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Review article

Physical mutagenesis: a platform for genomic plasticity and genetic variability in crops of agronomic interest

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Abstract

Abstract Modern plant breeding faces the challenge of developing resilient crop varieties for global food security. In this context, induced mutagenesis using physical agents, particularly ionizing radiation, has been positioned as an effective tool for generating genetic variability. This review explores the underlying molecular mechanisms, where radiation induces both direct and indirect damage to the DNA, leading to point mutations and, crucially, double-strand breaks (DSBs). These genomic alterations trigger genomic plasticity, which is fundamental to the success of plant breeding programs. Success stories are referenced, demonstrating the technique's efficacy in improving key agronomic traits. These include the creation of mutants with resistance or tolerance to different biotic or abiotic stress conditions, as well as genotypes with higher yield and nutritional value. The capacity of mutagenesis to optimize plant architecture is also demonstrated, which facilitates mechanical harvesting, significantly reduces field losses, and lowers production costs. In conclusion, the ability of physical agents to induce mutations in complex quantitative traits positions mutagenesis as a vital solution against climate change and the increasing demand for sustainable crops. The future integration of mutagenesis with omics technologies and gene-editing tools like CRISPR/Cas9 promises unprecedented precision and efficiency. This synergistic approach reaffirms that physical mutagenesis is not an obsolete technique, but a key platform, complementary to gene editing, for accelerating the development of a new generation of crops.

Keywords: food security, ionizing radiation, plant breeding, resilient varieties.

Mutagénesis física: una plataforma para la plasticidad genómica y la variabilidad genética en cultivos de interés agronómico

Resumen

El fitomejoramiento moderno enfrenta el desafío de desarrollar variedades de cultivos resilientes para la seguridad alimentaria global. En este contexto, la mutagénesis inducida con agentes físicos, particularmente la radiación ionizante, se ha posicionado como una herramienta eficaz para generar variabilidad genética. Esta revisión explora los mecanismos moleculares subyacentes, donde la radiación induce daño tanto directo como indirecto al ADN, lo que genera mutaciones puntuales y, de manera crucial, roturas de doble cadena (DSBs). Estas alteraciones genómicas desencadenan una plasticidad genómica fundamental para el éxito de los programas de fitomejoramiento. Se refieren casos de éxito que demuestran la eficacia de la técnica para mejorar rasgos agronómicos clave. Estos incluyen la creación de mutantes con resistencia o tolerancia a diferentes condiciones de estrés biótico o abiótico, así como genotipos con mayor rendimiento y valor nutricional. Se muestra también la capacidad de la mutagénesis para optimizar la arquitectura de la planta, lo que facilita la cosecha mecánica, reduce significativamente las pérdidas en el campo y disminuye los costos de producción. En conclusión, la habilidad de los agentes físicos para inducir mutaciones en caracteres cuantitativos complejos posiciona a la mutagénesis como una solución vital frente al cambio climático y la creciente demanda de cultivos sostenibles. La integración futura de la mutagénesis con tecnologías ómicas y herramientas de edición génica como CRISPR/Cas9 promete una precisión y eficiencia sin precedentes. Este enfoque sinérgico reafirma que la mutagénesis física no es una técnica obsoleta, sino una plataforma clave, complementaria a la edición génica, para acelerar el desarrollo de una nueva generación de cultivos.

Palabras clave: fitomejoramiento, radiación ionizante, seguridad alimentaria, variedades resilientes

1. Introduction

In a context of unprecedented population growth and the acceleration of climate change, global agriculture faces one of its most critical challenges [1]. Food security, a cornerstone of the social and economic stability of nations, is directly threatened by extreme climate variability, soil degradation, and the proliferation of pests and diseases—factors that have begun to undermine crop productivity globally [2]. This unsustainable pressure underscores the urgency of moving beyond traditional genetic improvement strategies and developing plant varieties that are intrinsically more resilient and productive to ensure the future of human nutrition [1].

Genetic variability is the cornerstone of plant breeding, serving as the driving force behind species adaptability and the development of new cultivars [3,4]. Historically, breeding programs have relied on traditional sources of variation, such as sexual recombination through crossing and spontaneous mutations [5]. However, in the context of modern challenges, these sources are increasingly limited. The slow emergence of natural mutations, coupled with the narrow genetic base of many domesticated crops, restricts the spectrum of available variability, making it difficult to obtain urgent traits such as tolerance to extreme conditions [6].

The pace of natural evolution, although constant, is insufficient to generate the variability needed to address the growing demands of food security [7]. In this context, induced mutagenesis using physical agents emerges as a proactive strategy, acting as an evolutionary accelerator that generates massive genetic variability, overcoming the limitations of natural selection [8,9]. Although historically fundamental to the success of modern agriculture, as evidenced during the Green Revolution, physical mutagenesis has intensified its relevance in the era of advanced biotechnology.

Far from being an obsolete technology, physical mutagenesis is positioned as a complementary platform to gene-editing tools like CRISPR-Cas [10]. The controlled application of gamma radiation or X-rays allows plant breeders to create a wide range of novel alleles and desirable agronomic traits [11,12]. This synergism is the main justification for its continued importance in the fight for food security, as it provides an inexhaustible source of variation for gene discovery and the creation of new alleles not found in nature [9].

This review transcends the conventional view of physical mutagenesis as a simple technique for inducing random mutations. Our main thesis establishes that this methodological strategy represents a robust platform for the efficient induction of genomic plasticity, a fundamental trait that confers upon plants the capacity to flexibly respond to their environment. This plasticity, in turn, facilitates the emergence of valuable agronomic characteristics, such as tolerance to biotic and abiotic stress conditions or increased biomass production. By adopting this new paradigm, we re-evaluate the potential of physical mutagenesis to drive adaptation and genetic innovation in crop improvement.

2. Mechanisms of action of ionizing radiation on DNA

Understanding the molecular mechanisms by which ionizing radiation induces mutations is fundamental to optimizing its use in plant breeding. The biological effects of agents such as gamma rays and X-rays are not limited to a single type of interaction, but rather manifest through a complex cascade of events that compromise the integrity of deoxyribonucleic acid (DNA), inducing changes ranging from structural and numerical alterations to visible chromosomal aberrations in plant species [13]. These phenomena occur through two main pathways which, although distinct, operate synergistically: direct damage, where the radiation energy directly impacts the DNA molecule, and indirect damage, a predominant mechanism mediated by the radiolysis of surrounding water molecules and the consequent formation of highly reactive free radicals [8].

The imbalance in cellular homeostasis caused by these interactions initiates a series of molecular events that, if not correctly repaired, lead to the formation of point mutations and chromosomal rearrangements [14]. It is these genomic alterations, and their wide range, that make ionizing radiation such a powerful tool for generating genetic variability, serving as the basis for the development of new and valuable agronomic traits [15]. Despite the emergence of precision technologies, the study of these mechanisms remains vital for understanding genomic plasticity and the continuous relevance of mutagenesis in the era of advanced biotechnology, constituting an essential point of comparison for evaluating the risks of new techniques and the evolution of the crop resilience paradigm [16].

2.1. Direct damage: primary mechanism of molecular interaction

Ionizing radiation, upon penetrating the cell, can interact directly with the DNA molecule, depositing its energy and causing immediate damage to its structure. This mechanism, known as direct damage, occurs when photons or ionizing particles, such as gamma rays or beta particles, impact the atoms that compose the deoxyribose-phosphate backbone or the nitrogenous bases of the double helix [17].

Although this interaction is energetically inefficient and accounts for a fraction of the total damage (approximately 30%), its genomic consequences are substantial. The absorption of energy can trigger the rupture of covalent bonds, resulting in single-strand breaks (SSBs) or, more critically, double-strand breaks (DSBs), which are the most severe lesions and the most difficult for cellular systems to repair [18].

DSBs are the most lethal type of lesion for the genome and the main trigger of mutations and chromosomal rearrangements. When the cell's repair systems fail to correct these lesions accurately, error-prone repair pathways, such as non-homologous end joining (NHEJ) [19,20], are initiated. These processes can result in the deletion of large DNA segments, as well as large-scale translocations and inversions—phenomena that excessively alter the genome structure and are crucial for generating the desirable genetic variability in plant breeding [17,21]. Therefore, by inducing these DSBs, direct damage becomes a fundamental pillar for creating the genetic diversity required for crop adaptation.

2.2. Indirect damage: the predominant mechanism of ionizing radiation

The primary mechanism by which ionizing radiation causes genetic damage is through an indirect pathway, which accounts for approximately 70% of the total DNA damage [17]. This process begins with the radiolysis of water, as ionizing radiation, upon passing through the cell nucleus, interacts with the water molecule (H_2O), the most abundant compound in the environment, instead of directly impacting the DNA. This interaction deposits its energy into the water molecules, causing their dissociation into a series of highly reactive and transient species, such as hydrogen radicals (•H), hydrated electrons (e_{aq}^{-}), and, most critically, the hydroxyl radical (•OH) [22].

These free radicals, particularly the •OH radical, are extremely reactive and rapidly migrate to attack the adjacent DNA molecule. The reactivity of the radical makes it a formidable aggressor, capable of causing a wide range of DNA lesions, including the oxidation of nitrogenous bases, the rupture of bonds in the deoxyribose-phosphate backbone, and the induction of SSBs [17]. The resulting SSBs are frequently converted into DSBs during DNA replication, which underscores the importance of indirect damage as the main driver of mutations and chromosomal rearrangements in induced mutagenesis.

3. Genomic effects of physically induced mutagenesis

Ionizing radiation has been positioned as a crucial tool in biology and plant breeding for inducing mutagenesis and generating genetic variability [9,23]. At the genomic level, its impact is manifested through a series of molecular lesions that drive mutation. These interactions produce a variety of damage, ranging from point mutations and small insertions/deletions (INDELs)—frequent due to base oxidation—to the most serious and destabilizing lesion: DSBs, which have a high impact on the genomic plasticity of irradiated plants [17,24].

Indeed, these DSBs are the hallmark of radiation damage. Their incorrect or incomplete repair can lead to complex chromosomal rearrangements, including large-scale translocations and deletions, which fundamentally reconfigure the genome and create the basis for genetic variability [18,21].

3.1. Point mutations and small insertions/deletions

Point mutations and small insertions/deletions (INDELs) represent smaller-scale alterations that can have a profound impact on gene function and phenotypic expression [24]. These small-scale mutations are the result of DNA damage. Indirect damage, mediated by the highly reactive •OH radical generated by water radiolysis, is a key mechanism for the induction of these mutations. The •OH is capable of oxidizing bases, creating lesions that, if not repaired correctly, can result in mutations and the induction of clustered damage [22,25].

At the molecular level, radiation damage is materialized in the alteration of nitrogenous bases and the rupture of phosphodiester bonds in the deoxyribose-phosphate backbone. When bases are oxidized, lesions such as 8-oxoguanine can form, which, during DNA replication, can incorrectly pair with adenine instead of cytosine, resulting in a point mutation [26,27].

Similarly, SSBs or the rupture of phosphodiester bonds can be incorrectly processed by repair systems, leading to the loss or addition of one or more nucleotides, generating INDELs that frequently induce frameshifts and the consequent loss of protein function [19].

In the context of plant breeding, the induction of small-scale mutations is of maximum relevance, given that they generate functional variability without incurring the lethal or unfavorable consequences associated with large-scale lesions. This distinction between small-scale genomic damage and destabilizing chromosomal-level damage is crucial [24,28]. Consequently, the detailed analysis of small-scale mutations is indispensable for unraveling genetic diversity and establishing the molecular basis of the phenotypic variability generated through induced mutagenesis [17].

3.2. Double-Strand Breaks (DSBs)

Exposure to ionizing radiation represents a significant threat to genome integrity, with DSBs being the most severe and biologically relevant lesion [17]. DSBs are characterized by the simultaneous or near-simultaneous rupture of both DNA strands, and they are formed as a result of both direct and indirect damage. The high linear energy transfer (LET) of certain types of radiation is particularly efficient in inducing complex and clustered DSBs, which exacerbates the challenge of cellular repair [29,30].

The critical role of DSBs lies in the difficulty of their repair. While SSBs are repaired with high fidelity, the repair of DSBs presents a significant risk of error. The cellular repair system can resort to two main pathways: homologous recombination (HR), which is a high-fidelity process, and non-homologous end joining (NHEJ), which is more error-prone [29,31].

If NHEJ repair is performed incorrectly or if multiple DSBs are repaired with each other, a variety of aberrant chromosomal rearrangements can be generated. These rearrangements, including translocations, deletions, and inversions, are the main causes of genomic instability and are considered the key events in induced plant mutagenesis [18,32].

In the context of plant breeding, the induction of DSBs is a dual strategy. They are the most dangerous lesions that can lead to cell death, but their faulty repair is the main source of large-scale genetic variability, which is fundamental for the creation of new crop varieties [9,30]. Understanding the formation and repair of DSBs is, therefore, essential for manipulating radiation mutagenesis in a controlled and effective manner.

3.3. Chromosomal rearrangements

Chromosomal rearrangements represent the most significant large-scale mutations and are a direct consequence of the incorrect repair of DSBs, the most lethal lesion induced by ionizing radiation. While the high-fidelity repair pathway, HR, generally ensures precise repair, the NHEJ pathway is error-prone [20,33]. If multiple DSBs are generated, the broken ends can be incorrectly joined, leading to chromosomal aberrations such as translocations and inversions; translocations occur when a chromosome fragment attaches to a non-homologous one, and inversions involve the reversal of a DNA segment within the same chromosome [34]. These events alter the genome structure and can fundamentally change gene expression by moving genes to new locations [32].

In addition to translocations and inversions, faulty DSB repair can also result in chromosomal deletions, the loss of an entire DNA segment, which may span multiple genes [18,20]. Deletions are particularly detrimental, as they can lead to the inactivation of essential genes or the disruption of genetic sequences, resulting in severe consequences for cell viability and function [35,36]. By inducing a high number of DSBs, radiation significantly increases the probability of these repair errors, making chromosomal rearrangements a distinctive characteristic of induced genetic damage [30,34].

In the field of plant breeding, the induction of chromosomal rearrangements is considered a double-edged sword: while they can be lethal to the individual, they represent a vital and historical source of genetic variability for the selection of desirable agronomic traits [8]. This calculated risk justifies the continued use of mutagenic agents in the generation of new cultivars. Rearrangements can alter the inheritance pattern of genes and confer new genetic combinations that result in improved agronomic characteristics, including the crucial resistance to diseases or tolerance to environmental stress.

This principle justifies the use of mutagenic agents to drive variability in crops and lays the foundation for modern chromosomal engineering [9,37]. The precise understanding of the mechanisms underlying these chromosomal rearrangements, particularly DSB repair, is crucial for optimizing mutagenesis techniques and selecting mutants efficiently [36,37].

4. Applications in plant genetic improvement

Traditionally, diversity has relied on natural variation, sexual recombination, and spontaneous mutations—processes that operate at an intrinsically low rate. However, to meet the demands of a growing population and adapt crops to increasingly unpredictable environmental and biotic conditions, breeders have strategically resorted to using induced mutagenesis with ionizing radiation as a powerful and efficient tool [38]. The capacity of radiation to induce a broad spectrum of mutations randomly and at a high frequency in the genome, which form the basis for improved resistance and productivity traits, solidifies its role as a fundamental pillar in sustainable agriculture [39].

Induced mutagenesis has proven to be one of the most efficient tools for accelerating the mutation rate and generating a wide range of genetic variability in crops [9,38]. This technique has been instrumental in the development of more than 3,400 mutant crop varieties cultivated worldwide, thus solidifying the role of mutagenesis as an indispensable tool in breeding [40].

Its contribution to global food security and the development of resilient cultivars in the face of the climate crisis is widely documented [39]. Its application includes the creation of new traits and agronomic improvements (tolerance to biotic and abiotic stress, improvements in terms of quality), the rectification of specific traits, and the generation of variability in vegetatively propagated crops [12,41].

4.1. Generation of genetic variability and genomic plasticity

Genetic variability is the engine of evolution and the fundamental pillar of any crop breeding program. Although natural diversity and traditional crosses have historically been the main source of new alleles, these processes are intrinsically slow and insufficient to meet the urgency of crop improvement in the current era [4,16,38]. To respond to growing global demands for agricultural production and the need to adapt crops to a changing environment, physically induced mutagenesis has solidified its role as a tool to accelerate the generation of this variability [9,42].

4.2. Improvement of agronomic traits

The adaptation of crops to biotic and abiotic stress conditions is a fundamental pillar for global food security, a challenge that has intensified due to climate change and the emergence of new pests and diseases. In this context, induced mutagenesis has solidified its role as a powerful and proven strategy to generate the necessary genetic variability for plant breeding. Unlike conventional breeding techniques, which rely on natural variability and are intrinsically slow, mutagenesis offers an efficient pathway for the creation of new alleles and the diversification of the gene pool, which is essential for the development of resilient crops in a changing environment [16]. This contrast underscores that traditional breeding, though valuable, is based on processes that do not align with the speed of current agricultural challenges.

At the molecular level, the key to the genetic improvement process resides in the induction of DSBs. Although DSBs represent the most dangerous type of DNA damage, their repair is the basis of genomic plasticity, resulting in a broad spectrum of mutations ranging from single base-pair changes to large-scale chromosomal rearrangements [43,44]. This massive variability, leveraged by plant breeders, has proven effective in improving key agronomic traits, including resistance and tolerance to pathogens [45], to drought and salinity [46], improvement of yield and nutritional value [47], and modification of plant architecture [48]. In this way, physical mutagenesis emerges as an indispensable tool in building more resilient and sustainable agricultural systems for the future.

4.2.1. Progress against biotic and abiotic stress challenges

Global food security faces an unprecedented crisis, demanding the development of resilient crops that can withstand biotic and abiotic stress, challenges intensified by climate change and the emergence of new pests [49,50].

In this context, induced mutagenesis with ionizing radiation has solidified its role as a fundamental and proven strategy to generate the necessary genetic variability for modern plant breeding [51]. Its most significant application is the improvement of crop resistance to various stress factors, both biotic (pests and diseases) and abiotic (environmental), thus demonstrating its crucial role in adapting agriculture to climate change [12,52].

The ability to generate a broad spectrum of mutations randomly and at high frequency allows breeders to access genetic variants that are not found in the natural germplasm [53]. This process is fundamental for the exploration of genetic diversity in plant species, thus constituting a strategic pillar in modern plant breeding [23].

For example, rice varieties with tolerance to multiple types of abiotic stress have been successfully developed through the combination of gamma radiation and in vitro tissue culture [54]. More specifically, the obtainment of rice mutants with tolerance to drought and salinity [55,56], as well as tolerance to submergence [57], has been validated. Similarly, the technique has been applied to develop chickpea lines tolerant to glyphosate [58], considering the challenge in agriculture for weed control.

On the other hand, it has also successfully generated mutants with tolerance to biotic stress, including quarantine diseases that threaten global food security. This is the case with resistance to the fungus *Fusarium oxysporum* f. sp. *cubense* (Foc), the causal agent of Fusarium wilt in banana [59], which is considered the most devastating disease of the Musa genus worldwide. Similarly, resistance has been achieved to the bacterium *Candidatus Liberibacter* [60], which causes Huanglongbing (HLB), considered the most destructive disease of citrus globally.

These advances not only confirm the technical feasibility of physical mutagenesis but also validate its crucial role in building more resilient and sustainable agricultural systems for the future. The use of cutting-edge analyses such as transcriptomic and metabolomic characterization allows for the identification of the molecular mechanisms that confer tolerance to abiotic stresses, such as salinity in barley [61]. Additionally, the implementation of advanced technologies like carbon ion beam radiation [62], strengthens mutagenesis as a precise tool for genetic improvement. Table 1 presents some progress in the generation of tolerant and resistant variants to different biotic and abiotic stress conditions in various crops of agronomic interest.

Table 1. Cases of physical mutagenesis: inducing biotic and abiotic stress tolerance in crops

Crop	Physical mutagen	Valued Trait(s)	Ref.
Wheat (*Triticum aestivum*)	Gamma rays	Resistance to *Puccinia triticina* (Leaf and stem rust)	63, 64
Rice (*Oryza sativa*)	Gamma rays	Tolerance to multiple types of abiotic stress	54
	Gamma rays	Salinity tolerance	56
	Gamma rays	Lodging resistance	65
	Gamma rays	Submergence tolerance	57
Barley (*Hordeum vulgare*)	Gamma rays	High salinity tolerance	61
Maize (*Zea mays*)	Gamma rays	Drought and salinity tolerance	66, 67

Soybean (*Glycine max*)	Gamma rays	Salinity tolerance	68
	Gamma rays	Tolerance to *Macrophomina phaseolina* (charcoal rot)	69
Potato (*Solanum tuberosum*)	Gamma rays	Resistance to *Rhizoctonia solani* (Stem canker and black scurf)	70
	Gamma rays	Resistance to *Ralstonia solanacearum* (Bacterial wilt)	71
Cassava (*Manihot esculenta*)	Gamma rays	Resistance to viruses (Viral diseases)	72
Sugarcane (*Saccharum officinarum*)	Gamma rays	Drought tolerance	73
Banana (*Musa paradisiaca*)	Gamma rays	Resistance to *Fusarium oxysporum* f. sp. cubense (Foc) (Fusarium wilt)	59
Cowpea (*Vigna unguiculata*)	Gamma rays	Drought resilience	74

4.2.2. Progress in yield and quality

The increasing global demand for food and the need for superior nutrition have positioned the improvement of crop yield and quality as central objectives of plant breeding [75,76]. In this context, induced mutagenesis with ionizing radiation has solidified its role as an invaluable tool in plant breeding, offering an effective pathway for the creation of genetic variability; this technique translates into higher productivity and superior nutritional value in crops [38,74].

Many advances confirm the crucial role of ionizing radiation not only in increasing productivity but also in enriching the nutritional profile of crops [77]. This potential is fundamental for addressing the challenges of global food security and malnutrition, positioning mutagenesis as a non-invasive and indispensable technology in modern breeding strategies [38].

Success stories validate its application, where it has been shown that optimizing radiation doses induces physiological and morphological changes that increase seed productivity in wheat [78]. Similarly, the impact of gamma radiation on the nutritional properties of barley microgreens has been validated [79]. These findings are complemented by studies in rice, where gamma ray mutagenesis not only increases agronomic yield but also induces profound changes in the plant's biochemical composition [80]. In legumes, new genetic lines with superior yield have been developed in lentils [81], peanut [82], and chickpea [83]. It has also been validated that gamma ray-induced mutations are an effective tool for biofortification, such as increasing the content of oil and protein levels in soybean [47], which enhances its nutritional value and industrial yield.

These findings not only confirm the capacity of ionizing radiation to increase productivity and yield but also validate its potential to enrich the nutritional profile of crops, a crucial factor for addressing global food security and malnutrition. Table 2 presents some progress in improving the yield, productivity, and nutritional quality in various crops.

Table 2. Cases of physical mutagenesis: improving crop yield and nutritional value

Crop	Physical mutagen	Valued Trait(s)	Ref.
Wheat (*Triticum aestivum*)	Gamma rays	Seed yield	77
Rice (*Oryza sativa*)	Gamma rays	Phytochemical and phytohormonal profiles	79
Barley (*Hordeum vulgare*)	Gamma rays	Phytochemical and bioactive compounds	78
	Nitrogen ion beam	High yield (grain weight and ear type)	84
Maize (*Zea mays*)	X-rays	Improvement in growth, yield, and nutritional value	85
Soybean (*Glycine max*)	Gamma rays	Increased oil and protein content	47
Potato (*Solanum tuberosum*)	Gamma rays	Physicochemical and functional properties	86
Sugarcane (*Saccharum officinarum*)	Gamma rays	Physiological, biochemical, and yield traits	87
Banana (*Musa paradisiaca*)	Gamma rays	Plant height and pseudostem girth	88
Coffee (*Coffea arabica* L.)	Gamma rays	Germination and seedling vigor	89
Tomato (*Solanum lycopersicum* L.)	Gamma rays	Increased phenolic compounds and carotenoids	90

4.2.3. Progress in plant architecture

Plant architecture is a crucial objective in plant breeding, since an optimal structure can directly influence photosynthetic efficiency, stress tolerance, and, fundamentally, the ease of harvest [91,92]. Induced mutagenesis with ionizing radiation has allowed for the specific modification of these morphological traits, enabling scientists to "design" plants with superior agronomic characteristics [93,94].

Ionizing radiation can induce mutations that alter plant height, panicle size, leaf angle, or even straw hardness, thereby generating improved genotypes that facilitate mechanical harvesting and reduce field losses [95,96]. Success stories in this area not only confirm the ability of mutagenesis to influence architecture but also validate its potential to transform agricultural productivity and make it more efficient. Some achievements obtained in various crops of agronomic interest through physical mutagenesis, focused on modifying plant architecture, are detailed in Table 3.

Table 3. Physical mutagenesis cases for advancing crop morpho architecture.

Crop	**Physical mutagen**	**Valued Trait(s)**	**Ref.**
Rice (*Oryza sativa*)	Gamma rays	Plant height (lodging resistance)	97
Barley (*Hordeum vulgare*)	Gamma rays	Plant height and effective tiller number	98
Wheat (*Triticum aestivum*)	Gamma rays	Production of Doubled Haploid (DH) Lines	99
Cotton (*Gossypium hirsutum* L.)	Linear electron accelerator	Fiber length and strength, plant morphology	100
Chili (*Capsicum annuum*)	Gamma rays	Height, branching, and plant hape/form. Number, weight, and size of the fruit.	101
Lentil (*Lens culinaris* Medik.)	Gamma rays	Plant height, root length, pod number	102
Peanut (*Arachis hypogaea* L.)	Gamma rays	Plant height, biomass, and leaf structure	103
Mango (*Mangifera indica*)	Gamma rays	Plant growth and leaf size	104
Banana (*Musa acuminata* L.)	Gamma rays	Short stature (lodging resistance)	105

Coffee (*Coffea arabica* L.)	Gamma rays	Short stature (lodging resistance)	106

5. Conclusions and future perspectives

Induced mutagenesis with physical agents, particularly ionizing radiation, has solidified its role as a powerful and irreplaceable tool in modern plant breeding. Throughout this work, we have elucidated that its effectiveness lies in the ability to generate broad and random genetic variability, while the underlying molecular mechanisms, such as DNA double-strand breaks (DSBs), provide the basis for developing genotypes with superior agronomic traits. The resulting genetic damage is not merely destructive; on the contrary, it fosters a genomic plasticity that, when channeled through rigorous selection programs, leads to the creation of new varieties with high-value attributes.

We have demonstrated, through concrete success stories, that physical mutagenesis is a proven strategy for improving resistance to biotic and abiotic stresses, optimizing yield and nutritional quality, and, crucially, redesigning plant architecture for greater harvesting efficiency. The ability to induce mutations in complex and quantitative characters positions this technique as a fundamental solution to the challenges of global food security, climate change, and the increasing demand for sustainable crops.

Looking ahead, the synergy between physical mutagenesis and cutting-edge omics technologies is the path forward for unprecedented advancement. The application of next-generation genomics will allow for the exhaustive characterization of mutants at the molecular level, precisely identifying the genes and altered alleles responsible for the desired phenotypes. This will not only accelerate the selection process but will also provide essential information to elucidate the molecular networks and genetic mechanisms underlying complex traits.

We propose the integration of mutagenesis with CRISPR/Cas9 technology. Induced mutagenesis programs could massively generate mutant libraries, which would then be screened using gene editing tools to rapidly identify and validate gene function. This combined approach could significantly reduce the development time for new varieties.

Furthermore, the use of ion beam radiation, which offers greater spatial precision and a lower random distribution of mutations, opens the door to more targeted and controlled mutagenesis, minimizing undesired effects and maximizing efficiency.

Physical mutagenesis is not a technology of the past; it is a key tool for the future of agriculture, facilitating the creation of a new generation of more resilient, nutritious, and productive crops for a constantly changing world.

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References

1. Munaweera T, Jayawardana N, Rajaratnam R, Dissanayake N. Modern plant biotechnology as a strategy in addressing climate change and attaining food security. Agric Food Secur. 2022;11(1):1-28. doi: 10.1186/s40066-022-00369-2.
2. Saleem A, Anwar S, Nawaz T, Fahad S, Saud S, Ur Rahman T, et al. Securing a sustainable future: the climate change threat to agriculture, food security, and sustainable development goals. J Umm Al-Qura Univ Appl Sci. 2025;11(3):595-611. doi: 10.1007/s43994-024-00177-3.
3. Swarup S, Cargill E, Crosby K, Flagel L, Kniskern J, Glenn K. Genetic diversity is indispensable for plant breeding to improve crops. Crop Sci. 2021;61(2):839-852. doi: 10.1002/csc2.20377.
4. Salgotra R, Chauhan B. Genetic diversity, conservation, and utilization of plant genetic resources. Genes (Basel). 2023;14(1):174. doi: 10.3390/genes14010174.
5. Martínez-Fortún J, Phillips D, Jones H. Natural and artificial sources of genetic variation used in crop breeding: A baseline comparator for genome editing. Front Genome Ed. 2022;4:937853. doi: 10.3389/fgeed.2022.937853.
6. Garland S, Curry H. Turning promise into practice: Crop biotechnology for increasing genetic diversity and climate resilience. PLoS Biol. 2022;20(7):e3001716. doi: 10.1371/journal.pbio.3001716.

7. Begna T, Teressa T. Genetic variability and its benefits in crop improvement: A review. Middle East J Agric Res. 2024;13(1):128-136. doi: 10.36632/mejar/2024.13.1.6.
8. Ma L, Kong F, Sun K, Wang T, Guo T. From classical radiation to modern radiation: past, present, and future of radiation mutation breeding. Front Public Health. 2021;9:768071. doi: 10.3389/fpubh.2021.768071.
9. Bharat R, Prathmesh S, Sarsu F, Suprasanna P. Induced mutagenesis using gamma rays: biological features and applications in crop improvement. OBM Genet. 2024;8(2):1-27. doi: 10.21926/obm.genet.2402233.
10. Wang Y, Zafar N, Ali Q, Manghwar H, Wang G, Yu L, Ding X, Ding F, Hong N, Wang G. CRISPR/Cas genome editing technologies for plant improvement against biotic and abiotic stresses: advances, limitations, and future perspectives. Cells. 2022;11:3928. doi: 10.3390/cells11233928.
11. Ghanim A. Physical Mutagenesis in Cereal Crops. In: Ghanim A, Sivasankar S, Rich P, editors. Mutation breeding and efficiency enhancing technologies for resistance to striga in cereals. Berlin: Springer; 2023. p. 13-27. doi: 10.1007/978-3-662-68181-7_2.
12. Dhole V, Jegadeesan S, Punniyamoorthy D. Use of gamma rays in crop improvement. In: Kumar N, editor. Plant mutagenesis. Sustainable Landscape Planning and Natural Resources Management. Cham: Springer; 2024. p. 135-157. doi: 10.1007/978-3-031-50729-8_11.
13. Gupta S, Datta A, Pramanik A, Biswas J, Karmakar R. X-ray and gamma irradiation induced chromosomal aberrations in plant species as the consequence of induced mutagenesis-an overview. Plant Arch. 2019;19(2):1973-1979. Available at: http://www.plantarchives.org/19-2/1973-1979%20(5366).pdf
14. Panneerselvam N, Kathiravan V. Physical and chemical agents induced structural and numerical changes. In: Khan A, editor. Mutagenesis, cytotoxicity and crop improvement: Revolutionizing food science. 2021. p. 325-362.
15. Geras'kin S, Bondarenko E, Bitarishvili S. Application of ionizing radiation for crop improvement. Planta. 2025;262(3):1-17. doi: 10.1007/s00425-025-04796-w.
16. Singer S, Laurie J, Bilichak A, Kumar S, Singh J. Genetic variation and unintended risk in the context of old and new breeding techniques. Crit Rev Plant Sci. 2021;40(1):68-108. doi: 10.1080/07352689.2021.1883826.

17. Duarte G, Volkova P, Fiengo Perez F, Horemans N. Chronic ionizing radiation of plants: An evolutionary factor from direct damage to non-target effects. Plants (Basel). 2023;12(5):1178. doi: 10.3390/plants12051178.
18. Miller V, Beying N, Schmidt C, Puchta H. Double strand break (DSB) repair pathways in plants and their application in genome engineering. In: Willmann MR, editor. Genome editing for precision crop breeding. Burleigh Dodds Science Publishing; 2021. p. 27-61. doi: 10.1201/9781003048237.
19. Raina A, Sahu PK, Laskar R, Rajora N, Sao R, Khan S, et al. Mechanisms of genome maintenance in plants: Playing it safe with breaks and bumps. Front Genet. 2021;12:675686. doi: 10.3389/fgene.2021.675686.
20. Shen H, Li Z. DNA double-strand break repairs and their application in plant DNA integration. Genes (Basel). 2022;13(2):322. doi: 10.3390/genes13020322.
21. Szurman-Zubrzycka M, Jędrzejek P, Szarejko I. How do plants cope with DNA damage? A concise review on the DDR pathway in plants. Int J Mol Sci. 2023;24(3):2404. doi: 10.3390/ijms24032404.
22. Ibáñez B, Melero A, Montoro A, San Onofre N, Soriano J. Molecular insights into radiation effects and protective mechanisms: a focus on cellular damage and radioprotectors. Curr Issues Mol Biol. 2024;46(11):12718. doi: 10.3390/cimb46110755.
23. Mir S, Faheem M, Sial M, Ullah G, Leghari K. Mutagenesis: exploring genetic diversity of industrial crop plants. In: Kumar N, editor. Industrial Crop Plants. Singapore: Springer Nature; 2024. p. 73-100. doi: 10.1007/978-981-97-1003-4_3.
24. Poetsch A. The genomics of oxidative DNA damage, repair, and resulting mutagenesis. Comput Struct Biotechnol J. 2020;18:207-219. doi: 10.1016/j.csbj.2019.12.013.
25. Goodhead D, Weinfeld M. Clustered DNA damage and its complexity: Tracking the history. Radiat Res. 2024;202(2):385-407. doi: 10.1667/RADE-24-00017.1.
26. EFSA Panel on Genetically Modified Organisms (GMO), Mullins E, Bresson JL, Dalmay T, Dewhurst IC, Epstein MM, Rostoks N, et al. In vivo and in vitro random mutagenesis techniques in plants. EFSA J. 2021;19(11):e06611. doi: 10.2903/j.efsa.2021.6611.
27. Grin I, Petrova D, Endutkin A, Ma C, Yu B, Li H, et al. Base excision DNA repair in plants: Arabidopsis and beyond. Int J Mol Sci. 2023;24(19):14746. doi: 10.3390/ijms241914746.
28. Cornforth M, Bedford J, Bailey S. Destabilizing effects of ionizing radiation on chromosomes: sizing up the damage. Cytogenet Genome Res. 2021;161(6-7):328-351. doi: 10.1159/000516523.

29. Zhao L, Bao C, Shang Y, He X, Ma C, Lei X, et al. The determinant of DNA repair pathway choices in ionising radiation-induced DNA double-strand breaks. BioMed Res Int. 2020;4834965. doi: 10.1155/2020/4834965.
30. Guo X, Ren J, Zhou X, Zhang M, Lei C, Chai R, et al. Strategies to improve the efficiency and quality of mutant breeding using heavy-ion beam irradiation. Crit Rev Biotechnol. 2024;44(5):735-752. doi: 10.1080/07388551.2023.2226339.
31. Vogt A, He Y. Structure and mechanism in non-homologous end joining. DNA Repair (Amst). 2023;130:103547. doi: 10.1016/j.dnarep.2023.103547.
32. Van de Kamp G, Heemskerk T, Kanaar R, Essers J. DNA double strand break repair pathways in response to different types of ionizing radiation. Front Genet. 2021;12:738230. doi: 10.3389/fgene.2021.738230.
33. Verma P, Tandon R, Yadav G, Gaur V. Structural aspects of DNA repair and recombination in crop improvement. Front Genet. 2020;11:574549. doi: 10.3389/fgene.2020.574549.
34. Dhar M, Koul A. Plant cytogenetics in the era of genome editing. Nucleus. 2024;67(3):595-609. doi: 10.1007/s13237-024-00524-z.
35. Raabe K, Sun L, Schindfessel C, Honys D, Geelen D. A word of caution: T-DNA-associated mutagenesis in plant reproduction research. J Exp Bot. 2024;75(11):3248-3258. doi: 10.1093/jxb/erae114.
36. Tuncel A, Pan C, Clem J, Liu D, Qi Y. CRISPR–Cas applications in agriculture and plant research. Nat Rev Mol Cell Biol. 2025;26:419-441. doi: 10.1038/s41580-025-00834-3.
37. Liu Y, Liu Q, Yi C, Liu C, Shi Q, Wang M, et al. Past innovations and future possibilities in plant chromosome engineering. Plant Biotechnol J. 2025;23(3):695-708. doi: 10.1111/pbi.14530.
38. Sharma V, Thakur M, Maan S, Verma K, Thakur A, Penna S. In vitro mutagenesis: a non-invasive technology for effective crop improvement to assure food and nutritional security—current trends, advancements and future perspectives. J Plant Growth Regul. 2025;44(2):484-507. doi: 10.1007/s00344-024-11484-8.
39. Penna S, Shirani Bidabadi S, Jain SM. Mutation breeding to promote sustainable agriculture and food security in the era of climate change. In: Penna S, Jain SM, editors. Mutation breeding for sustainable food production and climate resilience. Singapore: Springer Nature; 2023. p. 1-23. doi: 10.1007/978-981-16-9720-3_1.

40. Pathirana R. Mutations in plant evolution, crop domestication and breeding. Trop Agric Res Ext. 2021;24(3). doi: 10.4038/tare.v24i3.5551.
41. Manjaya J, Gupta S. Mutation breeding for adaptation to climate change in seed propagated crops. In: Raina A, Wani M, Laskar R, Tomlekova N, Khan S, editors. Advanced Crop Improvement. Vol. 2. Cham: Springer; 2023. p. 197-229. doi: 10.1007/978-3-031-26669-0_8.
42. Animasaun D, Oguntoye E. Mutagenesis in crop improvement: methods and applications. J Crop Improv. 2024;38(3):156-178. doi: 10.1080/15427528.2024.2336257.
43. Kaur G, Chhabra G, Praba UP, Singh R, Kaur S, Kaur J, et al. Mutagenesis in plant tissue culture. In: Kumar N, editor. Plant mutagenesis and crop improvement. Boca Raton: CRC Press; 2024. p. 180-206. doi: 10.1201/9781003392897.
44. Bhattacharya A, Parkhi V, Palan B, Char B. Mutagenesis and TILLING in the era of precise genome editing. In: Bhattacharya A, Parkhi V, Char B, editors. TILLING and Eco-TILLING for crop improvement. Singapore: Springer; 2023. p. 1-34. doi: 10.1007/978-981-99-2722-7_1.
45. Adhikari B, Roy A, Reddy H, Roy D, Das C, Bhattacharyya S, et al. Identification and analysis of gamma-irradiation-induced Stemphylium blight tolerant lentil (*Lens culinaris*) mutant. Int J Radiat Biol. 2024;100(12):1722-1730. doi: 10.1080/09553002.2024.2409667.
46. Khah M, Mir R, Alam Q. Induced mutation technology towards improving stress resilience in plants. In: Improving stress resilience in plants. Academic Press; 2024. p. 389-409. doi: 10.1016/B978-0-443-18927-2.00030-3.
47. Mohsen G, Soliman S, Mahgoub E, Ismail T, Mansour E, Alwutayd K, et al. Gamma-rays induced mutations increase soybean oil and protein contents. PeerJ. 2023;11:e16395. doi: 10.7717/peerj.16395.
48. Sao R, Sahu P, Patel R, Das B, Jankuloski L, Sharma D. Genetic improvement in plant architecture, maturity duration and agronomic traits of three traditional rice landraces through gamma ray-based induced mutagenesis. Plants (Basel). 2022;11(24):3448. doi: 10.3390/plants11243448.
49. Kuo W, Chung C, Juang K, Tung CW, Liu LyD. Challenges to agriculture production under climate change. In: Hussain N, Hung C, Wang L, editors. Agricultural nutrient pollution and climate change. Cham: Springer; 2025. p. 29-56. doi: 10.1007/978-3-031-80912-5_2.
50. Iqbal B, Alabbosh K, Jalal A, Suboktagin S, Elboughdiri N. Sustainable food systems transformation in the face of climate change: strategies, challenges, and policy implications. Food Sci Biotechnol. 2025;34(4):871-883. doi: 10.1007/s10068-024-01712-y.

51. Maan S, Sharma V, Brar J. Improvement of fruit crops through Radiation-Induced Mutations Facing Climate Change. In: Penna S, Jain SM, editors. Mutation breeding for sustainable food production and climate resilience. Singapore: Springer; 2023. p. 693-718.doi: 10.1007/978-981-16-9720-3_23.
52. Chakraborty N, Kant A, Debnath S. Application of nuclear techniques in crop improvement: a review. In: Kumar N, editor. Plant mutagenesis and crop improvement. Boca Ratón: CRC Press; 2024. p. 98-123. doi: 10.1201/9781003392897.
53. Bhardwaj S, Gautam N, Gautam Y, Mishra R. Role of mutation breeding in crop improvement. In: Kumar M, Mishra R, editors. Recent advances in plant breeding. Sharjah: Bentham Science Publishers; 2024. p. 46-61. doi: 10.37446/volbook102024/46-61.
54. Cabusora C, Desamero N, Chico M, Ticman H, Bagarra J, Valida G, et al. New multiple abiotic stress tolerant rice variety developed from combining tissue culture and gamma irradiation. Philipp J Sci. 2024;153(S1):46-61.
55. Bakiruly K, Zhalbyrov A, Kruglyak A, Aleksiayenak Y, Baimbetova G, Yershin Z, et al. Creation of salinity and drought resistant mutant rice forms by ionizing radiation (gamma and neutron radiation). 2023. doi: 10.20944/preprints202304.0590.v1.
56. Watson-Guido W, Arrieta-Espinoza G, Araya-Valverde E, Gatica-Arias A. Salinity stress effects on morphological traits and salt-responsive gene expression in gamma-irradiated rice mutant lines (*Oryza sativa* L. var. *indica*). Plant Cell Tiss Organ Cult. 2025;162(2):1-13. doi: 10.1007/s11240-025-03148-6.
57. Ray B, Nath U, Azad M. Mutagenesis for the development of submergence tolerance rice genotypes in Indica by gamma irradiation-induced mutation using ^{60}Co source isotope with marker assay. Int J Agric Environ Bioresearch. 2022;7(3). doi: 10.35410/IJAEB.2022.5723.
58. Ilyas M, Hameed A, Shah T. Field and biochemical evaluation of glyphosate tolerant chickpea (*Cicer arietinum* L.) mutants developed through induced mutagenesis. BMC Plant Biol. 2024;24(1):1028. doi: 10.1186/s12870-024-05733-x.
59. Costa T, Santos M, de Souza Junior L, Brito D, de Jesus Rocha A, Lino L, et al. Gamma radiation-induced mutagenesis in the development of Cavendish subgroup banana cultivars resistant to *Fusarium oxysporum* f. sp. *cubense*. Euphytica. 2025;221(9):147. doi: 10.1007/s10681-025-03595-4.

60. Purba D, Husni A, Akhidaya A, Kosmiatin M, Purwito A. Effect of gamma ray irradiation and in vitro selection on "Siem Banyuwangi" (*Citrus nobilis* (L)) to Huanglongbing disease. Agrivita. 2021;43(2):358. doi: 10.17503/agrivita.v43i2.2887.
61. Xu H, Halford N, Guo G, Chen Z, Li Y, Zhou L, et al. Transcriptomic and metabolomic analyses reveal the importance of lipid metabolism and photosynthesis regulation in high salinity tolerance in barley (*Hordeum vulgare* L.) leaves derived from mutagenesis combined with microspore culture. Int J Mol Sci. 2023;24(23):16757. doi: 10.3390/ijms242316757.
62. Zhang Y, Wang H, Du Y, Zhang L, Li X, Guo H, et al. Biological responses of an elite centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.) cultivar (Ganbei) to carbon ion beam irradiation. Front Plant Sci. 2024;15:1433121. doi: 10.3389/fpls.2024.1433121.
63. Ragini R, Murukan N, Sekhon NK, Chugh C, Agarwal P, Yadav P, et al. Breaking the association between gametocidal gene(s) and leaf rust resistance gene (LrS2427) in *Triticum aestivum-Aegilops speltoides* derivative by gamma irradiation. Mol Breed. 2024;44:54. doi: 10.1007/s11032-024-01491-8.
64. Murugan G, Kishore B, Murugasamy S, Paramasivan J, Vishwakarma G, Shaligram A, et al. Phenotypic and genotypic characterization of electron beam treated inter-specific (*Triticum dicoccum* Schrank X *Triticum carthlicum* Nevski) lines of emmer wheat for leaf rust and stem rust resistance. Int J Radiat Biol. 2025;101(6):614-625. doi: 10.1080/09553002.2025.2494547.
65. Rani M, Hasibuzzaman A, Begum S. Development of genetically diverse breeding lines through induced mutagenesis for the improvement of Chinigura and Kataribhog aromatic rice (*Oryza sativa* L.) landraces. Int J Radiat Biol. 2025;101(7):761-774. doi: 10.1080/09553002.2025.2498982.
66. Al-Sayed W, El-Shazly H, El-Nahas A, Omran A. Cytogenetic impact of gamma radiation and its effects on growth, yield and drought tolerance of maize (*Zea mays* L.). BMC Plant Biol. 2025;25(1):141. doi: 10.1186/s12870-025-06111-x.
67. Shaebani A, Norouzian M, Behgar M, Borzouei A, Karimzadeh H. Evaluating the role of gamma irradiation to ameliorate salt stress in corn. Int J Radiat Biol. 2023;99(3):523-533. doi: 10.1080/09553002.2022.2110302.
68. Atak Ç, Çelik Ö, Gümüş T, Meric S, Ayan A, Erdoğmuş M. Physiological characterization and assessment of genetic variability, yield, and quality properties of gamma-ray-induced salinity tolerant soybean (*Glycine max* (L.) Merrill) mutants. J Appl Bot Food Qual. 2024;97:140 doi: 10.5073/jabfq.2024.097.017.

69. Samudio-Oggero A, Romero G, Vergara W, Alvarenga O, Núñez J, Tórres B, et al. Determination of the method of induction of mutations by gamma radiation in soybeans (*Glycine max* L. Merrill) for tolerance to carbonic rot produced by the fungus *Macrophomina phaseolina* (Tassi Goid.). MethodsX. 2025;14:103251. doi: 10.1016/j.mex.2025.103251.
70. Kara A, Arici Ş. Determination of gamma rays efficiency against *Rhizoctonia solani* in potatoes. Open Chem. 2019;17(1):254-259. doi: 10.1515/chem-2019-0033.
71. Haque M, Miah M, Hasna M, Afroge M, Akhter S, Babu R. Enhancing potato productivity in Bangladesh: gamma irradiation-induced resistance to bacterial wilt caused by Ralstonia solanacearum. Bangladesh J Nucl Agric. 2025;39(1):101-113. doi: 10.3329/bjnag.v39i1.83341.
72. Baguma J, Ogwok E, Elegba W, Sarkodie A, Otu S, Apio H, et al. Effects of gamma irradiation and ethyl methane sulphonate on morphometric traits and prevalence of common viral diseases and whiteflies in cassava. Afr Crop Sci J. 2021;29(3):355-371. doi: 10.4314/acsj.v29i3.3.
73. Hartati R, Suhesti S, Wulandari S, Ardana I, Yunita R. In-vitro selection of sugarcane (*Saccharum officinarum* L.) putative mutant for drought stress. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing; 2021. Vol. 653. p. 012135. doi: 10.1088/1755-1315/653/1/012135.
74. Diallo S, Badiane F, Diédhiou I, Diouf M, Ngom M, Diouf D. Development of cowpea (*Vigna unguiculata*) mutant lines for dissecting resilience to drought through physiological and molecular crosstalk analysis. Plant Mol Biol Rep. 2025;43(2):428-446. doi: 10.1007/s11105-024-01473-2.
75. Hafeez A, Ali B, Javed M, Saleem A, Fatima M, Fathi A, et al. Plant breeding for harmony between sustainable agriculture, the environment, and global food security: an era of genomics-assisted breeding. Planta. 2023;258(5):97. doi: 10.1007/s00425-023-04252-7.
76. Paniza H. Challenges in plant breeding under climate change: a review. In: Abd-Elsalam K, Abdel-Momen S, editors. Plant quarantine challenges under climate change anxiety. Cham: Springer; 2024. p. 533–556. doi: 10.1007/978-3-031-56011-8_17.
77. Peter M, Uko S, Ahmad H, Babarabi A. The role of mutagenesis in global food security. LJSIR Book Series. Vol. 1. 2025. p. 62. doi: 10.62050/ljsir2025.book.v1.
78. Shabani M, Alemzadeh A, Nakhoda B, Razi H, Houshmandpanah Z, Hildebrand D. Optimized gamma radiation produces physiological and morphological changes that improve seed yield in wheat. Physiol Mol Biol Plants. 2022;28(8):1571-1586. doi: 10.1007/s12298-022-01225-0.

79. Aly A, Eliwa N, Abd El-Megid M, Maraei R. Impact of low-doses gamma radiation on phytochemicals and bioactive compounds in barley microgreens. Int J Radiat Biol. 2025;101(7):730-741. doi: 10.1080/09553002.2025.2494613.
80. Chauhan A, Checker R, Sahu P, Patel R, Baghel S, Sharma D, et al. Agronomic improvement using gamma ray induced mutagenesis is associated with changes in phytochemical and phytohormonal profiles in functional rice variety ‘Gathuwan’. BMC Plant Biol. 2025;25(1):1069. doi: 10.1186/s12870-025-07036-1.
81. Siddiqui M, Khan MT, Nizamani GS, Yasmeen S, Khan I, Khatri A, et al. Field evaluation of high yielding genotypes of lentil (*Lens culinaris* medik.) developed through induced mutagenesis. Pakistan J Agric Res. 2020;33(1):164-169. doi: 10.17582/journal.pjar/2020/33.1.164.169.
82. Mesbahi H, Saibari I, Ezziyyani M, Hamim A. The role of gamma irradiation to induce genetic variability and improve the yield of groundnut (*Arachis hypogaea* L). Arab J Basic Appl Sci. 2025;32(1):103-110. doi: 10.1080/25765299.2025.2500143.
83. Kamal M. Mutagenic effect of gamma rays on biochemical and yield-related traits in Chickpea. J Agric Food Sci Biotechnol. 2024;2(3):290-301. doi: 10.58985/jafsb.2024.v02i03.59.
84. Yu H, Zhang Y, Li H, Feng H. Mutagenesis of Highland barley (*Hordeum vulgare* L. Var. nudum) using nitrogen ion beam implantation: screening of phenotypic variations and comparative transcriptome analysis. BMC Genomics. 2025;26(1):681. doi: 10.1186/s12864-025-11856-8.
85. Mbah E. Improvement of growth, yield and nutritional status of maize (*Zea mays* L.) through X-ray bombardment of seed. Field Veg Crops Res/Ratarstvo Povrtarstvo. 2022;59(3):91-103. doi: 10.5937/ratpov59-38811.
86. Musitia V, Ayua E, Kinyua M, Kamau H. Characterization of physicochemical and functional properties of selected Irish potato varieties developed through gamma irradiation. Sci Prog. 2025;108(2). doi: 10.1177/00368504251336298.
87. Purankar M, Nikam A, Devarumath R, Penna S. Radiation induced mutagenesis, physio-biochemical profiling and field evaluation of mutants in sugarcane cv. CoM 0265. Int J Radiat Biol. 2022;98(7):1261-1276. doi: 10.1080/09553002.2022.2024291.
88. Nandariyah N, Yuniastuti E, Sukaya S, Yudhita S. Selection for growth traits on M1V1 generation of Raja Bulu Banana (*Musa paradisiaca* Linn.) obtained by gamma rays irradiation. Caraka Tani J Sustain Agric. 2021;36(1):97-109. doi: 10.20961/carakatani.v36i1.34492.

89. Dada K, Animasaun D, Mustapha O, Bado S, Foster B. Radiosensitivity and biological effects of gamma and X-rays on germination and seedling vigour of three *Coffea arabica* varieties. J Plant Growth Regul. 2023;42(3):1582-1591. doi: 10.1007/s00344-022-10643-z.
90. Kantoğlu K, İç E, Özmen D, Bulut F, Ergun E, Kantoğlu Ö, et al. Gamma rays induced enhancement in the phytonutrient capacities of tomato (*Solanum Lycopersicum* L.). Front Hortic. 2023;2:1190145. doi: 10.3389/fhort.2023.1190145.
91. Hilioti Z, Antunes D, Kalaitzis P, Merkouropoulos G. Manipulation of plant architecture for crop production. Front Plant Sci. 2024;15:1502833. doi: 10.3389/fpls.2024.1502833.
92. Singh H, Kumar N, Kumar A. Enhancing resource use efficiency in crops through plant functional traits. In: Kumar N, Singh H, editors. Plant functional traits for improving productivity. Singapore: Springer; 2024. doi: 10.1007/978-981-97-1510-7_6.
93. Gupta S, Sharma N. Application of mutagenesis in the improvement of industrial crops. In: Kumar N, editor. Industrial crops improvement. Sustainable Landscape Planning and Natural Resources Management. Cham: Springer; 2025. doi: 10.1007/978-3-031-75937-6_3.
94. Kantoğlu K, Peşkircioğlu H, Ellialtiğlu Ş, Kökpınar Ş. Radiation-Induced mutation for drought tolerance in vegetables. In: Chaudhry U, Öztürk Z, Gökçe A, editors. Drought Stress. Cham: Springer; 2025. doi: 10.1007/978-3-031-80610-0_15.
95. Guo W, Chen L, Herrera-Estrella L, Cao D, Tran L. Altering plant architecture to improve performance and resistance. Trends Plant Sci. 2020;25(11):1154-1170. doi: 10.1016/j.tplants.2020.05.009.
96. Elsherbiny H, Gaballah M, Hamad H, Sakr S, Elbadawy O, Alwutayd K, et al. Inducing potential mutants in rice using different doses of gamma rays for improving agronomic traits. Chil J Agric Res. 2024;84(3):380-390. doi: 10.4067/S0718-58392024000300380.
97. Ramchander S, Andrew-Peter-Leon M, Khan Y, Souframanien J, Arumugam M. Molecular and physiological characterization of early semi-dwarf mutants of rice and localization of SNP variants in Sd1 locus generated through gamma radiation. Int J Radiat Biol. 2024;100(4):650-662. doi: 10.1080/09553002.2024.2304827.
98. Ergün N, Akdogan G, İkincikarakaya S. Impact of gamma radiation on the agronomic properties of naked barley genotypes. Int J Agric Environ Food Sci. 2023;7(3):650-659. doi: 10.31015/jaefs.2023.3.19.

99. Bilgin O, Sarıer S, Başer İ, Balkan A. Enhancement of androgenesis and plant regeneration from wheat anther culture by seed pre-sowing gamma irradiation. Tekirdağ Ziraat Fakültesi Dergisi. 2022;19(2):354-365. doi: 10.33462/jotaf.993270.
100. Zhao Z, Liu Z, Zhou Y, Wang J, Zhang Y, Yu X, et al. Creation of cotton mutant library based on linear electron accelerator radiation mutation. Biochem Biophys Rep. 2022;30:101228. doi: 10.1016/j.bbrep.2022.101228.
101. Hashim A, Rafii M, Yusuff O, Harun A, Juraimi S, Misran A, et al. Genetic consequences of chronic gamma irradiation on agro morphological traits in chili under hydrogel enhance media. Heliyon. 2024;10(4):e25111. doi: 10.1016/j.heliyon.2024.e25111.
102. Pramanik B, Debnath S, Rahimi M, Helal M, Hasan R. Morphometric frequency and spectrum of gamma-ray-induced chlorophyll mutants identified by phenotype and development of novel variants in lentil (*Lens culinaris* Medik.). PLoS One. 2023;18(6):e0286975. doi: 10.1371/journal.pone.0286975.
103. Hafsa M, Mohammed E, Ahlem H, Ahlam H. Study of the effect of gamma irradiation on morpho-physiological parameters and germination of peanut seeds (*Arachis Hypogaea* L.) in fifth generation “M5” hybrids. In: Ezziyyani M, Kacprzyk J, Balas VE, editors. International conference on advanced intelligent systems for sustainable development. Vol. 1402. Cham: Springer; 2024. p. 758-765. doi: 10.1007/978-3-031-91334-1_67.
104. Perveen N, Dinesh M, Sankaran M, Bindu K, Shivashankara K, Ravishankar K, et al. Radiation induced mutations alter morpho-biochemical, anatomical and molecular responses in polyembryonic mango genotype Bappakkai. Plant Physiol Rep. 2025;30(2):284-295. doi: 10.1007/s40502-025-00860-5.
105. Hasim A, Shamsiah A, Hussein S. Induced mutations using gamma ray and multiplication of plantlet through micro cross section culture of banana (*Musa acuminata* cv. Berangan). In: IOP conference series: Earth and Environmental Science. IOP Publishing; 2021. Vol. 757. p. 012007. doi: 10.1088/1755-1315/757/1/012007.
106. Avendaño-Arrazate CH, Gómez-Simuta Y, Martínez-Bolaños M, Méndez-López I, Ortíz-Curiel S, Ariza-Flores R, et al. Gamma radiation of ^{60}Co on morphological and reproductive characteristics of M1 plants in Coffea arabica L. Ecosist Recur Agropecuarios. 2021;8(1). doi: 10.19136/era.a8n1.2730.

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