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*OBM Genetics*

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Review

# Induced Mutagenesis using Gamma Rays: Biological Features and Applications in Crop Improvement

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**Academic Editor:** Yuri Shavrukov

**Special Issue**: Plant Genetics and Mutation Breeding

*OBM Genetics*
2024, volume 8, issue 2
doi:10.21926/obm.genet.2402233

**Received:** December 24, 2023
**Accepted:** April 16, 2024
**Published:** April 29, 2024

**Abstract**

Induced mutagenesis has emerged as an essential field of plant breeding to address global food security challenges, offering tools to enhance crop productivity, resistance, and nutritional value. Among the mutation induction tools, the physical mutagen such as gamma rays holds promise for efficient mutation induction. Gamma rays, a type of high-energy electromagnetic radiation, possess unique characteristics that enable them to penetrate plant tissues and induce genetic mutations. The biological effects are influenced by various factors, including the source, type of radiation, dose rate, absorbed dose, and the sensitivity of the tissues and organs. Gamma rays have been successfully applied to various plant species, producing novel superior mutants for cultivation. This paper explores the different aspects of gamma irradiation, including the radiation facilities, the biological effects of gamma rays on plant species, and the potential applications to generate genetic diversity and unlock desirable trait improvement in crop plants. The paper also showcases successful examples of high-yielding mutants developed through gamma-ray mutagenesis and their impact on agriculture. The potential approach of plant mutagenesis offers to address challenges for plant improvement for sustainable and resilient food production.

**Keywords**

Induced mutations; gamma rays; crop improvement; biological effects; radiation; mutation breeding

## 1. Introduction

Global food security has become a formidable challenge as the world's population continues to proliferate. In response, innovative solutions must be in place to enhance crop yields, improve resistance to pests and diseases, and increase nutritional value [1]. Among the innovative tools in agriculture, induced mutagenesis has become a vital breeding tool for generating novel genetic variability. Induced mutations have played a pivotal role in improving crop plants and releasing many improved mutant varieties for cultivation [2, 3]. Mutant cultivars have contributed significantly to economic growth in many countries, and successful examples include mutants of durum wheat, mutant barley, and many mutant rice varieties grown in Asia and Australia [4, 5].

Radiation-induced mutagenesis has long captivated the scientific community for its ability to interact with biological molecules, especially DNA, leading to alterations in important traits [6]. Through radiation-induced mutagenesis, researchers can access and enhance the genetic variation of extensive genetic diversity within plant populations, accelerating the process of evolution in a directed and precise manner [7]. This unique approach to crop improvement has revolutionized plant breeding, making it a crucial pillar of crop improvement strategies. These genetic mutants constituted the foundational elements underpinning the Green Revolution, a phenomenon that conspicuously elevated wheat yields and ameliorated global nutritional scarcity to a significant degree [8]. Thus, radiation-induced mutagenesis continues to steer technological advances, effectively addressing the complex challenges of crop improvement. This article presents an overview of ionizing radiation, the gamma irradiation facilities employed in plant mutation breeding, and the biological effects of gamma rays on various plant species. Additionally, we highlight successful examples of mutants developed through gamma-ray mutagenesis and the potential of this technique in plant improvement.

### *1.1 Ionizing Radiation*

Ionizing radiation (IR), including X-rays, gamma rays, alpha particles, beta particles, protons, and neutron particularly gamma rays, has become a powerful ally in revolutionizing agriculture [9]. By harnessing gamma rays' ability to induce genetic mutations, researchers can unlock various beneficial traits in plants, thus opening doors to unprecedented genetic diversity and novel characteristics previously inaccessible through traditional breeding methods. Plant scientists can explore genetic diversity on an unparalleled scale through radiation-induced mutagenesis, opening the door to novel and desirable characteristics [10]. Researchers continually explore novel methodologies to enhance crop resilience, productivity, and nutritional value. Among these, gamma rays, a high-energy electromagnetic radiation, has emerged as a powerful tool for directed evolution in plant improvement [11]. Cellular effects of exposure to ionizing radiation (IR) are influenced by various factors, including the source, type of radiation, dose rate, absorbed dose, and the sensitivity of the organism or cells. IR exposure can directly and indirectly damage living cells, particularly affecting DNA, organelles and other cellular components. A notable aspect of ionizing radiation's application lies in the induction of genetic mutations, which expands genetic diversity and generates plants with desired traits. Examining the distribution of mutations resulting from various ionizing radiation sources provides valuable insight into these techniques' effectiveness, and Gamma radiation has yielded a substantial number (1685) of mutants [7].

### 1.1.1 Gamma Rays

With their exceptional energy and penetrating ability, Gamma rays have long been at the forefront of scientific discovery and practical applications. Gamma rays are a form of electromagnetic radiation with the highest energy, ranging from hundreds of keV (kilo-electron volts) to several MeV (mega-electron volts), and the shortest wavelength, typically less than 0.1 nanometres (10-12 meters) in the electromagnetic spectrum. While their use in fields such as medicine and industry is well-established, their entry into plant biology offers exciting opportunities to revolutionize agriculture [12]. At the heart of this new frontier lies radiation-induced mutagenesis, which capitalizes on gamma rays' remarkable capacity to induce genetic mutations in plant DNA. Through carefully controlled exposure, researchers can initiate a cascade of changes within the genetic material, generating a diverse spectrum of mutations that could lead to novel and advantageous traits in plants [8]. Gamma rays hold the promise of reshaping the agricultural landscape by addressing pressing challenges, from enhancing crop productivity and developing resistance to biotic and abiotic stresses to enriching nutritional content, and hence these high-energy rays can offer to innovative methods of developing resilient and nutritious crops for the future [12].

Significant advancements were made through gamma irradiation-induced mutation breeding during the 1960s [11]. These studies spanned various countries and crops. Japan led the charge in 1960 with the development of the Haya-Shinriki rice variety, with exceptional early maturity and quality, while Argentina followed suit in 1962 with the creation of the wheat strain Sinvalocho Gama, prized for its resistance to black stem and leaf rust. Russia joined in 1965 by introducing the tomato cultivar Luch 1, which was celebrated for its early maturity and bountiful yields of red fruit. India contributed with the Co 6608 mutant sugarcane in 1966, heralded for its resilience against red rot. China entered the scene in 1967, presenting the rice and maize hybrid Jidan 1, renowned for its robust resistance to leaf blight. Gamma irradiation played a pivotal role throughout these developments, either directly irradiating seeds, buds, or scions or indirectly through hybridization with gamma-induced mutants (Figure 1). These advancements showcased the potential of mutation breeding and underscored its role in enhancing crop traits for improved agricultural productivity and resilience.

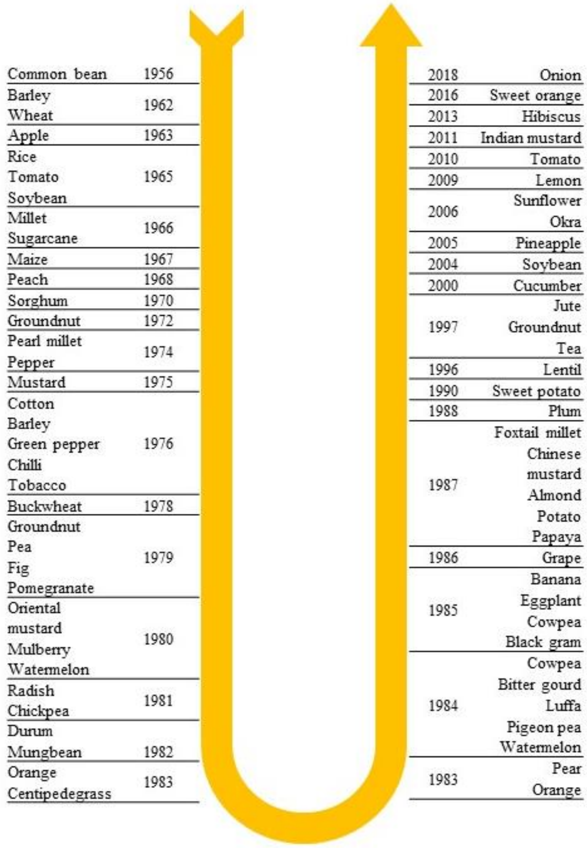


**Figure 1** Chronology of gamma rays- induced mutant development in crops.

Gamma-ray mutagenesis has several advantages over chemical and other mutagens [2]. These include high-frequency mutation induction with a broad mutational spectrum, high penetrance, and precise mutagenic process, thus enabling it as the preferred method to induce genetic variations leading to phenotypic alterations and desired agronomic traits [11]. Induced mutagenesis and cross-breeding are essential and alternative approaches for plant breeders to increase crop productivity and bring genetic changes in desired traits in a given crop. Compared to the transgenic method of gene manipulation, mutagenesis using gamma rays does not have a component of incorporation of alien genes from other plant species, which has environmental and biosafety-related concerns.

### *1.2 Biological Effects*

Cellular effects of exposure to ionizing radiation (IR) are influenced by various factors, including the source, type of radiation, dose rate, absorbed dose, and the sensitivity of the organism or cells. IR exposure can directly and indirectly damage living cells (Figure 2), particularly affecting DNA, organelles like mitochondria and chloroplasts, and other cellular components. Nuclear DNA damage is considered the primary direct consequence of IR exposure. The energy from radiation deposition onto nucleic acid molecules can produce unstable DNA radical cations, breaking phosphodiester bonds and causing base damage. Single-strand breaks (SSBs) and double-strand breaks (DSBs) are the most severe types of DNA damage caused by IR exposure. These breaks can disrupt chromatin organization, transcription, and replication, impacting essential molecular processes and cell functionality [13]. A significant part of the effects is triggered by IR exposure in cells with a high water composition, such as plant cells, is indirect. Water radiolysis occurs when ionizing radiation ionizes $H_2O$ molecules, producing reactive oxygen species (ROS) and free radicals. These ROS can cause oxidative stress, leading to DNA base modifications, SSBs, amino acid modifications, protein fragmentation, and lipid peroxidation. Hydroxyl radicals, in particular, are highly reactive and can damage many cellular molecules. ROS accumulation disrupts membranes' homeostasis, fluidity, ion transport, enzyme activity, protein synthesis, cross-linking, and DNA integrity, ultimately leading to cell death [14]. Although ROS generated upon IR exposure have detrimental effects on cells, they also play important roles as signaling molecules in cell metabolism, stress responses, and plant development. ROS are involved in hormone crosstalk and control various cellular processes from germination to senescence. However, IR exposure disrupts the delicate balance between ROS generation and detoxification, leading to an imbalance in ROS levels and contributing to cellular damage [15].

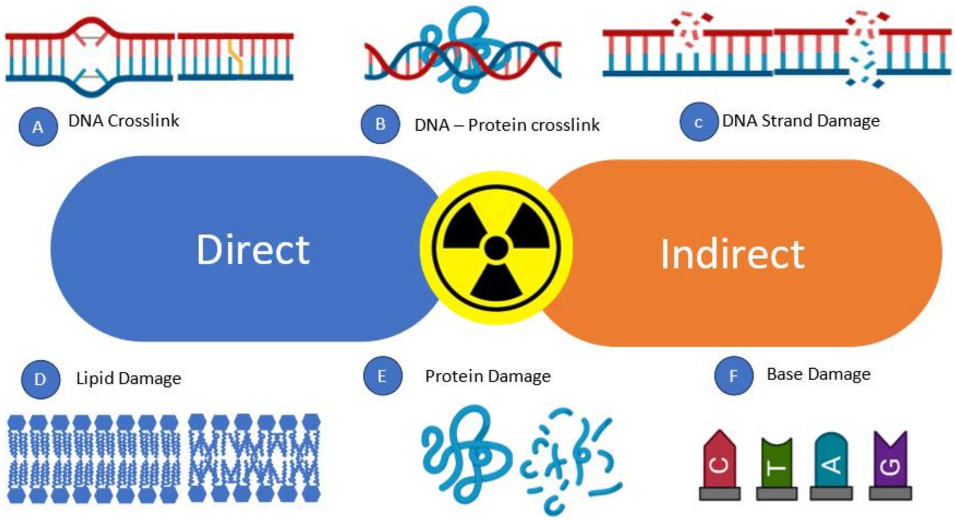


**Figure 2** Effects of exposure to ionizing radiation (IR): direct and indirect damage to living cells.

IR exposure can cause direct or indirect damage to chromatin, the complex of DNA and proteins within the cells. Unstable protein and DNA radicals can recombine and form covalent bonds, leading to DNA intra- or inter-strand crosslinks or DNA-protein crosslinks. These crosslinks prevent DNA strand separation, hampering cell homeostasis and genomic integrity by blocking transcription and replication. The repair process of inter-strand crosslinks may also produce additional DSBs [16]. IR exposure can cause direct DNA damage, organelle damage, and disruption of essential cellular processes, as well as indirect damage through ROS and oxidative stress [17]. The delicate balance between ROS signaling and cellular damage is perturbed upon IR exposure, leading to detrimental effects on cellular functionality and, in extreme cases, cell death.

### *1.3 Source of Gamma Rays*

In plant mutational breeding, the primary sources of gamma radiation-inducing plant mutations are radioactive isotopes, specifically Cobalt-60 ($^{60}Co$) and Cesium-137 ($^{137}Cs$). These artificial radioactive sources emit high-energy gamma rays during their radioactive decay and are commonly utilized in gamma irradiation facilities (Table 1). Cobalt-60 is widely used in gamma irradiation facilities for various applications, including plant mutation breeding [18]. Cobalt-60 has a half-life of approximately 5.27 years, making it a stable and reliable gamma radiation source. Cesium-137 is another artificial radioactive isotope used for gamma-ray irradiation in plant mutation breeding. Cesium-137 has a longer half-life of about 30.17 years and provides a stable and long-lasting source of gamma radiation [12, 19].

**Table 1** Physical properties of radioisotopes: $^{137}$Cs & $^{60}$Co.

| **Characteristics** | **Caesium-137 ($^{137}$Cs)** | **Cobalt-60 ($^{60}$Co)** |
|---|---|---|
| Symbol | $^{137}$Cs | $^{60}$Co |
| Half-life (t1/2) | 30.05 ± 0.08 years | 5.27 years |
| Decay Mode | Beta-minus (β-) and Gamma (γ) | Beta (β) and Gamma (γ) |
| Beta Decay Energy | 0.5120 MeV | 0.317 MeV |
| Gamma-Ray Energy | 0.6617 MeV | 1.1732 MeV, 1.3325 MeV |

## 2. Different Types of Gamma Radiation Facilities

Gamma irradiation facilities play a crucial role in plant mutation breeding to create new varieties with desirable traits [20]. These facilities utilize gamma radiation from radioactive sources, such as Cobalt-60 ($^{60}$Co) and Caesium-137 ($^{137}$Cs), to expose plant materials to controlled doses of ionizing radiation. Among the specialized facilities for this purpose are the Gamma Cell Irradiator, Gamma Phytotron, and Gamma Greenhouse (Table 2).

**Table 2** Different gamma radiation facilities used for mutation induction in plants.

| **Facility** | **Purpose** | **Ionizing Source** | **Target Plant Materials** | **Dose Rates** |
|---|---|---|---|---|
| Gamma Cell Irradiator | Plant mutagenesis and sterilization | Cobalt-60 ($^{60}$Co) | Seeds, cuttings, *in vitro* plant tissues | Controlled doses |
| Gamma Phytotron | Inducing mutations in plant DNA | Cobalt-60 ($^{60}$Co) | Potted plants, *In vitro* organ/tissue cultures/plant tissues | Chronic irradiation |
| Gamma Greenhouse | Mutation induction in plants | Caesium-137 ($^{137}$Cs) | Growing/mature plants | Chronic irradiation |

### *2.1 Gamma Cell Irradiator*

Gamma Cell irradiators, or gamma irradiation facilities or gamma chambers, are specialized equipment for exposing plant materials (seeds, cuttings, or plant tissue cultures) to controlled doses of gamma radiation. These facilities are designed specifically for plant mutagenesis, where the goal is to induce mutations in the DNA of plants to create new varieties with desirable traits [20]. Gamma cell irradiators typically use $^{60}$Co as the gamma radiation source. The radioactive Cobalt-60 is contained in a shielded chamber, and the gamma rays emitted during its decay are directed toward the target plant materials. The irradiation process is carefully controlled to ensure the desired dose of gamma radiation is delivered to the plant samples.

### *2.2 Gamma Phytotron*

The Gamma Phytotron is a specialized facility that employs chronic gamma irradiation to induce mutations. It operates using Cobalt-60 as a radiation source, with an activity level of about 400 curies. The facility has an irradiation room, a non-irradiation room, an acclimation glasshouse, and an operational room. Different dose rates are achieved by placing plants at varying distances from the $^{60}$Co source [21]. The primary purpose of the Gamma Phytotron is to induce beneficial mutations in plants through controlled, prolonged irradiation of living plants. This method generates genetic diversity and develops new plant varieties with desired traits while minimizing growth inhibition. Safety measures include concrete walls, lead-shielded doors around the radiation source, CCD camera monitoring, and automated control systems for environmental conditions [21]. The expansion of the gamma phytotron holds promise for fundamental research and mutagenesis initiatives to advance mutation breeding research and contribute to genetic improvements of crops.

### *2.3 Gamma Greenhouse*

The Gamma Greenhouse (GGH) specializes in inducing plant mutations, utilizing an 800 Ci $^{137}$Caesium- source to generate high-energy gamma rays. These gamma rays can break molecular bonds, particularly in DNA, leading to changes in protein expression [13]. The GGH facility has a concrete-shielded Gamma Greenhouse Dome, a Control Room, and a Tissue Culture Laboratory with a Hardening Area (as per experimental requirements) . Safety is maintained with a buffer zone and fencing around the source. Gamma irradiation is a crucial tool in plant mutagenesis, with chronic and acute radiation methods. Chronic radiation involves prolonged exposure, with the dose rate impacting its effects. Chronic irradiation results in significant, inheritable changes, making it valuable for creating new traits without excessive damage [14]. However, more research is needed in this area.

## 3. Gamma Rays - Mutagenic Effects in Plants

Gamma radiation has various effects on plants, and its impact depends on factors such as the dose, exposure time, and plant species. Several studies have investigated the effects of gamma radiation on plant germination, growth, development, and biochemical characteristics in crops like maize, tulip, wheat, and rice. Figure 3 has depicted a typical flowchart of the steps involved in isolating and developing mutants using conventional and tissue culture methods. Typically, plant seeds, vegetative propagules, or in vitro tissue cultures are exposed to gamma radiation at suitable doses. Then the irradiated plant population is handled through the seed generations or in vitro culture passages. Depending on the plant, ploidy, and desired trait improvement, the irradiated plants are screened for trait improvement in M3 generation or later generations (especially for in vitro cultures). The superior-performing mutants can be exploited directly as improved varieties or can serve as novel breeding material for developing new populations for improved varieties.

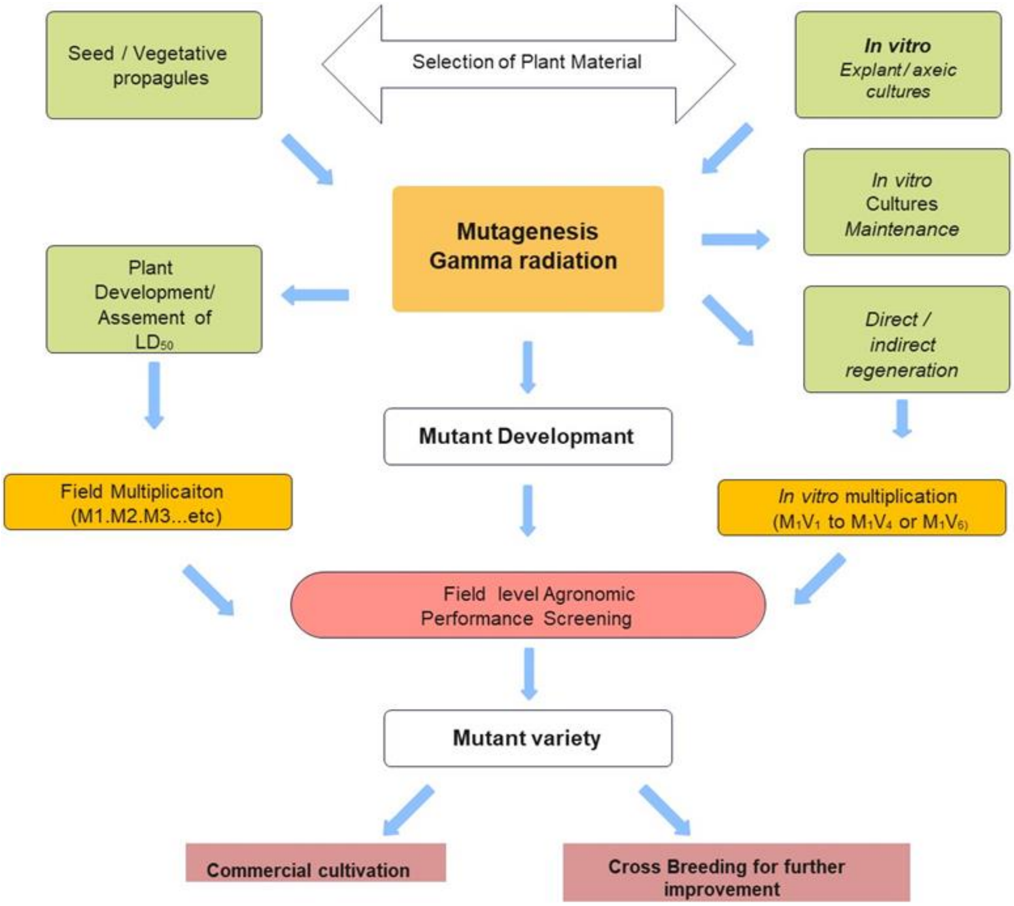


**Figure 3** Flow chart of the steps involved in the gamma radiation-induced mutagenesis and development of mutants.

In maize, exposure to gamma radiation at doses ranging from 0.1 to 1 kGy decreased the germination potential and physiological parameters of seedlings (root and shoot lengths) with increasing irradiation dose. High doses of gamma radiation (≤0.5 kGy) led to the death of plants within 10 days. Additionally, the content of photosynthetic pigments (chlorophyll a, chlorophyll b, carotenoids) showed an inversely proportional relationship to the doses of exposure. Electron spin resonance spectroscopy revealed that the concentration of radiation-induced free radicals linearly depended on the absorbed doses [22]. In tulips, gamma radiation had different effects depending on the dose. Low doses (5 Gy) stimulated bulb germination and improved the survival rate, while higher doses (20 to 100 Gy) significantly inhibited seed germination, growth, flowering rate, and petal number. Gamma radiation also caused changes in chlorophyll content, anthocyanin, flavonoid content, and leaf stomata micromorphology. Irradiation doses from 20 to 100 Gy enhanced the micronucleus rate and induced abnormal chromosomal division behaviour during mitosis. The irradiation doses from 20 to 100 Gy also increased the percentage of polymorphic bands in inter-simple sequence repeat (ISSR) analysis, suggesting genetic variations in tulips. Overall, 80 Gy was considered an appropriate radiation dose to enhance the efficiency of mutagenic breeding in tulip plants [23]. In bread wheat, exposure to gamma radiation at doses of 175, 200, and 250 Gy resulted in a decrease in physiological parameters such as flag leaf area, biomass (NDVI), and chlorophyll content (SPAD) but an increase in days of heading. The germination in mutagen-treated populations was lower than the control, and the dose of gamma rays affected the flag leaf area significantly. The expression of antioxidant-related and DNA-repair-related genes decreased under long-term gamma-ray exposure. Genotype-wise, the effects of gamma radiation varied, with BBVD7-2014 and BBVD22-2016 showing higher flag leaf area and chlorophyll content, respectively. Studies suggest that Gamma radiation could help alter physiological characteristics in wheat [24].

Gamma radiation can induce beneficial mutations in plants, leading to changes in growth, development, and physiological characteristics. However, high doses of gamma radiation can be harmful and inhibit plant growth and development. In rice, acute and chronic gamma irradiation had immediate and ensuing effects on the plant. Acute irradiation had a more significant and immediate impact on physiological parameters, photosynthetic efficiency, and growth. In contrast, chronic irradiation caused long-term damage, leading to reproductive failure in the form of reduced fertility rate and seed production [4]. In pumpkin, low doses (1-5 Gy) of gamma rays did not affect seedling growth significantly, while a high dose (50 Gy) led to growth inhibition. Gamma irradiation caused changes in chloroplasts, mitochondria, and endoplasmic reticulum, as well as the accumulation of hydrogen peroxide ($H_2O_2$) and altered localization of peroxidase (POD) in various tissues [25]. The impact of gamma radiation on plants should be carefully evaluated based on dose, exposure time, and specific plant species, and mutation breeding using gamma irradiation can be a valuable tool in plant improvement and breeding programs.

## 4. Radiation Sensitivity

The sensitivity of plant organisms to radiation emerges as a highly nuanced phenomenon shaped by a myriad of factors. Notably, the radiation sensitivities among different plant species and even within varieties of the same species can exhibit significant variations. The intricate interplay between radiation sensitivity and genome size adds another layer to this complexity. Furthermore, the distinctive sensitivities observed across different plant organs highlight the role of factors such as DNA content and water content in shaping the cellular response to radiation. Within this context, the cell cycle phase, particularly the S phase, emerges as a critical determinant of sensitivity [26]. Cells in this phase, where DNA content undergoes significant increases, and chromosomal DNA molecules are unpacked, stand out as the most vulnerable to the impact of ionizing radiation. A pivotal factor in radiation-induced DNA damage is the production of radicals, particularly hydroxyl radicals, through the intricate interplay between water and radiation [27]. This dynamic process becomes a significant catalyst for DNA damage, accentuating the susceptibility of plant cells to mutagenic effects. Paradoxically, low water content, such as in dry seeds, tends to confer higher resistance to radiation. This resilience, rooted in reduced water availability, adds a layer of adaptability to certain plant materials, shaping their capacity to withstand the potentially harmful effects of ionizing radiation. In this intricate tapestry of radiation sensitivity, the variability among plant species, genome sizes, and cell cycle phases manifests as a complex interplay that researchers must navigate. As gamma mutagenesis and similar techniques advance, a deep understanding of their sensitivities becomes indispensable, guiding scientists toward more precise and practical applications of radiation-induced mutagenesis in plant genetics and crop improvement [28-30].

## 5. Applications in Plant Improvement

Gamma radiation-induced mutation breeding has been a transformative approach in agriculture, yielding generating mutant variants with improved traits and characteristics. This study examines a dataset extracted from the FAO/IAEA Mutant Variety Database, ( [Mutant Variety Database - Home (iaea.org)](https://iaea.org) ) presenting insights into the distribution, trends, and categories of mutant variants developed through gamma radiation-induced mutagenesis **3433** released varieties across **75** countries and **238** species so far (Figure 4). This global dataset reveals the distribution of mutant variants across several countries [31]. China emerges as a leader in gamma-induced mutant variant development, with 825 variants, followed by Japan (501), India (341), Bangladesh (75), the Russian Federation (21657), and the United States (139). This global participation underscores the significance of gamma radiation in crop improvement and its adoption across diverse agricultural landscapes. Almost 75% of the mutants are derived through gamma induced mutagenesis. Examining the years of mutant production provides insights into temporal trends. The years 1983, 1985, and 1986 were marked high yielding varieties [31]. This temporal distribution also reflects the heightened research and development efforts. However, consistent mutant variant production has been observed over the decades, highlighting the sustained importance of gamma radiation-induced mutagenesis.The dataset categorizes mutant variants into distinct categories, shedding light on the diversity of crops subject to gamma radiation-induced mutagenesis (Figure 4). Cereals constitute the largest category, with 1621 mutant variants developed. This category's significance is unsurprising, given the global importance of cereals in food security. Flowers (667, legumes and pulses (468), food vegetables (90), edible oil plants (103), and fibre crops (65) follow the trend [31], contributing to a diverse array of crops benefiting from gamma radiation-induced mutagenesis.

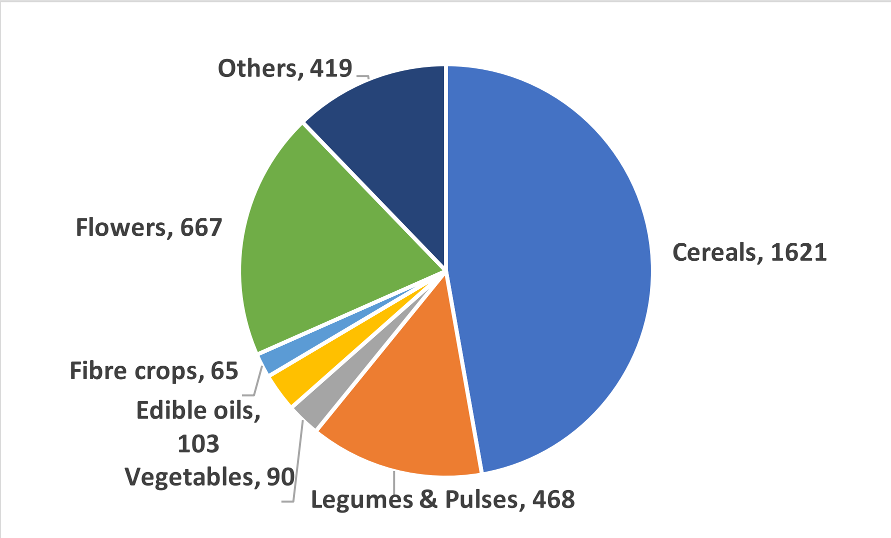


**Figure 4** Diversity of mutant varieties developed through induced mutagenesis.

The prominence of China, Japan, India, and other countries in mutant variant development reflects the global commitment to harnessing gamma radiation for crop improvement. The consistent production of mutant variants across decades indicates the sustained relevance of this approach in modern agriculture. The broad distribution across crop categories emphasizes the versatility of gamma radiation-induced mutagenesis in enhancing various agricultural products. The dataset underscores the importance of collaborative efforts in knowledge sharing and technology transfer facilitated by organizations such as the IAEA. By pooling expertise and resources, countries can collectively accelerate agricultural advancements, contributing to global food security and sustainability. Gamma radiation-induced mutagenesis continues to play a pivotal role in shaping agriculture worldwide. The data from the IAEA database provides a comprehensive snapshot of the global distribution, temporal trends, and categories of mutant variants developed through this approach. As countries continue to invest in research and development and as technology evolves, the impact of gamma radiation-induced mutagenesis on crop improvement is poised to expand, addressing the ever-growing challenges of food security and agricultural sustainability. The introduction of new mutant varieties of crops through radiation-induced mutagenesis has profoundly impacted agriculture, food security, and sustainability, contributing to various Sustainable Development Goals (SDGs) [7, 32].

The increase in rice and groundnut mutants developed through gamma ray-induced mutagenesis since 2000, with a notable concentration in South Asia, highlights a strategic shift towards utilizing advanced biotechnologies for crop improvement. For example, mutation breeding in India has witnessed the development of several prominent varieties [33] including a mutant derivative, Trombay groundnut (TG) variety TAG 24, the linseed variety TL99, with low linolenic acid content suitable for edible oil, the development of the first summer cowpea variety TC 901, high-yielding popular varieties of black gram, green gram, and. Sarsu et al. [34] highlighted that many mutant varieties in Asia, Europe, Latin America, and Africa contributed immensely to the successful economic impact. For example, cotton production was transformed with a broader impact on agriculture in Pakistan by the introduction of 'NIAB 78', which had an early maturity and higher yield and showed wider adaptability. In Peru, improved mutant barley and amaranth varieties have improved their thriving ability at up to 5000 m altitude, thus serving Andean local farmers more food income and enhancing their quality of life. Another mutant barley variety, Centenario II, occupies 18% of Peru's dedicated barley growing area, benefitting a large section of farmers. In Vietnam, several rice and soybean mutant varieties contributed to national socio-economic impact with the cultivation of the rice mutant varieties by more than 4 million farmers and successful soybean cultivation with the occupation of 50% of the soybean area by mutant varieties. This trend suggests a growing recognition of the importance of the mutant varieties in addressing food security challenges, with significant investment and collaboration aimed at enhancing productivity and nutritional quality to meet rising global demands while ensuring sustainability amidst environmental pressures [7]. The advances in genomics and next-generation sequencing methods have offered a new scope for the genome-wide characteristics of mutations induced by gamma rays for evaluating the mutants and, the mutagenic nature of gamma rays [35]. These studies can unravel the mechanisms of mutagenesis and help in fine-tuning the mutant screening for desirable characteristics.

Current and future strategies should integrate research efforts for a diverse panel of challenge driven targets [32], as listed below.

1. **Increased Food Availability:** The adoption of mutant varieties by farmers has led to greater crop yield and growing area. These new varieties have shown a remarkable 32.7% increase in productivity compared to their non-mutated counterparts. This increase in yield has translated into an additional 34.8 million tonnes of produce from 2000 to 2019, contributing significantly to SDG 2 (Zero Hunger).
2. **Improved Quality and Diversity:** The mutant varieties exhibit enhanced quality traits such as gluten-free properties, grain size, shape, color, milling quality, eating quality, and enhanced nutritional content. This may enhance crops' nutritional value and market prices, contributing to greater food diversity and accessibility, aligning with SDG.

3. **Environmental Sustainability:** The mutant varieties play a vital role in reducing agriculture's environmental footprint. They require lower inputs such as chemical fertilizers, pesticides, and water. This has positive implications for SDG 13 (Climate Action) by reducing the use of agrochemicals and for SDG 6 (Clean Water and Sanitation) by conserving water resources.
4. **Economic Benefits for Farmers:** Mutant varieties of crops have demonstrated economic advantages by providing significantly higher yields than traditional varieties. This increased productivity is likely to raise farmers' income and can significantly improve farmers' livelihoods and contribute to economic well-being, aligning with SDG 1 (No Poverty).
5. **Resilience to Environmental Challenges:** Some mutant varieties, like drought-tolerant crop varieties, contribute to the resilience of agriculture in regions with water scarcity or environmental extremities. The mutant varieties are more water-efficient and can thrive in challenging conditions, contributing to SDG 13 (Climate Action) by promoting climate-resilient agriculture.
6. **International Collaboration and Recognition:** The success of radiation-induced mutagenesis in developing mutant crop varieties is exemplified by the collaboration between countries. The development and sharing of mutant varieties demonstrate international cooperation in achieving agricultural sustainability. The development and adoption of mutant crop varieties through radiation-induced mutagenesis can promote positive impact on food security, sustainability, and economic prosperity.

## 6. Conclusions

In conclusion, utilizing gamma radiation-induced mutagenesis is a remarkable testament to humanity's ingenuity in addressing the multifaceted challenges confronting global food security and agricultural sustainability. As highlighted throughout this comprehensive review, ionizing radiation, particularly gamma rays, has catalyzed a paradigm shift in plant breeding and crop improvement strategies. Gamma radiation-induced mutagenesis offers a pathway to unlock the vast reservoir of genetic diversity in plant populations, thereby facilitating the development of novel crop varieties endowed with desirable traits. From enhancing productivity and resilience to improving nutritional content and quality, the transformative potential of gamma radiation-induced mutagenesis transcends traditional breeding constraints, offering a tailored approach to meet the evolving demands of a burgeoning global population. Establishing specialized gamma irradiation facilities, such as gamma cell irradiators, gamma phytotrons, and gamma greenhouses, underscores the concerted efforts to harness this innovative technology for the betterment of agriculture. These facilities provide controlled environments for precise manipulation of radiation doses, ensuring the targeted induction of beneficial mutations while minimizing undesirable effects on plant health and vitality.

As we stand at the precipice of unprecedented global challenges, from climate change to population growth, the imperative to harness innovative agricultural solutions and biotechnological interventions has never been more urgent. Gamma radiation-induced mutagenesis stands as a beacon of hope, offering a viable pathway to navigate the complexities of modern agriculture while fostering resilience, sustainability, and prosperity for generations to come. The journey of gamma radiation-induced mutagenesis embodies the spirit of human ingenuity and collaboration, transcending borders and boundaries in pursuit of a shared vision of a more food-secure, sustainable, and equitable world. Through continued investment, research, and international cooperation, we can fully unleash the transformative potential of this ground-breaking technology, ushering in a new era of agricultural prosperity and resilience on a global scale.

## Author Contributions

SP: Conceptualization, review, editing, finalization; FS: review & Validation. RAB, SPP: Investigation, Writing- original draft, editing.

## Competing Interests

The authors have declared that no competing interests exist.

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