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Gamma-Ray Technology in Secondary Metabolite Production for Sustainable Agriculture: Article Review

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Abstract

The increasing worldwide market for natural products (e.g., pharmaceuticals, food industry) has highlighted the necessity of a more economical and environment-friendly production process. This problem is solved by the gamma-ray as a very promising biotechnological method. Gamma irradiation produced over 60% of commercial varieties of mutant crop, because of its efficient physical mutagenesis and unique biological functions. This approach possesses the possibility of exploiting the mutagenic effects of ionizing radiation, and stimulating genetic variability in plants for agronomic traits (yield parameters) as well as at large crop scale level change in secondary metabolites profiles. In addition to mutagenic induction, gamma rays have been identified as an elicitor by inducing intense plant physiological and molecular changes which lead to the over-production of bioactive molecules. The mode of action might be through induction of DNA damage (e.g. single and double strand breaks) that feed into a novel pathway, or one differently regulated than the other pathways [19], resulting in up-regulation of other secondary metabolites. This review was therefore intended to make completely clear the bioprocess versatility of gamma irradiation, its biological modalities and their actions on in-vivo systems and factor that would translate into metabolite yield capacity crop quality and global agricultural sustainability. The application of this technology provides a real option not just to improve productivity of high-value natural products, but also in delivering new plant germplasms that will make a difference in food security under the challenge of climate change.

1. Introduction

Mounting world demand for naturally occurring compounds occurring compounds in pharmaceuticals, food and dye industries dictates the need for an expeditious method of production which is sustainable (Reshi et al., 2023). An in-depth knowledge of plant biosynthetic pathways of plant biosynthetic pathways and the factors that control synthesis of secondary metabolites becomes crucial for devising cost-effective and environmentally friendly approaches to meet this demand (Reshi et al., 2023). In such a scenario, the gamma-ray technology emerges as an attractive biotechnological tool. Gamma irradiation is a powerful physical mutagen which has contributed to plant breeding programs, with approximately 60% of all mutant crop varieties developed through induced genetic variation that give rise novel traits (Merina Chanu et al., 2020). This method applies mutagenic activity to generate genetic diversity, which can be used for the selection of plants with excellent agronomic traits and improved morphological characteristics, higher yield potential, and, most importantly, enriched secondary metabolite profiles (Hanifah et al., 2020; Chanu et al., 2020; Cahyaningsih et al., 2022).

Gamma radiations are not limited to trigger mutation but it is an elicitor, which brings about different physiological and molecular changes in the plant that may result in increased production of desired compound (Riviello-Flores et al., 2022). This capability to stimulate secondary metabolite

https://journal.uwgm.ac.id/agrifarm/index
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EISSN : 2540-8992
Page : 108-121
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production, positions gamma irradiation as a milestone for green revolution. It opens a path not only to boost the yield of valuable natural products, but also to produce new plant varieties resistant and/or tolerant to stress phenomena, importance for food security during climate change (Nur Hanifah et al., 2022; Riviello-Flores et al., 2022; Bharat et al., 2024). Therefore, the aim of this review is to systematically highlight various applications of gamma radiation which consider biological response in comparison to metabolite production, crop quality and agricultural sustainability.

2. Mechanisms of gamma ray induced mutation

Gamma rays are high-energy ionizing radiation, which induce molecular changes in plant DNA and result in point mutations, deletions, or chromosomal recombination (Du et al., 2022). These mutations are likely to influence the regulation of genes that participate in secondary metabolite biosynthesis pathways. If well managed, such mutant genotypes can exhibit beneficial agricultural traits including increased content of bioactive compounds, tolerance to stress and maintenance of yield stability (Devi et al., 2023). Gamma rays are strong physical mutagens that stimulate genetic mutations by producing free radicals that cause DNA damage in the form of single or double strands breaks which leads to rearrangement in chromosomes as well as point mutations taking place (Adabi & Rezaei, 2023; Musa et al., 2021). These modifications may appear as physiological, biochemical, and morphological changes in plants that affect key processes, including photosynthesis as well as fungal inhibition (Nandariyah et al., 2021). This induced variability is vital for plant breeding programs in generating genotypes with better desirable traits such as increased production of secondary metabolites (Nandariyah et al., 2021). These modifications of the genome can bring about new metabolic pathways or over express the existing ones leading to the increased production of desired secondary metabolites (Kiani et al., 2022, Muhallilin et al., 2019). The magnitude of these changes is dependent on several factors including the species of plant, its developmental stage as well as the particular gamma radiation dose used (Rodge et al., 2023; Riviello-Flores et al., 2022). The effective dose required to induce beneficial mutants without causing phytotoxicity varies for each plant species and growth stage and specific WE is very important to make it successful, This involves high variability depending on plant species, growth stage, and the specific tissue to be irradiated (Fadli et al., 2018; Arumingtyas & Ahyar, 2022). Prior review articles have confirmed the paramount contribution of mutation breeding towards sustainable agriculture. Scientists have well documented that genetically modified crop varieties are sustainable as they reduce dependence on chemical inputs by predisposing resistance to pests and diseases (Penna & Jain, 2023). Furthermore, these cultivars usually show greater nutrient use efficiency and abiotic stress tolerance, which would additionally contribute for environmental sustainability and increased resource-use efficiency. In addition to these positive effects, gamma-ray irradiation has been reported to cause useful alterations at the morphological levels like leaves of different shapes or increased seed yield which can be helpful in increasing agricultural productivity. However, researchers also emphasized that breeders must urgently start working on the development of climate-resilient mutant varieties to cope with environmental stresses and ensure food security (Sharma et al., 2022). In

https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
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Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

addition, by provide a powerful means to create new genetic variation in crop species, which contributes to breeding programmes for better agronomic traits and secondary metabolite profiles. This induction of genetic variability is more important to break the barriers of conventional breeding system and adds new traits which eventually produces improved varieties in terms of quality, quantity and time (Cahyaningsih et al., 2022; Bharat et al., 2024). Maximising the use of radiation (optimising dose) is crucial due to its potential adverse effects for both heat and radio sensitivity; however, well-timed doses can confer high levels of genetic gain (Saibari et al., 2023). For example, gamma irradiation at low dosages can improve growth traits and antioxidant activities, indicating a hormetic effect where slight stress induced by gamma irradiation drives adaptive response. On the other hand, high doses of gamma radiation can cause large amounts of oxidative stress that may cause DNA damage and consequently cell death because its generation outreaches to detoxification (Nindyaresmi et al., 2025). Neverthless, the mode of action followed by gamma radiation affecting secondary metabolite pathway is not fully elucidated yet but believed to be mediated through complex cellular signalistic pathways (Riviello-Flores et al., 2022; Abozahra et al., 2025; Fadli et al., 2018).

3. Application on secondary metabolite production

Gamma radiation is also able to increase the production of secondary metabolites by promoting genetic changes that lead to the activation of cryptic biosynthetic pathways or the upregulation of genes encoding key enzymes involved in well-known pathways (Riviello-Flores et al., 2022). For instance, mild doses of gamma irradiation have been reported to enhance *20-hydroxyecdysone* content in *Sesuvium portulacastrum* and *epicatechin* accumulation in *Hypericum triquetrifolium* callus cultures (Riviello-Flores et al., 2022). Such an influence is linked to radiationinduced induction of defense reactions, frequently implemented by special metabolites synthesis as the protective agents (Nindyaresmi et al., 2025). Also, higher levels of phenolics, flavonoids, and anthocyanins have been continuously showed with more applied doses of radiation over the literature as well as paclitaxel (Adabi & Rezaei, 2023). This upregulation is proposed to be a response to stress, related to how plants adapt to radiation-induced oxidative stress by producing a more extensive array of antioxidant compounds. This stress-triggered metabolic reprogramming can result in marked increase of the bioactivity and diversity of these compounds, which are beneficial for pharmaceuticals and agriculture applications (Wang et al., 2017). Additionally,the yields of defensive compounds and overall plant growth can increase following exposure to controlled dosesof gamma irradiation, which stimulates meristem tissue activity (Nur Hanifah et al., 2022). The effect of gamma radiation on metabolite production largely depends on the dose, duration of exposure, plant species, and studied compounds (Adabi & Rezaei 2023). For example, at low doses, plants have demonstrated increased cell proliferation and stimulated enzyme activity alongside increased crop yield and shrinkage of certain secondary metabolites (Riviello-Flores et al., 2022). This type of stimulatory effect with lower doses, mostly below 100 Gy, is a result of changes at the physiological and cytological levels in plants; these changes include increases in leaf length and width as reported for Echinacea purpurea (Cahyaningsih et al., 2022). In the same way, other works have described that 10 Gy dose can induce higher content of naphthodianthrones in Hypericum callus and the production of greater amounts of alizarin and purpurin on cell cultures of Rubia

AGRIFARM JOURNAL
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cordifolia (Riviello-Flores et al., 2022). On the other hand, despite the positive impact of low doses, high doses (beyond 20 Gy) have been reported to also decrease plant survival and perhaps trigger physiological deviations as observed in Chrysanthemum plants (Cahyaningsih et al., 2022). Nevertheless, this dose-dependent response indicates the crucial role of precise calibration for the achievement of optimal metabolic improvements while minimizing negative influence on plant viability (Adabi & Rezaei, 2023; Hanifah et al., 2022). Studies have shown that certain gamma irradiation doses like 20 and 25 Gy could substantially increase phenolic content in the calluses of Ferula gummosa Boiss up to 36.5% and 38.9%, respectively (Riviello-Flores et al., 2022) as well as promote accumulation of novel triterpenic compounds in Celosia cristata L., when not present in untreated controls (Riviello-Flores et al., 2022). Moreover, it has been reported that a low dose of gamma irradiation could affect bioactive compound and antioxidant activity of C. avellana: the relationship could be assumed between biomass formation and metabolite synthesis was inversely proportional (Adabi et al., 2023). This negative correlation indicates the metabolic trade-off in which investment is switched from growth to defense and additional secondary metabolites are produced instead of total biomass (Adabi & Rezaei, 2023). These results illustrate the intricate relationship between growth and secondary metabolism, allowing γ-radiation to act as an elicitor directing cellular choice (Adabi & Rezaei, 2023). Gamma-irradiation may induce genetic mutations that allow secondary metabolites to be produced in medicinal plants that can activate silent biosynthetic pathways or promote the activity of some enzymes, thus boosting production of bioactive compounds. Such induction is also dependent on the dose wherein low doses stimulate growth and secondary metabolite production, while high doses can be fatal for plant life (Jain et al., 2024). For example, the treatment of gamma irradiation (20–60 Gy) in Echinacea purpurea has enhanced plant survival, field performance and biological activity through controlling antioxidant enzymes leading to better production of proline and phenolic for tolerance against stress condition (Cahyaningsih et al., 2022). Such stimulation is hypothesized to be due to Activation of RNA and protein synthesis at early gertminating stage, Early cell division, Modulation in hormonal signalling pathways and Increased antioxidative potential within plant cells respectively.

4. Alignment with sustainable principles

A part from the direct effect on plant metabolism, gamma irradiation may be considered as a tool for multidimensional resolution of major problems of contemporary agriculture and a key factor to achieve sustainable development goals. This section explains the contribution of the technology in promoting environmentally sound practices, enhancing genetic base and stress tolerance as well as efficient use of resources in addition to economic sustainability in agricultural ecosystems. 1.1 Environment friendly technology The necessity to develop environmental friendly production technologies is growing fast due to population growth, shrinking land space and arable soils destruction (Mann et al., 2007; Buzby et al., 2019). This selective regulation of plant metabolism using gamma irradiation would be useful in sustainable agriculture and may allow the production of high-value compounds with reduced environmental footprint compared to those derived using conventional synthetic processes. Additionally, such measures can be of use both to reduce over

AGRIFARM JOURNAL
https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
EISSN : 2540-8992
Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

exploitation of field collected plants on the one hand and promotion of biodiversity conservation and reduction in disturbance to habitats (Kumar & Sankar, 2024). Its application is in line with modern sustainability standards by improving the usage of resources and reducing the eco-footprints involved in the production of precious natural products, thus contributing to an ecologically safe agriculture pattern. Moreover, plant genetic improvement science by radiation also opens new vistas for possibly unique crops and even forms more dynamic genetic pools of some chosen species to be utilized in the service of sustainable agriculture in such plants (Adabi & Rezaei, 2023; Alami et al., 2024). Furthermore, gamma radiation-mediated elicitation is a cost-effective alternative to enhance secondary metabolite production in plant cells as it does away with the requirement of exogenously added chemical elicitors which may be expensive and/or even pollutant to environment (Thakur et al., 2018; Kandoudi & Németh, 2022). To conclude, the ability of gamma irradiation for carrying out eco-friendly production and enriching the gene pool, effective use of resources while providing maximum economic yield make it a powerful method in environmental sustainability in agriculture. These advantages are especially relevant in an age of growing interest for natural products and urgent requirement for climate resilient food systems. The application of gamma ray technology helps in achieving the basic objectives of agriculture sustainability, by following :

4. 1 Eco-friendly and Non-Chemical Approach

This method is also compliant with organic farming principles as it excludes the use of synthetic reagents, and does not lead to a residue in the environment and final products (Adabi & Rezaei, 2023). This natural process eliminates reliance on toxic pesticides and fertilizers, preserving soil health and water quality. In addition, it is a way to improve crop resistance and quality to achieve global food security and ecological balance of agro-ecosystems. Furthermore, gamma irradiation may induce genetic changes in plants leading to increased resistance to diseases and tolerance to stress factors of the crop plants which might lead to less loss of crops and less demand for pesticide (Riviello-Flores et al., 2022). This fits into the larger goal of sustainable farming by enabling efficient high quality crop production with reduced environmental damage and overall health for the environment. This biotechnological approach enables the growth of various species under controlled conditions, including temperature, light and pH; it was demonstrated that increased amounts of metabolites are obtained compared to traditional cultivation (Miceli et al., 2023). For example, plant Echinacea purpurea in relation to a gamma-irradiation increment of leaf length and surface area at definite doses indicating the possibility of the dose impact on improvement of accumulation biomass under cultivation conditions (Cahyaningsih et al., 2022). These morphophysiological modifications, such as changes in the flowering color and shape caused by doses of 40 and 60 Gy, indicate the possibility of producing new genotypes with improved ornamental features and medicinal values (Cahyaningsih et al., 2022). In addition to morphological changes, the survival rate of E. purpurea plants cultivated in tropical lowland also increased after gamma irradiation implying an increased tolerance against stress conditions (Cahyaningsih et al., 2022).

AGRIFARM JOURNAL
https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
EISSN : 2540-8992
Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

4. 2 Genetic Diversity and Crop Resilience

Gamma rays are powerful means to generate genetic diversity in plant populations aimed at identification of novel traits associated with crop resistance against several biotic and abiotic stresses (Abozahra et al., 2025; Nandariyah et al., 2021). This induced genetic variation is of critical importance to breeding programs that seek to produce crops with improved resistance to disease, pestilence, drought, and salinity; necessities under climate change (Shabani et al., 2022). Such mutagenesis opens fast possibility for the generation of new variations that can survive (and produce foods) even in different harsh conditions and minimize the use of considerable resources (Wang et al., 2017; Cahyaningsih et al., 2022). Gamma rays induce base modifications and the break of single or double DNA strands, leading to advantageous mutations by repair mechanisms such as homologous recombination and non-homologous end-joining (Riviello-Flores et al., 2022). These genetic modifications are able to enhance plant vigor, yield and production of secondary metabolites in this antibiotic category (Cahyaningsih et al.,2022). For instance, in the Mentik Susu rice (Hanifah et al., 2020) have used gamma-ray irradiation doses of 100 Gy and 200 Gy to induce M4 with shorter stems and higher productivity. Such mutagenesis approaches can help not only in the genetic enhancement of food crops, but also facilitate developing novel agro-products with improved human nutritional and therapeutic properties. For example, limited doses of gamma irradiation were reported to enhance total plant dry weight and many of the morphological traits across species such as Chloris gayana (Nindyaresmi et al., 2025).

4.3 Resource Efficiency

This improved productivity and possibly greater genetic diversity represents a means of maximizing resource efficiency within sustainable agroecosystems, supporting the expediency gamma irradiation in this context (Nindyaresmi et al., 2025). For example, fresh, dry and organic matter yield of Chloris gayana cv. Callide in terms of higher biomass production and resource use efficiency (Nindyaresmi et al., 2025). These increases in yields are economically beneficial for farmers and offer a better use of land and water resources (Nindyaresmi et al., 2025). Additionally, gamma ray-induced mutants may result in the production of crops with the better-nutrient efficiency or more efficient photosynthesis to mitigate external inputs such as fertilisers (Shabani et al., 2022). This is another mistress of sustainable agriculture by reducing environmental impact and optimising yield. Molecular markers and protein profiling strategies can serve as useful means to investigate the genetic and biochemical changes induced by gamma-irradiation leading to identification of promising mutants. These generated molecular resources will further benefit the comprehension of the mechanisms underlying better traits and accelerate breeding (Susila et al., 2019). These results are essentials for the wise application of gamma irradiation for crop enhancement for tolerance to abiotic/biotic stresses and its predicted production with an eye to security food production under difficult environment (Susila et al., 2019). This type of design strategy that provided systematic mix of modern biotechnological tools in conjunction with classical plant breeding platform as envisaged through MAB approach indicates the paradigm shift for crop varietal development involving climate-resilient and high-yielding

AGRIFARM JOURNAL
https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
EISSN : 2540-8992
Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

varieties. In addition, its ability to induce genetic variation without genetic segregation and recombination is particularly attractive for use in plant breeding programs in terms of targeted genetic manipulation (Nindyaresmi et al., 2025).

4.4 Economic Sustainability

This way the method decrease the time of plant breeding in producing new varieties with higher economic value but lower cost for farmers. Specifically, increased organic matter accumulation between the treated (Chloris gayana and Sorghum sundanese) irradiated plants indicates an immediate mechanism for increasing biomass to utilize as feedstock or biofuels (Nindyaresmi et al., 2025). Additionally, the reduced breeding periods achieved by gamma ray exposed plants such as with time reduction required in breeding improved Sechium edule from five (5) years to two (2) is economical on the long run thus making better cultivars available much sooner for farmers' production benefits and national economy development (Riviello-Flores et al., 2022). This will result not only in maximum productivity but also increased economic resilience among farming communities, as higher quality products yield higher product prices. Furthermore, the genetic diversity generated by gamma irradiation may lead to increased seed yield which was documented in mutant rice lines leading to higher economic return for farmers (Hanifah et al., 2020). In this manner, risks associated with uncertainties of environmental factors and market fluctuation are reduced to enhance viable sustainable agriculture business (Hanifah et al., 2020). The use of gamma ray and in vitro technology can also serve as an alternative for increasing rates of crop improvement seems to be a sustainable alternative as response to global food security issue, through resistance and productivity improvements (Riviello-Flores et al., 2022; Potts et al., 2023). However, a dual treatment method such as this, especially in the gamma-rays irradiation in addition to physical mutagens; would be highly suggested because of its less harm on environment and the frequency of the desirable mutations is more common than chemical mutations (Due et al., 2019).

4.5 Challenges and Future Perspectives

In spite of its advantages, several challenges remain regarding the optimization of gamma irradiation procedures for different plant species and e the establishment of the stability and heritability of induced mutations in successive generations. Thus, further research is required to optimize the dosage and establish reliable screening procedures in order to more effectively detect and proliferate advantageous genetic variation (Riviello-Flores et al., 2022). Furthermore, the molecular mechanisms and how gamma-ray–induced mutations may influence gene expression under MD regimes need to be clarified for guided breeding. This increased insight will be instrumental in the development of novel agricultural crop cultivars with increased secondary metabolite production that are applicable for sustainable agriculture. For instance, an increase in the metabolic profile of other secondary metabolite that is useful for defense mechanism and commercial purposes can be clearly seen on plant when exposing them by gamma radiation (Cahyaningsih et al., 2022). This manipulation on plant biochemistry level is very exciting for the development of crops with a more resistance to pest and diseases which in turn decreased much reliance on synthetic pesticides as well promote sustainable

https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
EISSN : 2540-8992
Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

agriculture system (Damayanti et al., 2023). The potential of irradiation to induce these changes is of great value for breeding programs directed to obtaining economical produce varieties (species) which are ecologically sound and commercially sustainable as well (Riviello-Flores et al., 2022; Cahyaningsih et al., 2022). Furthermore, the preciseness of gamma-amusement to cause mutations rendering it applicable in altering metabolic pathways intending to produce increased quantity of particular compounds as plant extracted natural products have now become a high-dire need in pharmaceuticals and agriculture (Khamrit & Jongrungklang, 2024).

Although the gamma-ray technology is promising, there are several concerns:

4.5.1 Optimization of radiotherapy doses for different species considering the severity of mutations

Another key challenge of using gamma irradiation for crop breeding is to maintain the genetic integrity and inheritance of good traits generation after generation (Du et al., 2022). Moreover, mutations through molecular gamma irradiation are stochastic and thus efficient screening is needed to isolate an attractive phenotype from a large population (Nandariyah et al., 2021). In addition, the studies on gamma-ray-induced mutations and their effects on gene expression are very important to enhance the efficiency of targeted breeding programs (Cahyaningsih et al., 2022). This new information will be helpful to develop "super crops" for sustainable agriculture that will offer higher secondary metabolite content without the need of affecting any other physiological responses (Due et al., 2019; J & Soosairaj, 2024).

4.5.2 Coupling of mutation breeding with targeted improvement through molecular techniques

This seamless combination ensures the rapid mining and recovery of functional mutations, allowing breeders to greatly speed up their exploitation for developing new crop breeds. These developments make it possible to more rapidly screen germplasm for high phytochemical content, and can thus be used for improved breeding of agroecological types. Conversely, the study of epigenomic changes caused by gamma radiation may provide new ways to alter gene expression and metabolite profiles without changing the DNA sequence (Cahyaningsih et al., 2022). This would enable new avenues to enhance production of secondary metabolites and increased stress resilience in crops, which could positively impact on sustainable agricultural system (Riviello-Flores et al., 2022; Cahyaningsih et al., 2022; Hanifah et al., 2020).

AGRIFARM JOURNAL
https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
EISSN : 2540-8992
Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

4.5.3 Developing biosecurity and regulatory regimes to govern responsible deployment

Furthermore, the molecular mechanisms and how gamma-ray–induced mutations may influence gene expression under MD regimes need to be clarified for guided breeding. This increased insight will be instrumental in the development of novel agricultural crop cultivars with increased secondary metabolite production that are applicable for sustainable agriculture. For instance, an increase in the metabolic profile of other secondary metabolite that is useful for defense mechanism and commercial purposes can be clearly seen on plant when exposing them by gamma radiation (Cahyaningsih et al., 2022). This manipulation on plant biochemistry level is very exciting for the development of crops with a more resistance to pest and diseases which in turn decreased much reliance on synthetic pesticides as well promote sustainable agriculture system (Damayanti et al., 2023). The potential of irradiation to induce these changes is of great value for breeding programs directed to obtaining economical produce varieties (species) which are ecologically sound and commercially sustainable as well (Riviello-Flores et al., 2022; Cahyaningsih et al., 2022). Furthermore, the preciseness of gamma-amusement to cause mutations rendering it applicable in altering metabolic pathways intending to produce increased quantity of particular compounds as plant extracted natural products have now become a high-dire need in pharmaceuticals and agriculture (Khamrit & Jongrungklang, 2024).

5. Conclusion

A holistic approach to crop improvement utilizing gamma-ray technology is essential for establishing high-yielding and sustainable agricultural systems. This technology not only enhances secondary metabolite production but also fortifies food security against the adverse effects of climate change. By inducing beneficial mutations, gamma irradiation increases plant genetic diversity, facilitating the development of crop varieties with superior resilience to environmental challenges. Furthermore, the capacity of this method to augment bioactive compound synthesis offers significant industrial applications in pharmaceuticals and food sectors. Ultimately, gamma-ray irradiation presents an eco-friendly and economically viable strategy to address the global demand for natural products while ensuring long-term food and medicinal security.

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https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
EISSN : 2540-8992
Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

References

Abozahra, M. S., Amin, M. A., Sarker, T. C., Abd-ElGawad, A. M., & Aboelezz, E. (2025). Molecular, biophysical, and biochemical studies on irradiated Zea mays seeds using various sources of gamma rays for dosimetrical applications. *Scientific Reports*, *15*(1). https://doi.org/10.1038/s41598-025-87531-5

Adabi, R., & Rezaei, A. (2023). Influence of mild γ-irradiation on growth and paclitaxel biosynthesis in hazel (Corylus avellana L.) in vitro culture. *Plant Cell Tissue and Organ Culture (PCTOC)*, *156*(1). https://doi.org/10.1007/s11240-023-02618-z

Alami, M. M., Guo, S., Mei, Z., Yang, G., & Wang, X. (2024). Environmental factors on secondary metabolism in medicinal plants: exploring accelerating factors. *Medicinal Plant Biology*, *3*(1), 0. https://doi.org/10.48130/mpb-0024-0016

Arumingtyas, E. L., & Ahyar, A. N. (2022). Genetic diversity of chili pepper mutant (Capsicum frutescens L.) resulted from gamma-ray radiation. *IOP Conference Series: Earth and Environmental Science*. https://doi.org/10.1088/1755-1315/1097/1/012059

Bharat, R. A., Prathmesh, S. P., Sarsu, F., & Suprasanna, P. (2024). Induced Mutagenesis using Gamma Rays: Biological Features and Applications in Crop Improvement. *OBM Genetics*, *8*(2), 1. https://doi.org/10.21926/obm.genet.2402233

Cahyaningsih, A. P., Etikawati, N., & Yunus, A. (2022). Morphological characters variation of Indonesian accession Echinacea purpurea in response to gamma-ray irradiation. *Biodiversitas*. https://doi.org/10.13057/biodiv/d231045

Chaudhary, J., Deshmukh, R., & Sonah, H. (2019). Mutagenesis Approaches and Their Role in Crop Improvement. In *Plants* (Vol. 8, Issue 11, p. 467). Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/plants8110467

Damayanti, F., Roostika, I., Musliman, A., & Widodo, A. (2023). Improvement of Genetic Variation of cv Grand Naeni Bananas Through Gamma-Ray Irradiation and In Vitro Selection Using Fusaric Acid. *Research Square (Research Square)*. https://doi.org/10.21203/rs.3.rs-3332804/v1

Devi, A. M., Devi, K. K., Devi, P. P., Devi, M. L., & Das, S. (2023). Metabolic engineering of plant secondary metabolites: prospects and its technological challenges [Review of *Metabolic engineering of plant secondary metabolites: prospects and its technological challenges*]. *Frontiers in Plant Science*, *14*. Frontiers Media. https://doi.org/10.3389/fpls.2023.1171154

Du, Y., Feng, Z., Wang, J., Jin, W., Wang, Z., Guo, T., Chen, Y., Feng, H., Yu, L., Li, W., & Zhou, L. (2022). Frequency and Spectrum of Mutations Induced by Gamma Rays Revealed by Phenotype

AGRIFARM JOURNAL
https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
EISSN : 2540-8992
Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

Screening and Whole-Genome Re-Sequencing in Arabidopsis thaliana. *International Journal of Molecular Sciences*, *23*(2), 654. https://doi.org/10.3390/ijms23020654

Due, M. S., Susilowati, A., & Yunus, A. (2019). The effect of gamma rays irradiation on diversity of Musa paradisiaca var. sapientum as revealed by ISSR molecular marker. *Biodiversitas*. https://doi.org/10.13057/biodiv/d200534

Fadli, N., Syarif, Z., Satria, B., & Akhir, N. (2018). The Effect of Gamma Cobalt-60 Ray Irradiation on Cultivar Growth in Taro White (Xhanthosoma Sagittifolium L.). *International Journal of Environment, Agriculture and Biotechnology*. https://doi.org/10.22161/ijeab/3.6.9

Hanifah, W. N., Parjanto, Hartati, S., & Yunus, A. (2020). The performances of m4 generation of mentik susu rice mutants irradiated with gamma-ray. *Biodiversitas*. https://doi.org/10.13057/biodiv/d210915

J, J. H., & Soosairaj, S. (2024). Effect of UV B Rays on the Specific Phytochemical Synthesis in Trigonella Foenum-Graecum L. And Raphanus Sativus L. *Research Square (Research Square)*. https://doi.org/10.21203/rs.3.rs-5546273/v1

Jain, D., Bisht, S., Parvez, A., Singh, K., Bhaskar, P., & Koubouris, G. (2024). Effective Biotic Elicitors for Augmentation of Secondary Metabolite Production in Medicinal Plants. *Agriculture*, *14*(6), 796. https://doi.org/10.3390/agriculture14060796

Kandoudi, W., & Németh, É. (2022). Stimulating secondary compound accumulation by elicitation: Is it a realistic tool in medicinal plants in vivo? *Phytochemistry Reviews*, *21*(6), 2007. https://doi.org/10.1007/s11101-022-09822-3

Keiper, F., & Atanassova, A. (2022). Enabling Genome Editing for Enhanced Agricultural Sustainability. *Frontiers in Genome Editing*, *4*. https://doi.org/10.3389/fgeed.2022.898950

Khamrit, R., & Jongrungklang, N. (2024). Determining Optimal Mutation Induction of Philodendron billietiae Using Gamma Radiation and In Vitro Tissue Culture Techniques. *Horticulturae*, *10*(11), 1164. https://doi.org/10.3390/horticulturae10111164

Kiani, D., Borzouei, A., Ramezanpour, S., Soltanloo, H., & Saadati, S. (2022). Application of gamma irradiation on morphological, biochemical, and molecular aspects of wheat (Triticum aestivum L.) under different seed moisture contents. *Scientific Reports*. https://doi.org/10.1038/s41598-022-14949-6

Kumar, D. A. S., & Sankar, P. D. (2024). Plant Bioactive Compounds: Crucial Pharmacological Properties and Role of Elicitors in Enhancing Production. *Indian Journal of Pharmaceutical Education and Research*, *58*(4), 1034. https://doi.org/10.5530/ijper.58.4.115

AGRIFARM JOURNAL
https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
EISSN : 2540-8992
Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

Merina Chanu, A., Thokchom, R., Bhaigyabati, T., Sandhyarani Devi, N., Ronald Meitei, T., & Bhaigyabati, T. (2020). Effect of gamma irradiation on the chlorophyll content of tree tomato (Solanum betaceum Cav.) in M1 generation. *~ 33 ~ The Pharma Innovation Journal*.

Miceli, N., Kwiecień, I., Nicosia, N., Speranza, J., Ragusa, S., Cavò, E., Davì, F., Taviano, M. F., & Ekiert, H. (2023). Improvement in the Biosynthesis of Antioxidant-Active Metabolites in In Vitro Cultures of Isatis tinctoria (Brassicaceae) by Biotechnological Methods/Elicitation and Precursor Feeding. *Antioxidants*, *12*(5), 1111. https://doi.org/10.3390/antiox12051111

Mohanta, T. K., Mishra, A. K., Mohanta, Y. K., & Al-Harrasi, A. (2021). Space Breeding: The Next-Generation Crops [Review of *Space Breeding: The Next-Generation Crops*]. *Frontiers in Plant Science*, *12*. Frontiers Media. https://doi.org/10.3389/fpls.2021.771985

Muhallilin, I., Aisyah, S. I., & Sukma, D. (2019). The diversity of morphological characteristics and chemical content of celosia Cristata plantlets due to gamma ray irradiation. *Biodiversitas*. https://doi.org/10.13057/biodiv/d200333

Musa, Y., Sjahril, R., Nadir, M., Khaerani, P. I., & Sakinah, A. I. (2021). Early growth of post-gamma irradiated Indigofera zollingeriana. *IOP Conference Series Earth and Environmental Science*, *807*(3), 32026. https://doi.org/10.1088/1755-1315/807/3/032026

Nandariyah, Yuniastuti, E., Sukaya, & Yudhita, S. I. (2021). Selection for Growth Traits on M1V1 Generation of Raja Bulu Banana (Musa paradisiaca Linn.) Obtained by Gamma Rays Irradiation. *Caraka Tani: Journal of Sustainable Agriculture*. https://doi.org/10.20961/carakatani.v36i1.34492

Nindyaresmi, A., Umami, N., Kurniawati, A., Anggriani, R., Agussalim, A., & Rahman, M. M. (2025). Mutagenesis Effect Using Gamma Ray Radiation on Morphological Changes, Productivity, and Genetic Variation in Chloris gayana cv. Callide. *Pertanika Journal of Tropical Agricultural Science*, *48*(2). https://doi.org/10.47836/pjtas.48.2.13

Ntsefong, G. N., Ernest, F. P., Constant, L.-L.-N. B., Kinsley, T. M., Hervé, Z. A., Noelle, M. H., & Martin, B. J. (2023). Gamma Ray Induced Mutagenesis for Crop Improvement: Applications, Advancements, and Challenges. In *IntechOpen eBooks*. IntechOpen. https://doi.org/10.5772/intechopen.1002997

Nur Hanifah, W., Nandariyah, Widiyastuti, Y., & Yunus, A. (2022). Morphology and physiology of Echinacea purpurea in the vegetative phase result of gamma ray irradiation. *IOP Conference Series: Earth and Environmental Science*. https://doi.org/10.1088/1755-1315/1016/1/012015

Oliveira, A. C. de, & Vanavichit, A. (2023). Editorial: Generating useful genetic variation in crops by induced mutation, volume III. *Frontiers in Plant Science*, *14*. https://doi.org/10.3389/fpls.2023.1301977

https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
EISSN : 2540-8992
Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

Penna, S., & Jain, S. M. (2023). *Mutation Breeding for Sustainable Food Production and Climate Resilience*. https://doi.org/10.1007/978-981-16-9720-3

Potts, J., Jangra, S., Michael, V. N., & Wu, X. (2023). Speed Breeding for Crop Improvement and Food Security. *Crops*, *3*(4), 276. https://doi.org/10.3390/crops3040025

Reshi, Z. A., Ahmad, W., Лукаткин, А. С., & Javed, S. B. (2023). From Nature to Lab: A Review of Secondary Metabolite Biosynthetic Pathways, Environmental Influences, and In Vitro Approaches [Review of *From Nature to Lab: A Review of Secondary Metabolite Biosynthetic Pathways, Environmental Influences, and In Vitro Approaches*]. *Metabolites*, *13*(8), 895. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/metabo13080895

Riviello-Flores, M. de la L., Cadena-Íñiguez, J., Ruíz-Posadas, L. del M., Arévalo-Galarza, Ma. de L., Castillo-Juárez, I., Soto-Hernández, M., & Castillo-Martínez, C. R. (2022). Use of Gamma Radiation for the Genetic Improvement of Underutilized Plant Varieties [Review of *Use of Gamma Radiation for the Genetic Improvement of Underutilized Plant Varieties*]. *Plants*, *11*(9), 1161. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/plants11091161

Rodge, R. R., Rajan, R., Sharma, S., & Singh, T. (2023). Standardization of suitable Gamma irradiation doses 60 Co for mutagenesis in strawberry (Fragaria × annanasa Duch) cv. Chandler. *Research Square (Research Square)*. https://doi.org/10.21203/rs.3.rs-3643574/v1

Saibari, I., Barrijal, S., Mouhib, M., Belkadi, N., & Hamim, A. (2023). Gamma irradiation-induced genetic variability and its effects on the phenotypic and agronomic traits of groundnut (Arachis hypogaeaL.). *Frontiers in Genetics*, *14*. https://doi.org/10.3389/fgene.2023.1124632

Scharff, L. B., Saltenis, V. L. R., Jensen, P. E., Baekelandt, A., Burgess, A. J., Burow, M., Ceriotti, A., Cohan, J., Geu-Flores, F., Halkier, B. A., Haslam, R. P., Inzé, D., Lankhorst, R. K., Murchie, E. H., Napier, J. A., Nacry, P., Parry, M. A. J., Santino, A., Scarano, A., … Pribil, M. (2021). Prospects to improve the nutritional quality of crops. *Food and Energy Security*, *11*(1). https://doi.org/10.1002/fes3.327

Shabani, M., Alemzadeh, A., Nakhoda, B., Razi, H., Houshmandpanah, Z., & Hildebrand, D. F. (2022). Optimized gamma radiation produces physiological and morphological changes that improve seed yield in wheat. *Physiology and Molecular Biology of Plants*, *28*(8), 1571. https://doi.org/10.1007/s12298-022-01225-0

Sharma, P., Singh, S. P., Iqbal, H. M. N., Parra-Saldívar, R., Varjani, S., & Tong, Y. W. (2022). Genetic modifications associated with sustainability aspects for sustainable developments [Review of *Genetic modifications associated with sustainability aspects for sustainable developments*]. *Bioengineered*, *13*(4), 9509. Taylor & Francis. https://doi.org/10.1080/21655979.2022.2061146

Susila, E., Susilowati, A., & Yunus, A. (2019). The morphological diversity of Chrysanthemum resulted from gamma ray irradiation. *Biodiversitas*. https://doi.org/10.13057/biodiv/d200223

AGRIFARM JOURNAL
https://journal.uwgm.ac.id/agrifarm/index
Volume 14, No 2, December, 2025
EISSN : 2540-8992
Page : 108-121
DOI : 10.24903/ajip.v14i2.3844

Thakur, M., Bhattacharya, S., Khosla, P. K., & Puri, S. (2018). Improving production of plant secondary metabolites through biotic and abiotic elicitation. *Journal of Applied Research on Medicinal and Aromatic Plants*, *12*, 1. https://doi.org/10.1016/j.jarmap.2018.11.004

Tsugawa, H., Rai, A., Saito, K., & Nakabayashi, R. (2021). Metabolomics and complementary techniques to investigate the plant phytochemical cosmos [Review of *Metabolomics and complementary techniques to investigate the plant phytochemical cosmos*]. *Natural Product Reports*, *38*(10), 1729. Royal Society of Chemistry. https://doi.org/10.1039/d1np00014d

Wang, X., Ma, R., Cui, D., Cao, Q., Shan, Z., & Jiao, Z. (2017). Physio-biochemical and molecular mechanism underlying the enhanced heavy metal tolerance in highland barley seedlings pre-treated with low-dose gamma irradiation. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-14601-8