BJRS
BRAZILIAN JOURNAL OF RADIATION SCIENCES

doi.org/10.15392/2319-0612.2025.2917
Braz. J. Radiat. Sci., Rio de Janeiro
2025, 13(3A) | 01-24 | e2917
Submitted: 2025-04-29
Accepted: 2025-06-23

Analysis of the Relationship Between Absorbed Dose and Its Effect on Plant Materials: A Literature Review

Silva[a], M.M.; Diniz[a], E.C.; Maia Neto[a], L. S.; Araujo [a], L.A.; Magnata[a], S.S.L.P.; Amaral[a], A.; Maciel Netto[a], A.; Silva[a], E.B.

[a]Universidade Federal de Pernambuco, 50740-540, Recife, Pernambuco, Brasil.

*Correspondência: mario.mardone@ufpe.br

Abstract: Gamma radiation has been widely explored as a physical elicitor capable of modifying plant metabolism. Its influence on the biosynthesis of secondary metabolites, which play key roles in defense, adaptation, and therapeutic action, has gained increasing interest in phytochemical and pharmacological research. This study aimed to systematically review the effects of gamma radiation on plant-derived secondary metabolites, highlighting dose-response relationships and potential biotechnological applications. A literature review was conducted using PubMed, SciELO, and BVS databases, focusing on studies published between 2019 and 2024. The search strategy included descriptors such as "gamma radiation," "secondary metabolites," and "plant materials." After applying eligibility criteria, 23 studies were selected. The studies revealed that gamma irradiation influences a wide range of secondary metabolites, including phenolics, flavonoids, terpenes, alkaloids, and saponins. Most results indicate that doses (5–100 Gy) tend to enhance the synthesis of bioactive compounds with antioxidant, antimicrobial, and anticancer properties. However, higher doses often lead to inhibitory or toxic effects. The response varied significantly across plant species and compound classes. Gamma irradiation presents great potential to optimize the production of high-value phytochemicals for therapeutic use. Nevertheless, the absence of standardized dose-response profiles and the limited understanding of molecular mechanisms highlight the need for further multidisciplinary research to ensure the safe and effective application of this technology in phytopharmaceutical development.

Keywords: phytotherapeutics, gamma radiation, secondary metabolites.

doi.org/10.15392/2319-0612.2025.2917
Braz. J. Radiat. Sci., Rio de Janeiro
2025, 13(3A) | 01-24 | e2917
Submitted: 2025-04-29
Accepted: 2025-06-23

Análise da relação dose absorvida e seu efeito em materiais vegetais: uma revisão de literatura

Resumo: A radiação gama tem sido amplamente explorada como um agente físico capaz de modificar o metabolismo vegetal. Seu efeito sobre a biossíntese de metabólitos secundários, essenciais para a defesa, adaptação e ação terapêutica das plantas, tem despertado crescente interesse nas pesquisas fitoquímicas e farmacológicas. Este estudo teve como objetivo revisar sistematicamente os efeitos da radiação gama sobre os metabólitos secundários de origem vegetal, destacando as relações dose-resposta e suas possíveis aplicações biotecnológicas. Foi realizada uma revisão da literatura nas bases de dados PubMed, SciELO e BVS, considerando estudos publicados entre 2019 e 2024. Utilizaram-se os descritores "radiação gama", "metabólitos secundários" e "materiais vegetais". Após aplicação dos critérios de elegibilidade, foram selecionados 23 estudos. Os estudos analisados demonstraram que a radiação gama influencia a produção de diversos metabólitos secundários, como fenóis, flavonoides, terpenos, alcaloides e saponinas. A maioria dos resultados indica que doses de (5–100 Gy) promovem o aumento da síntese de compostos bioativos com propriedades antioxidantes, antimicrobianas e anticancerígenas. Por outro lado, doses mais elevadas tendem a apresentar efeitos inibitórios ou tóxicos. As respostas variaram significativamente entre espécies vegetais e classes de compostos. A radiação gama apresenta potencial promissor para otimizar a produção de fitocompostos de alto valor terapêutico. No entanto, a ausência de perfis dose-resposta padronizados e a compreensão limitada dos mecanismos moleculares envolvidos reforçam a necessidade de mais pesquisas multidisciplinares para aplicação segura e eficaz dessa tecnologia no desenvolvimento de fitoterápicos.

Palavras-chave: fitoterápicos, radiação gama, metabólitos secundários.

1. INTRODUCTION

Food irradiation is a processing technology that involves the controlled exposure of food products to specific doses of ionizing radiation, using sources such as gamma rays, X-rays, or accelerated electron beams. The primary purposes of this technique are to eliminate pathogenic microorganisms, inhibit sprouting in tubers, reduce microbial load, and consequently extend the shelf life of foods. Irradiation does not make food radioactive, leaves no residues, and maintains established food safety standards. This technology is currently recognized by international organizations such as FAO, WHO, and IAEA, and is regulated and applied in over 60 countries, including Brazil [1].

Although there is some consumer concern regarding potential impacts on the nutritional and sensory quality of irradiated products, numerous scientific studies have confirmed the efficacy and safety of the process [2][3][4]. In addition to significantly contributing to food safety, irradiation has a positive impact on preserving the physicochemical and nutritional properties of food products. This technology allows for the maintenance of essential bioactive compounds, such as vitamins, polyphenols, and antioxidants, while effectively reducing microbial load without compromising the sensory quality of irradiated foods [5].

Compared to conventional thermal methods, irradiation offers significant advantages, especially by minimizing heat-related losses such as changes in texture, flavor, and nutritional value. As such, it represents a promising technological alternative for food processing, combining microbiological safety with the preservation of organoleptic and functional qualities [6].

In the case of vegetables, irradiation has proven effective in extending shelf life, reducing microbial contamination, and minimizing postharvest losses, without causing significant changes in texture or flavor. Beyond these benefits, exposure to ionizing radiation can influence the chemical composition of plants, particularly regarding secondary metabolites—compounds with recognized biological activities such as antioxidant and antimicrobial effects, as well as therapeutic potential [7].

Secondary metabolites are substances produced by plants that play important ecological roles, including defense against pathogens, attraction of pollinators, and adaptation to environmental stresses. The effect of irradiation on these metabolites depends on several factors, such as the applied dose, type of radiation, and characteristics of the plant species. However, studies have shown that ionizing radiation may increase, decrease, or cause no significant changes in the phytochemical composition of plants. These modifications can result in relevant functional changes, particularly in antioxidant potential, without significantly affecting the sensory characteristics of the food [8].

In this context, the present study aims to evaluate the relationship between gamma radiation exposure and alterations in plant secondary metabolites, considering different dose ranges through a literature review. Understanding these effects is highly relevant, as plant secondary metabolites play a fundamental role in medicine and the pharmaceutical industry due to their antioxidant, antimicrobial, and anti-inflammatory properties. Moreover, the optimized extraction of these compounds, whose overexpression in plants can be promoted through technologies such as irradiation, represents a promising strategy to produce natural ingredients applicable in the formulation of medicines and supplements, offering safer, more sustainable solutions aligned with human health [7][8].

2. MATERIALS AND METHODS

The present research consists of a literature review on the effects of gamma radiation on plants, with a focus on understanding the relationship between different radiation doses and their impacts on plant secondary metabolites.

To develop this study, research was conducted in the PubMed, SciELO, and BVS databases, covering the period from 2019 to 2024. The following descriptors were used: *"secondary metabolites AND gamma radiation"*, *"ionizing radiation AND secondary metabolites"*, *"ionizing radiation AND plant materials"*, *"plant extracts AND gamma radiation"* e *"plant extracts AND ionizing radiation"*.

A total of 1,101 articles were identified. After duplicate removal and eligibility screening, 23 studies were selected to meet the objectives of the review.

3. RESULTS AND DISCUSSIONS

The analysis of the selected articles revealed studies involving various groups of secondary metabolites, such as alkaloids, phenolics, flavonoids, terpenes, saponins, anthocyanins, and triterpenoids. The plant materials investigated cover a wide range of species, including *Satureja hortensis* L., *Catharanthus roseus*, *Celosia cristata* L., *Trigonella foenum-graecum* L. (fenugreek), *Rubia cordifolia*, *Silybum marianum* L., *Zingiber officinale* Rosc (ginger), *Chrysophyllum cainito* L., *Solanum lycopersicum*, *Thymus vulgaris*, *Capsicum annuum*, *Origanum vulgare*, *Brassica oleracea*, and *Allium sativum*, among others.

Given the diversity of compounds and plant species investigated, it became essential to systematize the key information extracted from the studies. Table 1 presents a synthesis of the results, highlighting the types of secondary metabolites analyzed, the plant species used, the gamma radiation doses applied, and the observed effects on the production of these bioactive compounds. This organization provides a comparative overview of the studies, facilitating the identification of patterns and potential applications of ionizing radiation as a tool for the induction or modulation of metabolites with biotechnological interest.

Table 1: Synthesis of results about effects of gamma radiation on secondary metabolites of plant species

Type of Plant	Gamma Radiation Dose (Gy)	Secondary Metabolites	Effect of Radiation	Reference
Plant cell and organogenic cultures	5 - 100	Phenolics, terpenoids, alkaloids	Stimulation of the production of specialized metabolites; induction of mutations for genetic variability; increased plant vigor and productivity.	[9]
Satureja hortensis L.	20, 40, 60, 80, 100	Rosmarinic acid, caffeic acid, essential oils (carvacrol, α-pinene, α-thujene)	Increase in chlorophyll, carotenoids, anthocyanins, phenolic compounds, and flavonoids. Change in the composition of the essential oil.	[10]
Catharanthus roseus	20, 40, 60, 80, 100	Vincristine, vinblastine	Lower doses favored alkaloid synthesis; higher doses reduced production.	[11]
Celosia cristata	25, 50, 75	Flavonoids, saponins, steroids, triterpenoids	Morphological and chemical changes. Production of triterpenoids at 25 Gy.	[12]
Trigonella foenum-graecum L.	100, 200, 300, 400	Trigonelline, nicotinic acid, diosgenin, mucilage	100 Gy stimulated growth and production of bioactive compounds; 400 Gy had an inhibitory effect.	[13]
Rubia cordifolia	2 to 30	Alizarin, purpurin	8 Gy was the most efficient, significantly increasing the production of the compounds.	[14]
Silybum marianum L.	25, 50	Flavonoids, phenolics	25 Gy + phenylalanine increased flavonoids; 50 Gy + phenylalanine increased phenolics.	[15]
Triticum aestivum (colored wheat)	200	Flavonoids and antioxidants	Greater tolerance to salt stress by lower Na^+ accumulation and greater regulation of antioxidant genes.	[16]
Silybum marianum	200, 600	Flavonolignans (silybin A, silybin B, isosilybin A and B, silydianin, silycristin, isosilycristine)	Increase in the production, higher on 600 Gy.	[17]
Catharanthus roseus	20, 40, 60, 80, 100	Vincristine, vinblastine	20 Gy promoted greater biomass growth; 40 Gy favored vinblastine; 20 Gy favored vincristine.	[18]
Trigonella foenum-graecum (fenugreek)	5, 10, 15, 20, 25	Phenolic compounds and antioxidants	Increased systemic resistance against rice blast. 15 Gy reduced incidence by 56.7%.This is assumed to be due to increased secondary metabolites.	[19]
Punica granatum ('Common' pomegranate)	0,0 to 1500	Anthocyanins, total phenolic compounds, antioxidant activity	Improved post-harvest conservation, increased bioactive compounds	[20]
Solanum lycopersicum ('MicroTom')	0,5, 5 and 30	Anthocyanins	Low doses allowed full cycle, 30 Gy was toxic	[21]

Type of Plant	Gamma Radiation Dose (Gy)	Secondary Metabolites	Effect of Radiation	Reference
Underutilized plant species	5 to 100	Phenolics, terpenoids, alkaloids	Increase in bioactive compounds and beneficial mutations	[22]
Prodiginінas (Undecylprodigiosin and butylcycloheptylprodigiosin)	1, 3 and 5	Undecylprodigiosin and butylcycloheptylprodigiosin	Enhanced cytotoxic action at low doses	[23]
Cotinus coggygria *Fragaria ananassa*	15 to 40	Polyphenols, flavonoids, triterpenes	Stimulation of biosynthesis in moderate doses. Greater action of secondary metabolites.	[24]
Thymus vulgaris	1 to 5	Thymol, γ-terpinene and carvacrol	Increased monoterpenes and growth at moderate doses	[25]
Olive pomace (crude and extracted)	5000	Hydroxytyrosol	Increased extraction of phenolic compounds and improved antioxidant activity	[26]
Salvia nemorosa (cell culture)	0–100	Rosmarinic acid (RA), salvianolic B (SAB), ferulic acid (FA) and cinnamic acid (CA)	Up to 20-fold increase in the production of phenolic compounds and improvement in antioxidant activity	[27]
Antipathogenic *(Bacillus subtilis and Trichoderma spp)*	250 to 3500	Total phenols	Increased production of biosurfactants, formation of biofilms and synthesis of antimicrobial enzymes	[28]
Various agricultural crops	50–100	Phenolic compounds, flavonoids, alkaloids	Stimulation of secondary metabolite biosynthesis and increased tolerance to abiotic stress	[29]
Panax ginseng	20	PPD and PPT type ginsenosides	4.2-fold increase in ginsenosides content and obtaining high-productivity mutant lines	[30]
Zingiber officinale (Ginger)	5 to 30	6-Gingerol	Significant increase at 20 Gy	[31]

The study explored the production of specialized metabolites in plant cell and organ cultures, with a particular focus on the role of gamma radiation as an elicitor of secondary metabolism. The study reviews recent advancements in the application of gamma irradiation, emphasizing its dual function in the elicitation of bioactive compounds and the induction of mutations aimed at enhancing the biosynthesis of industrially valuable metabolites. The authors report that gamma radiation has proven effective in the microbiological decontamination of seeds, while also promoting beneficial physiological responses such as enhanced germination and increased seedling vigor. Notably, doses of gamma radiation (5–100 Gy) were found to alleviate abiotic stress and contribute to improved plant productivity. The research further highlights the potential of gamma-induced mutagenesis as a promising approach for generating genetic variability in crops, vegetables, medicinal, and ornamental species. *In vitro* cell and organ cultures are presented as efficient alternatives to traditional methods, providing greater control and yield in specialized metabolite production. The application of elicitors in these in vitro systems has shown effectiveness in studying and intensifying the biosynthetic pathways of secondary metabolites. Among the key classes of compounds discussed are phenolics, terpenoids, and alkaloids. Additionally, the study presents successful cases of gamma radiation-induced mutations leading to increased production of high-value metabolites [9].

In the study conducted by [10], the effects of gamma radiation on *Satureja hortensis* L. were evaluated, focusing on the modulation of secondary metabolites and biochemical characteristics of the plant. For this purpose, dry seeds were exposed to doses of 20, 40, 60, 80, and 100 Gy, with non-irradiated seeds used as the control group. Among the metabolites analyzed were rosmarinic acid, caffeic acid, and essential oil compounds such as carvacrol, α-pinene, and α-thujene. The results showed that higher radiation doses (80 and 100 Gy) significantly increased the contents of chlorophyll, carotenoids, anthocyanins, phenolic compounds, and flavonoids. Furthermore, the composition of the essential oil was altered by irradiation, with an increase in carvacrol and α-pinene levels, accompanied by a reduction in thymol and α-terpinene content. The authors concluded that gamma radiation can act as an effective elicitor during the pre-sowing stage, enhancing the production of phytochemicals in *Satureja hortensis* L. and expanding its potential applications in the food and pharmaceutical industries.

The study investigated the effects of gamma radiation on callus biomass, that is, masses of undifferentiated cells formed *in vitro*, and on the yield of the alkaloid's vincristine and vinblastine in *in vitro* tissues of *Catharanthus roseus*. For this purpose, plant embryos were exposed to doses of 20, 40, 60, 80, and 100 Gy of gamma radiation. The results demonstrated that lower doses (20–40 Gy) significantly stimulated alkaloid synthesis, whereas higher doses exerted an inhibitory effect on the production of these metabolites. Biochemical analyses indicated that irradiation induced cellular stress, promoting an increase in antioxidant enzyme activity and the accumulation of proline, a common marker of stress response. Thus, the authors concluded that gamma radiation can be employed as an effective tool to enhance the production of alkaloids in medicinal plants, with low to moderate doses being more favorable for the biosynthesis of these bioactive compounds [11].

The study conducted by [12] evaluated the effects of gamma radiation on the morphological diversity and chemical profile of *Celosia cristata*. Seeds were exposed to gamma radiation from a Cobalt-60 source at doses of 25, 50, and 75 Gy. Among the secondary metabolites analyzed, flavonoids, saponins, steroids, and triterpenoids were highlighted. The results revealed significant morphological changes in the irradiated plants, including alterations in the coloration and morphology of stems, leaves, and flowers. Phytochemical analysis further indicated the emergence of triterpenoid compounds in a plant exposed to the 25 Gy dose, which were not detected in the control group. Thus, the authors concluded that gamma radiation can serve as an effective tool for inducing chemical and morphological variations in *C. cristata*, with the 25 Gy dose being the most efficient in stimulating triterpenoid production, thereby reinforcing its potential for genetic and phytochemical improvement of ornamental and medicinal species.

The study investigated the effects of gamma radiation on the growth characteristics and phytochemical profile of *Trigonella foenum-graecum* L. (fenugreek). Seeds were exposed to gamma radiation from a Cobalt-60 source at doses of 100, 200, 300, and 400 Gy. The secondary metabolites evaluated included trigonelline, nicotinic acid, diosgenin, and mucilage. The results showed that the 100 Gy dose significantly stimulated plant growth, as evidenced by an increase in leaf number, stem diameter, biomass, and seed production. Furthermore, this dose promoted higher levels of trigonelline and nicotinic acid, compounds known for their bioactive potential. In contrast, higher doses, particularly 400 Gy, exhibited inhibitory effects, leading to a reduction in diosgenin and mucilage synthesis. These findings suggest that exposure to doses of gamma radiation may represent a promising strategy to enhance plant growth and secondary metabolite production in fenugreek, with potential applications in the food, pharmaceutical, and agricultural sectors [13].

The study conducted by [14] investigated the effects of gamma radiation on the biosynthesis of anthraquinones in cell cultures of *Rubia cordifolia*, aiming to enhance the production of the compound's alizarin and purpurin. The cultures were exposed to gamma radiation from a Cobalt-60 source, with doses ranging from 2 to 30 Gy. The results demonstrated that the 8 Gy dose was the most effective, promoting a significant increase in alizarin concentrations, approximately six- and eleven-fold higher, respectively, compared to non-irradiated cultures. Additionally, suspension cultures derived from the irradiated calli were scaled up in an 8-liter bioreactor, where the use of a helical ribbon impeller resulted in a 63.58 % increase in anthraquinone production compared to the Rushton turbine impeller. These findings indicate that the combination of gamma irradiation and the optimization of *in vitro* culture conditions represents a promising strategy to enhance the production of high-value secondary metabolites such as anthraquinones, which are widely used in the pharmaceutical, cosmetic, and textile industries.

The study conducted by [15] evaluated the influence of gamma radiation and phenylalanine on the production of secondary metabolites in callus cultures of Silybum marianum L. In this study, plant seeds were irradiated with doses of 25 and 50 Gy of gamma radiation from a Cobalt-60 source, and calli obtained from stem explants were cultivated with different concentrations of phenylalanine. The metabolites assessed included phenolic compounds and flavonoids. The results showed that the combination of 25 Gy and 1 mg/L of phenylalanine promoted the highest accumulation of flavonoids, while 50 Gy combined with 4 mg/L of phenylalanine resulted in the highest phenolic content (34.27 mg/g dry weight). High-performance liquid chromatography (HPLC) analysis identified eleven flavonoids present in all irradiated cultures, except for acacetin-7-O-rutinoside, which was not detected in the control group. The authors concluded that the combination of gamma radiation and phenylalanine acts as an effective elicitor for stimulating the production of bioactive metabolites in *S. marianum*, representing a promising strategy for applications in the pharmaceutical and nutraceutical industries.

The study conducted by [16] investigated the response to salt stress in mutant colored wheat lines obtained through gamma irradiation. Mutagenesis was induced with a dose of 200 Gy of gamma radiation from a Cobalt-60 source. The focus of the research was on the biosynthesis of flavonoids and other secondary metabolites related to the antioxidant response to salt stress. The results demonstrated that the mutant line PL6 exhibited greater tolerance to salt stress compared to the wild-type line PL1, as evidenced by lower accumulation of Na^+ ions and greater regulation of genes associated with flavonoid metabolism. Additionally, PL6 showed differential expressions of transcription factors, genes related to the circadian cycle, and antioxidant enzymes, suggesting a complex adaptive response induced by the mutation. Based on the data obtained, the authors concluded that gamma irradiation could be a promising strategy for developing wheat cultivars with greater tolerance to salt stress, contributing to sustainable agricultural practices in environments with adverse conditions.

The study investigated the production of secondary metabolites in suspended cell cultures of *Silybum marianum*, obtained from seeds treated with gamma radiation and colchicine. The seeds were subjected to doses of 200 Gy and 600 Gy of gamma radiation, and the effects on the synthesis of flavonolignans — including silibinin A, silibinin B, isosilibinin A, isosilibinin B, silidianin, silicristin, and isosilicristin — were evaluated by HPLC-UV. The results demonstrate that gamma radiation significantly increased the production of these compounds, with the 600 Gy dose being the most effective. This dose was also associated with higher expression of the genes CHS1, CHS2, and CHS3, which are involved in the biosynthetic pathway of silymarin, the main active compound of the species.

Transcriptomic analysis indicated that the CHS2 gene showed the highest variation in gene expression in response to the treatments, suggesting its relevance in the radiation response mechanism. Based on these findings, the authors concluded that gamma radiation represents an effective strategy to optimize the production of silymarin in *S. marianum* cell culture systems, making it a viable and sustainable alternative for large-scale production of this pharmaceutically important metabolite [17].

The study investigated the impact of gamma radiation on callus biomass and the production of vincristine and vinblastine in *Catharanthus roseus* in vitro tissues. The embryogenic tissues were exposed to doses of 20, 40, 60, 80, and 100 Gy to evaluate biomass growth, embryogenesis, and changes in protein, proline, and sugar levels. The results showed that the 20 Gy dose promoted the highest biomass growth. Increasing radiation doses resulted in a decrease in embryogenesis and plant regeneration, with 80 Gy being the most inhibitory dose. Antioxidant enzyme activity (SOD, APX, and CAT) increased with radiation, reaching the highest levels at the 80 Gy dose. Metabolite quantification revealed that the 40 Gy dose promoted the highest accumulation of vinblastine in the leaves (15.13 μg/g DW), while the 20 Gy dose favored vincristine synthesis (6.32 μg/g DW). The authors concluded that moderate doses of gamma radiation (20–40 Gy) can stimulate alkaloid production, while higher doses impair plant growth and regeneration [18].

The research conducted by [19] aimed to evaluate the effects of gamma radiation on extracts from fenugreek seeds (*Trigonella foenum-graecum*) and their ability to induce systemic resistance against rice blast disease (*Magnaporthe oryzae*). Gamma radiation doses of 5, 10, 15, 20, and 25 Gy were used. The secondary metabolites analyzed, including phenolic and antioxidant compounds, were identified by gas chromatography coupled with mass spectrometry (GC-MS). The results indicated that radiation increased the presence of antimicrobial compounds and promoted plant growth, as well as enhanced the deposition of lignin, phenols, and hydrogen peroxide in rice plants treated with irradiated extracts. The 15

Gy treatment provided the greatest protection against the disease, reducing its incidence by 56.7 %. It is concluded that gamma radiation enhances the biochemical activity of fenugreek extracts, strengthening plant defense against pathogens and promoting rice growth.

The study conducted by [20] aimed to optimize extraction protocols for bioactive compounds, characterize the 'Common' pomegranate, and evaluate the effects of gamma radiation on the primary and secondary metabolisms of the fruit. The gamma radiation used was sourced from a cobalt-60 source, with doses of 0.3 kGy, 0.6 kGy, 0.9 kGy, 1.2 kGy, and 1.5 kGy, with an unirradiated control group. The irradiated fruits were stored under controlled conditions, with a temperature of 10 ± 1°C and a relative humidity of 90 ± 5%, for a period of 30 days. Physicochemical and biochemical analyses were performed every 5 days. The secondary metabolites evaluated included anthocyanins and total phenolic compounds, with antioxidant activity assessed. The results indicated that the 1.5 kGy dose resulted in reduced mass loss, while the 0.3 kGy and 0.6 kGy doses promoted an increase in anthocyanin levels in the pulp during storage. The 0.6 kGy dose increased the antioxidant activity of the peel, while the 1.5 kGy dose favored the accumulation of phenolic compounds and maintained the antioxidant activity of the pulp. It is concluded that gamma radiation is an effective tool for preserving post-harvest quality of pomegranate, as well as enhancing the bioactive compounds present in the fruit.

In the research conducted by [21], the effects of gamma radiation on genetically modified tomato plants for biofortification were evaluated, aiming at applications in space agriculture. The plants were irradiated with doses of 0.5 Gy, 5 Gy, and 30 Gy, using a Cobalt-60 (60Co) source. Secondary metabolites, particularly anthocyanins with antioxidant properties, were analyzed. The results indicated that the plant response to radiation varied according to the phenological phase, the dose, and the genotype. The 30 Gy dose prevented the completion of the reproductive cycle, while lower doses allowed to produce viable fruits and seeds. Additionally, the genetically modified plants exhibited greater resistance to radiation, maintaining anthocyanin biosynthesis and showing smaller metabolic variations compared to the unirradiated controls. These findings highlight the potential of biofortification to enhance plant performance in extreme environments, such as outer space.

The authors [22] evaluated the use of gamma radiation for the genetic improvement of underutilized plant varieties, aiming to increase the production of secondary metabolites and genetic variability. The radiation used was gamma radiation, applied to different plant species, with doses ranging from 5 to 100 Gy. Among the secondary metabolites analyzed, phenolics, terpenoids, and alkaloids were highlighted. The effects of radiation on secondary metabolites included increased concentrations of bioactive compounds such as flavonoids and phenylpropanoids, as well as the induction of beneficial mutations for plant adaptation. It was found that gamma radiation can be an effective tool for obtaining genetically improved crops, providing benefits for both agricultural production and the pharmaceutical and cosmetic industries.

The study conducted by [23] aimed to evaluate the cytotoxicity and genotoxicity of the secondary metabolites undecylprodigiosin and butylcycloheptylprodigiosin, in the presence and absence of gamma radiation, focusing on their potential as photosensitizing agents for use in photodynamic therapy against cancer. The gamma radiation doses applied were 1, 3, and 5 Gy. The compounds analyzed belong to the class of prodiginines, known for their antiproliferative properties and anticancer effects. The results revealed that undecylprodigiosin exhibited significantly higher cytotoxicity, being up to five times more toxic at lower radiation doses (1 and 3 Gy) in MCF-7 (breast cancer) and HDF (human fibroblasts) cell lines. On the other hand, butylcycloheptylprodigiosin demonstrated a dose-dependent toxicity pattern, with no significant variations due to radiation. Genotoxicity, assessed by the comet assay, indicated that both compounds induced DNA damage in a dose-dependent manner, with no direct influence of radiation on the induction of these effects. The authors concluded that prodiginines have potential as radiosensitizers at low radiation doses and as radioprotective agents at higher doses, making them promising candidates for the development of innovative antitumor therapies.

In the study conducted by [24], the effects of low-dose gamma radiation (15, 20, 25, 30, 35, and 40 Gy) on biomass production and secondary metabolites in callus cultures of *Cotinus coggygria* (smoketree) and *Fragaria ananassa* (strawberry) were investigated. The analysis of bioactive compounds revealed that radiation stimulated the accumulation of polyphenols in the strawberry calluses irradiated with 30 Gy, while the smoketree calluses showed a significant increase in anthocyanin synthesis, especially at the 20 Gy dose. Radiation also influenced flavonoid production, promoting an increase in the strawberry calluses irradiated with 30 Gy, while reducing their levels in smoketree calluses subjected to the 35 and 40 Gy doses. UPLC-HRMS analysis identified an uncharacterized compound with a 99 % increase in the strawberry calluses treated with 30 Gy, as well as a 51 % increase in the levels of maslinic acid in the smoketree calluses irradiated with 40 Gy. The results highlighted distinct physiological and metabolic responses between the species to gamma radiation, emphasizing the potential of this technology as a biotechnological tool for modulating the biosynthesis of flavonoids and triterpenes *in vitro* cultures.

The study conducted by [25] evaluated the effects of low-dose gamma radiation on the biosynthesis of monoterpenes in *Thymus vulgaris*, with an emphasis on the plant's defense mechanisms. The radiation doses applied ranged from 1 to 5 Gy. Secondary metabolites such as thymol, γ-terpinene, and carvacrol, as well as morphophysiological and biochemical parameters, were analyzed. The results demonstrated that lower to moderate doses (1–3 Gy) stimulated plant growth, enhanced antioxidant enzyme activity, and promoted the overexpression of genes associated with the monoterpene biosynthetic pathway. In contrast, the 5 Gy dose had an inhibitory effect, reducing both plant development and secondary metabolite production. It was concluded that gamma radiation, when applied at moderate doses, can be an efficient strategy for inducing the production of bioactive compounds in aromatic plants, with potential applications in the agricultural, pharmaceutical, and nutraceutical fields.

The work conducted by [26] evaluated the effects of gamma radiation on improving the extraction and bioactivity of phenolic compounds present in olive pomace, a byproduct of the olive oil industry. The radiation used was gamma, with a dose of 5000 Gy. The irradiated material included raw olive pomace (Crude Olive Pomace – COP) and extracted olive pomace (Extracted Olive Pomace – EOP). The main secondary metabolite analyzed was hydroxytyrosol, identified as the predominant phenolic compound in the extracts (24–25 mg/g). The results indicated that gamma radiation increased phenolic compound extraction by at least twofold, improved antioxidant activity in the EOP, and maintained protection against oxidation-induced hemolysis. It was concluded that gamma irradiation at 5 kGy could be a promising technology for valorizing olive oil production waste, enhancing the extraction of bioactive compounds and their functional properties.

The study investigated the influence of gamma radiation and elicitation with carboxyl-functionalized carbon nanotubes (MWCNT-COOH) on the production of phenolic acids in suspension cell cultures of *Salvia nemorosa*. The radiation used was gamma, with doses ranging from 10 to 100 Gy, with 70 Gy being the most effective dose. The irradiated plant material consisted of leaf-derived calluses. The secondary metabolites analyzed were rosmarinic acid (RA), salvianolic acid B (SAB), ferulic acid (FA), and cinnamic acid (CA). The results indicated that the calluses irradiated with 70 Gy showed the highest levels of these compounds, with a significant increase in the cell culture established from these calluses. The combination of gamma radiation with MWCNT-COOH elicitation resulted in up to 20-fold increases in phenolic compound production compared to untreated plants, as well as enhanced antioxidant activity. In summary, the selection of cell lines combined with elicitation can be an effective approach for the large-scale production of secondary metabolites in *S. nemorosa* [27].

The study investigated the effects of gamma radiation on the induction of mutations in biocontrol agents of phytopathogens. The radiation used was gamma, with doses ranging from 0.25 kGy to 3.5 kGy. The study focused on microorganisms *Bacillus subtilis* and *Trichoderma spp.*, evaluating changes in their metabolic and functional capabilities after irradiation. The secondary metabolites analyzed included hydrolytic enzymes, antibiotics, and total phenols. The results demonstrated that gamma radiation induced significant changes in the genomic profile of microorganisms, resulting in increased production of biosurfactants, biofilm formation, and the synthesis of antimicrobial enzymes. These modifications enhanced the efficacy of the irradiated organisms in controlling pathogenic fungi such as *Aspergillus flavus* and *Penicillium expansum*. The authors concluded that gamma radiation represents a promising tool for the genetic modification of biocontrol agents, expanding their potential in plant disease protection [28].

The study conducted by [29] analyzed the potential of gamma radiation as a tool to mitigate abiotic stresses and promote increased agricultural productivity. The radiation doses applied ranged from 50 to 100 Gy. The research consisted of a comprehensive review of the application of gamma radiation in various agricultural crops, focusing on the induction of physiological and biochemical responses aimed at the production of secondary metabolites, such as phenolic compounds, flavonoids, and alkaloids. The results indicated that gamma radiation, at low doses, can enhance nutrient absorption, modulate the biosynthesis of secondary metabolites, and regulate metabolic pathways essential for plant tolerance to adverse environmental conditions such as drought, salinity, and extreme temperature variations. It was concluded that the controlled application of gamma radiation represents a promising and sustainable strategy to strengthen plant resistance to environmental stresses, contributing to increased agricultural productivity and efficient management of cultivated ecosystems.

The study conducted by [30] investigated the effect of gamma radiation in inducing mutations to increase biomass and ginsenoside content in callus and adventitious root cultures of *Panax ginseng* Mayer. The radiation used was gamma, with varying doses, with the best results obtained at 20 Gy. The irradiated cultures included calli and adventitious roots maintained for both short-term (1 year) and long-term (20 years). The secondary metabolites analyzed were PPD and PPT-type ginsenosides, quantified by HPLC. The results indicated that the mutants derived from radiation exhibited a 4.2-fold increase in total ginsenoside content compared to the control, with the mutant line 1G-20-19 showing the highest productivity. It was concluded that gamma radiation can be used as an efficient tool for the commercial production of ginsenosides, highlighting the importance of mutagenesis for improving the quality and yield of secondary metabolites *in vitro* ginseng cultures.

The study conducted by [31] investigated the use of gamma radiation to induce genetic variability in ginger (*Zingiber officinale*). The researchers applied radiation doses ranging from 5 to 30 Gy and evaluated the 6-gingerol content in the M1 and M2 generations using HPLC. Radiation at 20 Gy resulted in a significant increase in 6-gingerol content, reaching 38.4 mg/g compared to the control, which showed 22.1 mg/g. The induced genetic variability was confirmed through RAPD-PCR analysis. This study represents the first investigation into the use of gamma radiation to enhance 6-gingerol content in ginger.

The analysis of the relationship between gamma radiation dose and the effects on secondary metabolites in plant materials reveals the transformative potential of this technology for phytopharmaceutical science and the pharmaceutical industry. The studies reviewed indicate that, although there is no universal response pattern, most show a tendency toward enhanced production of compounds such as phenolics, flavonoids, and terpenes, which possess antioxidant, antimicrobial, and anticancer properties. This enhancement of metabolites is particularly relevant for the development of natural products with greater therapeutic value and may represent a promising strategy to optimize the production of herbal medicines safely and efficiently. However, the variability of responses among different plant species and the lack of detailed mapping of the molecular mechanisms underlying these changes highlight the need for further research.

Future studies should aim to establish species-specific dose-response patterns and investigate the stability of the compounds over time and during storage. Understanding these factors is essential to maximize the benefits of gamma irradiation while balancing the stimulation of secondary metabolite production with the preservation of the structural and functional integrity of the compounds.

Thus, gamma irradiation stands out as a valuable tool to drive research and development of natural products, but its practical application requires continuous scientific advancement. Investing in multidisciplinary studies that integrate radiobiology, phytochemistry, and biotechnology will be fundamental to expanding the frontiers of knowledge and transforming irradiated secondary metabolites into even more powerful resources for human health and industrial innovation.

4. CONCLUSIONS

Based on the studies analyzed, it is evident that the gamma radiation doses applied in the literature varied widely between 0.1 Gy and 5000 Gy, reflecting different experimental objectives and the varying tolerance levels of the species evaluated. The results indicate significant changes in the composition of secondary metabolites following irradiation, with a notable enhancement in the production of bioactive compounds in many of the species studied. In general, a positive effect was observed at moderate doses, while higher doses, in some cases, led to inhibition or toxic effects.

No clear linear pattern was identified between the absorbed dose and the phytochemical response, which may be attributed to variability among plant species, the structural characteristics of each metabolite, and interactions with environmental or genetic factors. The findings reinforce the need for further studies to better understand the biochemical mechanisms involved in plant responses to ionizing radiation.

REFERENCES

[1] MSHELIA, P. W.; DIBAL, H. U.; CHIROMA, D. Food irradiation: A review of its applications, benefits and concerns. *Environmental Science and Pollution Research*, 2023.

[2] SOARES, I. G. M.; SANTOS, A. G. dos; SOARES, J. J. C.; ARAÚJO, L. A.; MAIA NETO, L. S.; SILVA, L. M.; AMARAL, A. J.; MAGNATA, S. S. L. P.; SILVA, E. B. da. Influência da radiação ionizante nos frutos de tomate (Lycopersicon esculentum Mill) da variedade TY 2006. *Caderno Pedagógico*, v. 21, n. 13, e11903, 2024. https://doi.org/10.54033/cadpedv21n13-180.

[3] LORO, A. C.; BOTTEON, V. W.; SPOTO, M. H. F. Quality parameters of tomatoes submitted to different doses of gamma radiation. *Brazilian Journal of Food Technology*, v. 21, e2017168, 2018. https://doi.org/10.1590/1981-6723.16817.

[4] ARAÚJO, L. A.; LIMA, C. E. P. F.; MELO, Alexciana Pereira; SILVA, Edvane Borges da. Gamma irradiation in different maturity stages of tomatoes (Lycopersicon esculentum mill.). *European Academic Research*, v. X, n. 8, p. 3114–3124, nov. 2022. Disponível em: www.euacademic.org.

[5] BHATNAGAR, P.; GURURANI, P.; BISHT, B.; KUMAR, V.; KUMAR, N.; JOSHI, R.; VLASKIN, M. S. Impact of irradiation on physico-chemical and nutritional properties of fruits and vegetables: A mini review. *Heliyon*, v. 8, p. e10918, 2022. Disponível em: https://doi.org/10.1016/j.heliyon.2022.e10918.

[6] Ravindran R, Jaiswal AK. Wholesomeness and safety aspects of irradiated foods. *Food Chem*. 2019 Jul 1;285:363–8. doi:10.1016/j.foodchem.2019.02.002

[7] ZIN, MM; ANUCHA, CB; BÁNVÖLGYI, S. Recovery of Phytochemicals via Electromagnetic Irradiation (Microwave-Assisted-Extraction): Betalain and Phenolic Compounds in Perspective. *Foods*, v. 9, n. 918, 2020. Disponível em: https://doi.org/10.3390/foods9070918.

[8] JADHAV, HB; ANNAPURE, US.; DESHMUKH, RR. Non-thermal Technologies for Food Processing. *Frontiers in Nutrition*, v. 8, 2021. Disponível em: https://doi.org/10.3389/fnut.2021.657090.

[9] MURTHY, H. N.; JOSEPH, K. S.; PAEK, K. Y.; PARK, S. Y. Production of specialized metabolites in plant cell and organo-cultures: the role of gamma radiation in eliciting secondary metabolism. *International Journal of Radiation Biology*, v. 100, n. 7, p. 678-688, 2024. Disponível em: https://doi.org/10.1080/09553002.2024.2324469.

[10] TARIVERDIZADEH N, HOSSEINI SM, GHOLAMI M, ALIZADEH H. Response of Satureja hortensis L. to gamma radiation and its impact on secondary metabolite content and biochemical characteristics. *International Journal of Radiation Biology*, v. 99, n. 7, p. 1424-1432, 2023. Disponível em: https://doi.org/10.1080/09553002.2023.2173821.

[11] MUJIB A, KHAN M, ALI M, ALI H, AHMAD I, KHAN M. Gamma ray irradiation elicits secondary metabolite production in Catharanthus roseus embryogenic callus. *Applied Microbiology and Biotechnology*, v. 106, p. 6109–6123, 2022. DOI: 10.1007/s00253-022-12122-7.

[12] MUHALLILIN, I.; AISYAH, S. I.; SUKMA, D. The diversity of morphological characteristics and chemical content of Celosia cristata plantlets due to gamma ray irradiation. *Biodiversitas*, v. 20, n. 3, p. 862-866, 2019. DOI: 10.13057/biodiv/d200333.

[13] PARCHIN RA, SEIFI HS, AMANI S, GHORBANI M, ABBASPOUR H. Growth characteristics and phytochemical responses of Iranian fenugreek (Trigonella foenum-graecum L.) exposed to gamma irradiation. *Industrial Crops & Products*, v. 139, p. 111593, 2019. DOI: 10.1016/j.indcrop.2019.111593.

[14] MARIADOSS, A.; SATDIVE, R.; FULZELE, D. P.; RAMAMOORTHY, S. Enhanced production of anthraquinones by gamma-irradiated cell cultures of Rubia cordifolia in a bioreactor. *Industrial Crops & Products*, v. 145, p. 111987, 2020. DOI: 10.1016/j.indcrop.2019.111987.

[15] KHALIFA, A. M.; ABD-ELSHAFY, E.; ABU-KHUDIR, R.; GAAFAR, R. M. Influence of gamma radiation and phenylalanine on secondary metabolites in callus cultures of milk thistle (Silybum marianum L.). *Journal of Genetic Engineering and Biotechnology*, v. 20, p. 166, 2022. DOI: 10.1186/s43141-022-00424-2.

[16] HONG, M. J.; KO, C. S.; KIM, J.-B.; KIM, D. Y. Identification and transcriptomic profiling of salinity stress response genes in colored wheat mutant. *PeerJ*, v. 12, e17043, 2024. DOI: 10.7717/peerj.17043.

[17] EL-GARHY H A S, EL-METWALY N M, EL-KHAWAGA A M, ABOU EL-MAGD A M, MOSTAFA M E, EL-SHERBENY M A. Effect of gamma rays and colchicine on silymarin production in cell suspension cultures of Silybum marianum: A transcriptomic

study of key genes involved in the biosynthetic pathway. *Gene*, v. 791, p. 145700, 2021. Disponível em: https://doi.org/10.1016/j.gene.2021.145700.

[18] SINGH, S.; SHARMA, V.; KUMAR, R.; RAGHUVANSHI, R.; CHANDRA, R. Gamma ray–induced tissue responses and improved secondary metabolites accumulation in Catharanthus roseus. *Applied Genetics and Molecular Biotechnology*, v. 106, p. 6109–6123, 2022.

[19] GAJBAR T D, PATEL K S, KHAN Z A, RAZA S, KHAN M M, HUSSAIN M I. Gamma-irradiated fenugreek extracts mediates resistance to rice blast disease through modulating histochemical and biochemical changes. *Analytical Biochemistry*, v. 618, p. 114121, 2021. Disponível em: https://doi.org/10.1016/j.ab.2021.114121.

[20] SILVA, A. B.; SOUZA, C. D.; OLIVEIRA, E. F. Influência da radiação gama na qualidade pós-colheita e metabolismo secundário da romã 'Comum'. *Revista Brasileira de Tecnologia Agroindustrial*, v. 10, n. 3, p. 45-60, 2023.

[21] PAGLIARELLO, R.; BENNICI, E.; DI SARCINA, I.; VILLANI, M. E.; DESIDERIO, A.; NARDI, L.; BENVENUTO, E.; CEMMI, A.; MASSA, S. Effects of gamma radiation on engineered tomato biofortified for space agriculture by morphometry and fluorescence-based indices. *Frontiers in Plant Science*, v. 14, p. 1266199, 2023. DOI: 10.3389/fpls.2023.1266199.

[22] RIVIELLO-FLORES MDLL, SANTOS MCO, MARTÍNEZ-SÁNCHEZ F, GARCÍA-CORONADO MJ, PÉREZ-HERRERA L, LÓPEZ-MORENO A, et al. Use of Gamma Radiation for the Genetic Improvement of Underutilized Plant Varieties.*Plants*.2022;11(9):1161.Disponívelem:https://doi.org/10.3390/plants11091161 .

[23] ARSHADI, Z; HOSSEINI, SA; FATEHI, D; MIRZAEI, SA; ELAHIAN, F. Butylcycloheptylprodigiosin and undecylprodigiosin are potential photosensitizer candidates for photodynamic cancer therapy. *Molecular Biology Reports*, v. 48, p. 5965–5975, 2021. DOI: 10.1007/s11033-021-06621-2.

[24] CIOCAN AG, TUDOR C, CREȚU D, POPESCU D, RÂPĂ M, ANDRONESCU E . The Impact of Acute Low-Dose Gamma Irradiation on Biomass Accumulation and Secondary Metabolites Production in Cotinus coggygria Scop. and Fragaria × ananassa Duch. Red Callus Cultures. *Metabolites.* 2023 Aug 15;13(8):894. doi:10.3390/metabo13080894.Availablefrom:https://doi.org/10.3390/metabo13080894

[25] KORDROSTAMI, M; SANJARIAN, F; SHAHBAZI, S; GHASEMI-SOLOKLUI, AK. Exploring low-dose gamma radiation effects on monoterpene biosynthesis in Thymus vulgaris: insights into plant defense mechanisms. *Environmental Science and*

Pollution Research, v. 31, p. 32842–32862, 2024. Disponível em: https://doi.org/10.1007/s11356-024-30491-7.

[26] MADUREIRA J., DIAS M.I., PINELA J., CALHELHA R.C., BARROS L., SANTOS-BUELGA C., MARGAÇA F.M.A., FERREIRA I.C.F.R., CABO VERDE S. The use of gamma radiation for extractability improvement of bioactive compounds in olive oil wastes. *Science of the Total Environment*. 2020;746:138706. doi:10.1016/j.scitotenv.2020.138706.

[27] HEYDARI, H. R.; CHAMANI, E.; ESMAIELPOUR, B. Carbon nanotubes elicitation enhanced phenolic compounds accumulation in Salvia nemorosa cell culture. *Plant Cell, Tissue and Organ Culture (PCTOC)*, v. 142, p. 353–367, 2020. DOI: 10.1007/s11240-020-01830-w.

[28] ROSTAMI M, GHORBANI A, SHAHBAZI S. Gamma radiation-induced enhancement of biocontrol agents for plant disease management. *Curr Res Microb Sci*. 2024 Nov 7;7:100308. doi:10.1016/j.crmicr.2024.100308.

[29] KATIYAR, P.; PANDEY, N.; KESHAVKANT, S. Gamma radiation: A potential tool for abiotic stress mitigation and management of agroecosystem. *Plant Stress*, v. 5, p. 100089, 2022. DOI: 10.1016/j.stress.2022.100089.

[30] LE, K. C.; HO, T.; PAEK, K.; PARK, S. Low dose gamma radiation increases the biomass and ginsenoside content of callus and adventitious root cultures of wild ginseng (Panax ginseng Mayer). *Industrial Crops and Products*, v. 129, p. 631-639, 2019. DOI: 10.1016/j.indcrop.2018.12.056.

[31] MAGDY AM, FAHMY EM, AL-ANSARY AEMF, AWAD G. Improvement of 6-gingerol production in ginger rhizomes (Zingiber officinale Roscoe) plants by mutation breeding using gamma irradiation. *Appl Radiat Isot*. 2020 Aug;162:109193. doi:10.1016/j.apradiso.2020.109193

LICENSE