield per plant also showed a significant increase of +14.21% at 250 Gy for Giza-171. However, the yield components showed a decline at higher doses, particularly at 450 Gy, indicating the sensitivity of wheat varieties to higher doses. In M2, the highest stimulation for grain yield and its components was recorded at +9.76% (control vs. 250 Gy for Giza-171) for the number of spikes per plant, +8.04% (control vs. 350 Gy for Gemmeiza-12) for the number of grains per spike, and +29.26% (control vs. 350 Gy for Gemmeiza-12) for 1000-grain weight. Grain yield per plant also showed a significant increase of +34.46% at 350 Gy for Line-1. However, the opposite trend was observed at higher doses, confirming the sensitivity of wheat varieties to excessive gamma irradiation.

Table 8. Reduction (negative values) or stimulation (positive values) of grain yield and its components for six bread wheat genotypes as influenced by gamma ray in M1 and M2 generations.

Genotypes	Cont. versus 250 Gy		Cont. versus 350 Gy		Cont. versus 450 Gy	
	M1	M2	M1	M2	M1	M2
			Number of spikes/plant			
Misr-2	1.46	2.51	-4.40	-2.09	-17.41	-11.82
Gemmeiza-12	4.66	0.44	-16.33	-10.43	-22.63	-19.53
Giza-171	4.97	9.76	-7.53	-4.14	-26.91	-19.39
Shandweel-1	3.93	1.71	-3.93	-0.39	-22.28	-12.24
Line-1	-3.36	-6.31	-9.05	-7.94	-24.57	-20.93
Line-3	0.87	6.38	-4.36	-2.52	-14.11	-7.57
			Number of grains/spike			
Misr-2	5.75	1.40	-1.79	-3.33	-24.95	-22.77
Gemmeiza-12	9.26	7.50	7.08	8.04	-7.35	-9.16
Giza-171	1.88	1.98	-8.29	-3.06	-19.54	-12.50
Shandweel-1	0.93	1.54	-0.26	-1.17	-14.98	-12.14
Line-1	-1.50	-0.17	-6.52	-2.81	-20.97	-18.38
Line-3	-0.74	-0.09	-9.01	-8.13	-15.98	-15.21
			1000-grain weight (g)			
Misr-2	12.00	-9.38	4.03	-19.89	-17.96	-16.24
Gemmeiza-12	8.98	6.05	3.78	29.26	-5.30	15.67
Giza-171	-2.80	-4.79	-6.45	-13.47	-11.29	-5.12
Shandweel-1	1.96	-5.75	0.94	-14.17	-7.67	-18.55
Line-1	-3.82	-2.90	-7.10	25.18	-15.20	17.86
Line-3	-0.36	-1.15	-3.47	-8.92	-12.64	-7.77
			Grain yield/plant (g)			
Misr-2	8.35	-4.49	-0.78	-20.04	-15.62	-25.05
Gemmeiza-12	11.40	-11.53	8.47	31.15	-15.81	15.26
Giza-171	14.21	6.45	5.16	-0.48	-3.50	-10.97
Shandweel-1	4.93	1.28	-1.00	2.21	-18.31	-6.38
Line-1	0.09	-4.53	-4.47	34.46	-14.44	30.66
Line-3	-0.37	-7.06	-2.81	-4.95	-12.59	-18.35

Correlation and factor analyses

The simple correlation coefficients between grain yield per plant and various earliness, morpho-physiological, and agronomic traits of bread wheat in the M1 generation are presented in Table 9. The results revealed a highly significant positive correlation between wheat grain yield per plant and several traits, including plant height, flag leaf efficiency, spike length, number of fertile spikelets per spike, number of spikes per plant, number of grains per spike, and 1000-grain weight. Additionally, a significant positive association was observed among earliness traits, such as days to heading, flowering, and maturity, suggesting that these traits could serve as reliable indicators of early maturation in wheat. Earliness traits also exhibited a positive correlation with the number of sterile spikelets and spike grain weight. In contrast, earliness traits were negatively correlated with plant height, spike length, number of fertile spikelets per spike, number of spikes per plant, number of grains per spike, 1000-grain weight, and grain yield per plant. This suggests that early-maturing wheat genotypes tend to have reduced values for these yield-related traits. Grain-filling period showed a significant positive correlation with flag leaf area but was negatively correlated with flag leaf chlorophyll content and spike grain weight. Plant height, on the other hand, had a highly significant positive correlation with flag leaf area, spike length, number of fertile spikelets per spike, as well as grain yield and its components. Conversely, plant height was negatively correlated with spike grain weight and the number of sterile spikelets, indicating that shorter plants tend to have heavier spike grain weights but more sterile spikelets. Flag leaf area had a significant positive correlation with the number of spikes per plant, and 1000-grain weight. Flag leaf efficiency exhibited a significant positive correlation with both flag leaf chlorophyll content and grain yield per plant. However, a negative correlation was observed between flag leaf area and both flag leaf efficiency and chlorophyll content, while flag leaf chlorophyll content had a negative association with spike length. Spike length showed a significant positive correlation with the number of fertile spikelets per spike, number of spikes per plant, number of grains per spike, 1000-grain weight, and grain yield. This suggests that selection for longer spikes could result in improved yield traits, particularly an increase in the number of fertile spikelets. However, a significant negative correlation was observed between spike length and both the number of sterile spikelets and spike grain weight, likely due to the negative relationship between spike length and spikelet number, as well as nutrient competition. The number of fertile spikelets per spike was positively correlated with grain yield and its components, but negatively correlated with the number of sterile spikelets and spike grain weight. In contrast, the number of sterile spikelets showed a positive correlation with spike grain weight but negative correlations with the number of spikes per plant, number of grains per spike, and 1000-grain weight. These findings suggest that reducing the number of sterile spikelets could improve yield components.

In the M2 generation (Table 10), similar trends were observed, with a significant positive correlation between grain yield and traits like plant height, flag leaf area, flag leaf chlorophyll content, spike length, number of fertile spikelets per spike, grain weight per spike, number of spikes per plant, number of grains per spike, and 1000-grain weight. In contrast, earliness traits showed a significantly negative correlation with grain yield, indicating the inverse relationship between early maturation and yield. Additionally, the number of sterile spikelets per spike was negatively correlated with grain yield.

The results of factor analysis for the M1 generation (Table 11) revealed three factors accounting for 91.507% of the total variability. Factor 1, which explained 68.50% of the variance, included nine variables, such as grain-filling period, plant height, flag leaf efficiency, spike length, grain weight per spike, number of fertile spikelets per spike, number of spikes per plant, number of grains per spike, and 1000-grain weight. Factor 2, which accounted for 15.57% of the variance, consisted of four variables: days to heading, days to flowering, flag leaf chlorophyll content, and number of sterile spikelets per spike. Factor 3, explaining 7.44% of the variance, included days to maturity and flag leaf area. In the M2 generation, factor analysis revealed three factors accounting for 92.04% of the total variability (Table 12). Factor 1 explained 62.60% of the variance and included similar variables to Factor 1 in M1, such as grain-filling period, plant height, flag leaf chlorophyll content, flag leaf efficiency, grain weight per spike, number of fertile spikelets per spike, number of spikes per plant, number of grains per spike, and 1000-grain weight. Factor 2, accounting for 16.60% of the variance, consisted of days to heading, flag leaf area, and number of sterile spikelets per spike, while Factor 3, which explained 12.84% of the variance, included days to flowering, days to maturity, and spike length. The results from both generations highlight the importance of morpho-physiological traits, including flag leaf characteristics, spike length, and number of fertile spikelets, in determining grain yield and its components. These traits can serve as valuable selection criteria in breeding programs aimed at improving wheat productivity under varying environmental conditions.

Table 9. Simple correlation coefficients between grain yield per plant and earliness, morpho-physiological and agronomic traits of bread wheat in the M1 generation.

Character	DH	DF	DM	GFP	PH	FLA	FLE	FLCC	SL	NFSS	NSSS	GWS	NSP	NGS	TGW	GY
DH	1.00	0.40**	0.81**	-0.26*	-0.66**	-0.10	-0.16	0.06	-0.30*	-0.51**	0.38**	1.00**	-0.52**	-0.51**	-0.57**	-0.46**
DF		1.00	0.45**	-0.07	-0.36**	-0.03	-0.15	-0.07	-0.35**	-0.58**	0.50**	0.40**	-0.63**	-0.57**	-0.56**	-0.19
DM			1.00	0.13	-0.67**	0.15	-0.25*	-0.11	-0.33**	-0.44**	0.37**	0.81**	-0.49**	-0.53**	-0.59**	-0.50**
GFP				1.00	0.08	0.26*	0.07	-0.25*	0.09	0.21	-0.07	-0.26*	0.10	0.12	0.05	0.06
PH					1.00	0.24*	0.06	-0.22	0.61**	0.52**	-0.52**	-0.66**	0.56**	0.61**	0.63**	0.57**
FLA						1.00	-0.56**	-0.31**	0.21	0.17	-0.20	-0.10	0.25*	0.15	0.25*	-0.06
FLE							1.00	0.32**	-0.01	0.05	0.08	-0.16	-0.08	0.14	0.01	0.28*
FLCC								1.00	-0.24*	-0.17	0.15	0.06	-0.22	-0.14	-0.19	-0.10
SL									1.00	0.51**	-0.52**	-0.30*	0.44**	0.61**	0.53**	0.54**
NFSS										1.00	-0.66**	-0.51**	0.78**	0.81**	0.74**	0.30*
NSSS											1.00	0.38**	-0.66**	-0.74**	-0.70**	-0.24*
GWS												1.00	-0.52**	-0.5**	-0.57**	-0.46**
NSP													1.00	0.72**	0.73**	0.24*
NGS														1.00	0.88**	0.34**
TGW															1.00	0.30*
GY																1.00

DH: days to heading, DF: days to flowering, DM: days to maturity, GF: Grain filling period, PH: plant height, FLA: Flag leaf area, FLE: Flag leaf efficiency, FLCC: Flag leaf chlorophyll content, SL: Spike length, NFSS: Number of fertile spikelets/ spike, NSSS: Number of sterile spikelets/ spike, GWS: Grain weight/ spike, NSP: Number of spikes/ plant, NGS: Number of grains/spike, TGW: 1000-grain weight, and GYP: Grain yield/ plant. * $P < 0.05$, ** $P < 0.01$

Table 10. Simple correlation coefficients between grain yield per plant and earliness, morpho-physiological and agronomic traits of bread wheat in the M2 generation.

Character	DH	DF	DM	GFP	PH	FLA	FLE	FLCC	SL	NFSS	NSSS	GWS	NSP	NGS	TGW	GY
DH	1.00	0.59**	0.59**	0.22*	-0.22*	0.01	- 0.27*	-0.47**	-0.26*	-0.45**	0.44**	-0.43**	-0.39**	-0.47**	-0.42**	-0.37**
DF		1.00	0.73**	-0.03	-0.43**	-0.14	-0.16	-0.49**	-0.46**	-0.52**	0.50**	-0.57**	-0.51**	-0.61**	-0.51**	-0.44**
DM			1.00	0.66**	-0.50**	-0.08	- 0.25*	-0.58**	-0.63**	-0.60**	0.47**	-0.58**	-0.53**	-0.62**	-0.53**	-0.53**
GFP				1.00	-0.26*	0.03	-0.19	-0.32*	-0.43**	-0.30**	0.14	-0.23*	-0.22*	-0.24*	-0.21*	-0.23*
PH					1.00	0.27*	0.05	0.40**	0.66**	0.48**	-0.40**	0.60**	0.57**	0.56**	0.61**	0.60**
FLA						1.00	-0.84**	0.15	0.07	0.35**	-0.27*	0.23*	0.44**	0.35**	0.44**	0.28*
FLE							1.00	0.14	0.24*	-0.01	-0.07	0.32**	-0.10	0.01	-0.08	0.14
FLCC								1.00	0.59**	0.60**	-0.46**	0.52**	0.43**	0.56**	0.45**	0.49**
SL									1.00	0.48**	-0.36**	0.60**	0.42**	0.60**	0.49**	0.51**
NFSS										1.00	-0.55**	0.47**	0.72**	0.74**	0.69**	0.60**
NSSS											1.00	-0.58**	-0.59**	-0.69**	-0.66**	-0.60**
GWS												1.00	0.58**	0.64**	0.64**	0.73**
NSP													1.00	0.71**	0.72**	0.79**
NGS														1.00	0.86**	0.69**
TGW															1.00	0.65**
GY																1.00

DH: days to heading, DF: days to flowering, DM: days to maturity, GF: Grain filling period, PH: plant height, FLA: Flag leaf area, FLE: Flag leaf efficiency, FLCC: Flag leaf chlorophyll content, SL: Spike length, NFSS: Number of fertile spikelets/ spike, NSSS: Number of sterile spikelets/ spike, GWS: Grain weight/ spike, NSP: Number of spikes/ plant, NGS: Number of grains/spike, TGW: 1000-grain weight, and GYP: Grain yield/ plant. * $P < 0.05$, ** $P < 0.01$.

Table 11. Summary of factor loading for some important traits of M_1 generation.

Variables	Loading	Percentage of total
Factor 1		68.50
Grain filling period (day)	-0.098	-1.40
Plant height (cm)	0.912	13.02
Flag leaf efficiency (g/ cm^2)	0.940	13.42
Spike length (cm)	0.642	9.16
Grain weight/ spike (g)	0.941	13.43
Number of fertile spikelets/ spike	0.881	12.57
Number of spikes/plant	0.903	12.89
Number of grains/ spike	0.968	13.82
1000-grain weight (g)	0.917	13.09
Factor 2		15.57
Days to heading (day)	0.240	13.09
Days to flowering (day)	0.487	26.55
Flag leaf chlorophyll content (SPAD)	0.801	43.68
number of sterile spikelets/ spike	0.306	16.68
Factor 3		7.44
Days to maturity (day)	0.132	22.53
Flag leaf area (cm^2)	0.454	77.47
Cumulative variance		91.507

Table 12. Summary of factor loading for some important traits of M_2 generation.

Variable	Loading	Percentage of total
Factor 1		62.60
Grain filling period (day)	-0.176	-2.49
Plant height (cm)	0.952	13.45
Flag leaf chlorophyll content (SPAD)	0.914	12.91
Flag leaf efficiency (g/cm^2)	0.777	10.98
Grain weight/ spike (g)	0.974	13.76
Number of fertile spikelets/ spike	0.965	13.63
Number of spikes/plant	0.906	12.80
Number of grains/ spike	0.844	11.92
1000-grain weight (g)	0.923	13.04
Factor 2		16.60
Days to heading (day)	0.776	39.90
Flag leaf area (cm^2)	0.926	47.61
Number of sterile spikelets/ spike	0.243	12.49
Factor 3		12.84
Days to flowering (day)	0.403	30.86
Days to maturity (day)	0.184	14.09
Spike length (cm)	0.719	55.05
Cumulative variance		92.04

Discussion

The present study evaluated the impact of gamma irradiation on various characteristics of six bread wheat genotypes, including earliness, morpho-physiological traits, spike properties, and yield components, across two generations (M1 and M2).Our findings revealed substantial variation in responses of assessed wheat genotypes to different gamma irradiation doses, indicating the influence of irradiation on the genetic makeup of the used cultivars. Gamma irradiation significantly affected the earliness characteristics of wheat genotypes. In the M1 generation, gamma irradiation led to significant delays in days to heading, flowering, and maturity, consistent with earlier studies. These delays are likely due to enhanced vegetative growth and cell elongation caused by the irradiation, which prolonged the plant vegetative period before transitioning to reproductive growth (Osnato *et al.,* 2022). Interestingly, the grain filling period, which is a critical determinant of final yield, showed no significant change in the M1 generation, but tended to shorten with increasing gamma doses in the M2 generation. This suggests that while gamma irradiation might delay the reproductive stages, it may also have a stimulating effect on grain filling under certain conditions (Kiani *et al.,* 2022). The observed variation in earliness traits among wheat genotypes indicates considerable genetic diversity, which is valuable for selection and breeding programs aimed at improving earliness or adaptability to specific environmental conditions (Kamara *et al.,* 2021). In particular, Misr-2 could be considered one of the earliest genotypes, which could be advantageous in breeding programs targeting early maturity and reduced sensitivity to late-season stress. These results are supported by similar findings from Abro *et al.,* (2019), who observed that gamma irradiation could enhance vegetative growth and yield traits, including earliness. The interaction between gamma-ray dose and cultivar was significant for all earliness traits, with Misr-2 showing the best performance in the control treatment, and Shandweel-1 performing better under the 350 Gy dose for the grain filling period. This highlights the importance of genotype-by-environment interactions and suggests that optimal gamma doses might vary depending on the genotype and trait of interest.

Gamma irradiation significantly influenced the morpho-physiological traits of wheat genotypes. In the M1 generation, significant differences were observed in plant height, flag leaf area, chlorophyll content, and flag leaf efficiency. The irradiation doses affected plant height differently, with the shortest plants recorded under high doses (450 Gy). This reduction in height is a desirable trait for increasing lodging resistance in wheat. This reduction in plant height could be associated with the stimulation of gibberellic acid, which affects shoot elongation. These findings align with studies by Albokari (2014) who reported semi-dwarf mutants with improved agronomic traits resulting from gamma irradiation. Flag leaf area, chlorophyll content, and flag leaf efficiency showed substantial improvement under moderate irradiation doses (250 and 350 Gy), indicating that gamma irradiation can enhance photosynthetic efficiency, which is critical for grain yield. Misr-2, Gemmeiza-12, and Shandweel-1 performed well in terms of flag leaf chlorophyll content and efficiency, suggesting their potential for higher photosynthetic capacity and improved grain yield. These findings are consistent with the work of Abaza *et al.,* (2020); Hong *et al.,* (2022) and Hong *et al.,* (2025), who observed that gamma irradiation improved agronomic traits and physiological characteristics, leading to enhanced yield performance. In the M2 generation, the response to gamma irradiation was more pronounced, with significant decreases in plant height and flag leaf area under higher doses (350 and 450 Gy), while leaf area efficiency increased. These changes likely reflect the adaptation of wheat genotypes to the mutagenic stress induced by gamma irradiation, enhancing their photosynthetic efficiency and grain yield under stress conditions.

Gamma irradiation significantly impacted spike characteristics, with the 250 Gy dose generally improving spike length and fertile spikelets per spike compared to higher doses. The reduction in spike length and grain weight per spike under higher irradiation doses suggests that excessive gamma radiation may negatively affect spike development, possibly due to cellular damage or impaired metabolic processes. The significant variability in spike characteristics among wheat genotypes further highlights the genetic diversity available for breeding programs. The interaction between gamma-ray dose and cultivar was also significant for spike characteristics, with the best results for spike length observed in Shandweel-1 under the 250 Gy dose. Misr-2 demonstrated superior performance in terms of grain weight and number of fertile spikelets, while Line-3 exhibited the poorest performance, emphasizing the importance of genotype selection in optimizing gamma irradiation treatments. These findings support previous research by El-Degwy and Hathout (2014), who reported significant differences in spike characteristics due to gamma treatments.

Gamma irradiation significantly influenced yield and its components in both the M1 and M2 generations. The 250 Gy dose resulted in significant increases in the number of spikes per plant, grains per spike, 1000-grain weight, and grain yield per plant, while higher doses (350 and 450 Gy) led to a decline in these traits. This suggests that lower irradiation doses may stimulate certain yield components, but excessive doses can be detrimental. These findings are consistent with earlier studies by Awaad *et al.*, (2018) and Shabani *et al.*, (2022), who observed variable responses in yield components due to gamma irradiation. Among the genotypes, Misr-2, Gemmeiza-12, and Shandweel-1 consistently outperformed others in terms of yield components, demonstrating their potential for use in breeding programs aimed at improving yield under mutagenic stress. The interaction between gamma-ray dose and cultivar was significant for all yield components, with Misr-2 showing the best performance under the 250 Gy dose for number of spikes per plant and grain yield per plant. These results underscore the importance of selecting appropriate doses for different genotypes to maximize yield potential.

Recent literature demonstrated the value of gamma irradiation in enhancing morpho-physiological traits and yield components in wheat, aligning with the results observed in this study. In this context, Shabani *et al.*, (2022) showed that optimized doses of gamma radiation (100–200 Gy) significantly improved key yield-related traits, including flag leaf area, number of grains per spike, and spike number per plant, leading to yield increases of more than 45% in some mutant wheat lines. Their findings also indicated improvements in physiological parameters such as photosynthetic rate, water use efficiency, and chlorophyll content, supporting the observation in this study that moderate irradiation doses promote photosynthetic efficiency and, consequently, higher grain yield. More investigations confirmed the optimal range for wheat mutation breeding lies between 250–300Gy. Moreover, a recent multi-year study of Rana *et al.*, (2024) evaluated gamma ray-induced mutant populations in wheat and has further substantiated the benefits of moderate irradiation doses in the range of 100–300 Gy. This approach not only maximizes genetic variability across essential agronomic traits such as grain weight, spike length, grains per spike, and plant height but also minimizes the detrimental effects observed at higher radiation levels. This strategy facilitates the identification of novel wheat mutants exhibiting enhanced agronomic growth traits, yield components and quality parameters. These results align well with current finding and reinforce the concept that carefully moderated gamma radiation doses can effectively balance the induction of beneficial mutations while preserving overall plant vigor, ultimately contributing to the development of improved wheat cultivars with higher yield potential and better grain quality.

The results of the correlation and factor analyses presented in this study provide valuable insights into the relationships between various agronomic, morpho-physiological, and earliness traits with grain yield in bread wheat genotypes subjected to different doses of gamma irradiation. The analysis of the M1 and M2 generations revealed significant trends that can be leveraged for improving wheat breeding strategies, particularly those aimed at enhancing grain yield under irradiation stress. In both generations, grain yield showed highly significant positive correlations with several yield-related traits, including plant height, flag leaf efficiency, spike length, and 1000-grain weight. These findings are consistent with studies of Ullah *et al.*, (2021) and Choudhary *et al.*, (2025) who highlighted the role of these traits in enhancing grain yield in wheat. Notably, traits such as the number of spikes per plant, number of grains per spike, and number of fertile spikelets per spike were positively correlated with grain yield, emphasizing their potential as selection criteria in wheat breeding programs focused on yield improvement. However, the relationship between earliness traits (such as days to heading, flowering, and maturity) and grain yield presents a more complex picture. In both generations, earliness traits showed significant negative correlations with grain yield and its components, suggesting that earlier maturing wheat plants may experience a trade-off in terms of reduced yield potential. This finding aligns with earlier research by Singh *et al.*, (2024), who reported similar negative correlations between earliness and yield traits in wheat. This inverse relationship was also observed between earliness traits and other yield-related traits, such as spike grain weight and plant height, confirming that early-maturing wheat plants may exhibit reduced growth and yield potential. Therefore, it is essential to consider the balance between earliness and yield potential when selecting wheat genotypes for breeding programs. In the M2 generation, the correlation results further emphasized the role of key traits like plant height, flag leaf area, and spike length in driving grain yield. Interestingly, the negative correlation between earliness traits and grain yield was more pronounced in M2, possibly due to the segregation effects. This observation suggests that the impact of irradiation stress might induce genetic variability that affects the relationship between earliness and yield traits, emphasizing the need to evaluate genotypes under diverse environmental conditions to identify the most promising candidates for breeding.

The factor analysis results corroborated the findings from the correlation analysis by identifying patterns of interrelationships among the different traits. In both M1 and M2 generations, the first factor, which included traits such as grain filling period, plant height, flag leaf efficiency, spike length, and 1000-grain weight, accounted for the majority of the variance. This indicates that these traits are crucial in determining wheat grain yield and can serve as primary selection criteria in breeding programs aimed at improving yield under stress conditions. The significant contribution of the first factor to the total variance (68.50% in M1 and 62.60% in M2) underscores the importance of morpho-physiological traits in determining yield potential. In contrast, the second and third factors, which were associated with earliness traits such as days to heading, flowering, and maturity, and the number of sterile spikelets per spike, accounted for a smaller portion of the total variance. The negative correlations between earliness traits and yield components, as identified in the correlation analysis, were reflected in their position in the second and third factors. These results further support the idea that selecting for earliness, while beneficial for reducing the growing period, may come at the cost of reduced yield potential, particularly under the influence of irradiation stress. The shift in the relative contribution of factors from M1 to M2, with a higher contribution from Factor 3 in M2, highlights the nature of trait interactions under the influence of gamma irradiation. The increased contribution of earliness-related traits in M2 suggests that irradiation may have induced genetic variability that affected the expression of these traits. The effect of irradiation on trait correlations and the overall factor structure indicates that breeding strategies should account for both the direct and indirect effects of gamma irradiation on wheat genotypes. Hence, the results emphasize the importance of selecting both morpho-physiological traits and yield-related traits in wheat breeding programs. While earliness traits can be useful for improving adaptability and reducing the growing period, they should be carefully balanced with traits that contribute to higher grain yield. In particular, traits such as plant height, flag leaf area, spike length, and number of fertile spikelets per spike should be prioritized, as they showed significant positive correlations with grain yield in both generations. Furthermore, the impact of gamma irradiation on the relationships between traits indicated the potential for using irradiation as a tool to induce genetic variability and improve wheat performance under stress conditions. However, the potential trade-offs between earliness and yield must be considered when selecting early-maturing genotypes. Future breeding programs should aim to identify genotypes that can achieve early maturity without compromising key yield components, such as spike grain weight and number of grains per spike. These results are in agreement with those obtained by Ebrahimnejad and Rameeh (2016) and Charly-Emmanuel *et al.*, (2022).

Conclusion

This study demonstrated that moderate doses of gamma irradiation could effectively induce beneficial genetic variation in wheat, leading to improved morpho-physiological traits such as increased flag leaf efficiency and chlorophyll content, as well as altered spike and yield components. Gamma irradiation, particularly at doses of 250 Gy, promoted vegetative growth, enhanced photosynthetic efficiency, and improved several key yield components, such as number of spikes per plant, grains per spike, 1000-grain weight, in addition to grain yield per plant. While higher doses (350 Gy and 450 Gy) tended to reduce these traits, they still contributed to the generation of genetic variability among wheat genotypes, which is essential for breeding programs aimed at improving stress tolerance, productivity, and other desirable traits. These changes could enhance the photosynthetic capacity and yield potential, particularly under stress conditions. The observed improvements in leaf traits and agronomic characters can contribute to greater adaptation to climate variability. Therefore, gamma irradiation serves as a valuable tool for generating genetic diversity to support future wheat breeding efforts aimed at improving yield stability under challenging environmental conditions. Moreover, the results indicated the importance of selecting wheat genotypes based on key morpho-physiological traits, such as plant height, spike length, and flag leaf efficiency, which show strong positive correlations with grain yield. The negative relationship between earliness traits and yield highlights the trade-offs breeders must consider when selecting for early-maturing varieties.

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