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Examining the Effects of Space Radiation on Crop Yields and the Implications for Sustainable Crop Production in Long-Duration Space Exploration Missions

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ABSTRACT

Space radiation represents an important environmental challenge to sustainable crop production during long-duration space exploration beyond the protective influence of the Earth's atmosphere and magnetic field. This study reviewed recent scientific evidence on the effects of space radiation on crop yields and plant productivity using literature published between 2024 and 2026. Relevant studies were obtained from Scopus, Web of Science, ScienceDirect, SpringerLink, PubMed, Google Scholar, and the NASA Technical Reports Server. The reviewed evidence indicates that ionizing radiation can influence crop performance by affecting cellular processes, physiological functions, growth, reproduction, genetic stability, and the quality of harvested products. High radiation exposure was generally associated with reduced growth and yield, impaired photosynthetic activity, reproductive abnormalities, reduced seed production, oxidative stress, tissue damage, genetic mutations, and changes in crop quality. However, the severity of these effects varied according to radiation type, dose, exposure duration, crop species, genotype, and developmental stage. From the review, it was established that understanding radiation tolerance and developing appropriate protective and crop-management strategies are essential for maintaining reliable food production in future space-based agricultural systems.

KEYWORDS: *Space radiation; Crop yield; Ionizing radiation; Plant growth; Space agriculture.*

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1. Introduction

Space radiation is one of the major considerations in the development of sustainable crop-production systems for long-duration human missions beyond Earth, where plants are exposed to ionizing radiation in the absence of the full protection provided by the terrestrial atmosphere and geomagnetic field. Maffei et al. (2024) explained that ionizing radiation, together with altered gravity and other space-related environmental conditions, can affect plant physiology, development, growth, and productivity. Also, plant responses to ionizing radiation and reported effects at molecular, cellular, physiological, developmental, and reproductive levels, with potential consequences for plant resistance and agricultural performance (Mishra et al., 2024). In addition, plants are said to possess different mechanisms for adapting to ionizing radiation, although prolonged exposure can produce biological

damage and influence the development and survival of plant populations (Geras'kin, 2024). Arantes et al. (2025) reviewed the combined influence of microgravity and ionizing radiation on plants and emphasized that radiation represents a significant constraint to plant growth and food production in extraterrestrial environments. According to Nithimethachoke et al. (2026) who demonstrated that gamma irradiation produces dose-dependent changes in rice seedling development and metabolic processes, highlighting the importance of radiation tolerance in selecting crops for space agriculture, understanding the effects of space radiation on crop yields is essential for determining the feasibility of producing sufficient and nutritionally valuable food during future space missions, particularly through its effects on crop yield, plant growth and biomass, photosynthetic efficiency, flowering and fruit formation, seed production, plant stress and tissue damage, genetic stability, and overall crop quality. Although recent studies have established that space radiation can affect plant growth, metabolism, reproduction, and genetic stability, limited research has integrated these effects in relation to overall crop yield and food-production capacity**.** Also, majority of the existing studies largely focus on individual physiological, biochemical, or genetic responses rather than their combined effects on agricultural productivity. In addition, evidence from different crop species and space-relevant radiation conditions remains limited and fragmented. This review therefore addresses the gap by synthesizing recent 2024–2026 evidence on how radiation-induced changes collectively influence crop productivity and the feasibility of sustainable space agriculture.

2. Methodology

The study adopted a review research method to examine and synthesize scientific evidence on the effects of space radiation on crop yields and plant productivity. In this work, relevant research works published recently especially between 2024 and 2026 were identified from major academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, PubMed, Google Scholar, and NASA Technical Reports Server (NTRS)**.** The search used combinations of keywords such as “space radiation” AND “crop yield”, “ionizing radiation” AND “plant growth”, “cosmic radiation” AND “crop production”, “gamma radiation” AND “seed production”, and “space agriculture” AND “plant development”. Peer-reviewed journal articles, review papers, conference papers, and relevant technical reports addressing radiation effects on agriculturally important plants were considered. Studies were selected based on their relevance to plant growth, biomass accumulation, photosynthesis, reproduction, seed production, physiological stress, genetic changes, and crop quality. Particular attention was given to studies involving gamma rays, heavy ions, protons, and other radiation types used as analogues of space radiation. For each selected study, information on the research aim, method, radiation exposure, plant species, major findings, and conclusion was extracted and critically reviewed. The findings were subsequently synthesized according to the identified effects of space radiation on crop productivity to provide an integrated assessment of the implications for sustainable crop production during long-duration space missions.

3. Results and Analysis

This section presents the results obtained from the analysis of the effects of space radiation on crop yield. The findings are discussed based on the major effects identified from the reviewed studies, with emphasis on how exposure to space radiation may influence crop productivity and overall plant performance.

3.1. Reduced Crop Yield

Reduced crop yield is defined as a decrease in the quantity of fruits, grains, seeds, vegetables, or other agricultural products produced by plants exposed to space radiation. This reduction may result from radiation-induced damage to plant growth, reproductive processes, and physiological functions. Space radiation can significantly influence crop productivity by exposing plants to high-energy particles capable of damaging their cellular and genetic structures. When radiation levels are sufficiently high, the resulting cellular damage can interfere with important physiological processes required for normal plant development and reproduction. Such exposure may reduce the plant's ability to produce healthy leaves, flowers, fruits, grains, and seeds throughout the growing period. Radiation-induced stress can also affect nutrient utilization, water uptake, and metabolic activities that support crop development. As the severity and duration of radiation exposure increase, these physiological disturbances may become more pronounced and reduce the productive capacity of the plant. Plants subjected to excessive radiation may therefore produce fewer harvestable products than plants growing under normal conditions. In addition, radiation damage to reproductive tissues can reduce successful flowering, fertilization, and seed development. The combined effects of these disturbances can lead to substantial reductions in the quantity of agricultural products obtained at harvest, though, the magnitude of yield reduction varies

according to radiation dose, exposure duration, crop species, developmental stage, and environmental conditions. Zhang et al. (2024) studied the effects of space-relevant radiation on crop seeds and subsequent plant productivity using simulated galactic cosmic rays (GCR) and solar particle events (SPE) at different radiation doses. The study evaluated Arabidopsis and several crop species, with particular attention to seed viability, seedling development, fruiting, and yield. The results showed that 40 and 80 cGy exposures significantly affected tomato development, delayed fruiting, and reduced total tomato yield, with the higher dose producing more severe effects. The study concluded that prolonged or high-dose space radiation can impair crop productivity through radiation-induced damage occurring beyond the germination stage.

Also, De Francesco et al. (2025) investigated the effects of chronic low-dose gamma radiation and simulated reduced gravity on *Brassica rapa* microgreens using four controlled treatment conditions involving radiation, altered gravity, and their combination. The researchers assessed germination, fresh weight, root development, hypocotyl/root ratio, and physiological responses associated with oxidative stress. The findings indicated that chronic radiation significantly affected fresh biomass, while the combination of radiation and reduced gravity produced additional effects on root development and plant morphology. The researchers concluded that radiation can reduce plant productivity even when germination remains unaffected, thereby presenting a potential limitation to sustainable crop production during long-duration space missions.

3.2. Reduced Plant Growth and Biomass

Reduced plant growth and biomass is defined as a decrease in the development of roots, stems, leaves, and the overall amount of plant material produced by plants exposed to space radiation. Space radiation can affect plant growth by interfering with cellular processes responsible for the development and accumulation of plant biomass. High-energy radiation can cause damage to DNA, cell membranes, proteins, and other cellular components involved in normal plant growth and development. Such damage may interfere with cell division and cell expansion, which are essential processes for the formation of roots, stems, leaves, and other plant structures. Consequently, plants exposed to excessive radiation may exhibit reduced height, smaller leaves, shorter roots, and weaker stems compared with plants receiving lower radiation exposure. Radiation-induced damage to the root system can further reduce the plant's capacity to absorb water and essential nutrients required for continued growth. At the same time, damage to leaves and other photosynthetic tissues can limit the production of energy needed for biomass accumulation. These effects can progressively reduce the amount of dry matter produced by the plant during its growth cycle. Reduced biomass production may subsequently affect flowering, fruit development, seed formation, and final crop productivity. The severity of growth reduction depends on the type and intensity of radiation, duration of exposure, plant species, and developmental stage at which exposure occurs.

According to Arantes et al. (2025) who reviewed the effects of microgravity and ionizing radiation on plant development in space, in which the authors synthesized findings from experimental studies involving crops and model plants exposed to spaceflight conditions and simulated ionizing radiation, the radiation can interfere with cellular processes, root and shoot development, photosynthetic activity, and biomass accumulation, although responses vary with radiation dose and plant species. The authors concluded that understanding radiation-induced growth inhibition is essential for selecting tolerant crops and designing effective environmental protection systems for future space agriculture. As reported by Arrichiello et al. (2025) in their work on how different radiation qualities affect the growth and development of *Brassica rapa* microgreens using X-rays, carbon ions, and iron ions at different doses, their results demonstrated that radiation type and dose produced distinct developmental responses, with carbon ions delaying differentiation and iron ions producing moderate anatomical alterations. The study concluded that plant growth under space-radiation conditions is strongly dependent on both radiation quality and dose, emphasizing the need to consider high-LET radiation when evaluating crop growth for space missions.

3.3. Reduced Photosynthetic Efficiency

Reduced photosynthetic efficiency is defined as a decline in the ability of plants to effectively convert light energy, carbon dioxide, and water into chemical energy through photosynthesis. Space radiation can reduce photosynthetic efficiency by damaging the cellular structures responsible for capturing and converting light energy into chemical energy. High-energy radiation can affect chloroplasts, photosynthetic pigments, proteins, and cellular membranes that are essential for effective photosynthesis. When these structures are damaged, the ability of plants to absorb light and convert carbon dioxide and water into energy-rich compounds may be reduced. This reduction in photosynthetic activity

limits the amount of energy and organic matter available for plant growth and development. Radiation-induced oxidative stress may further damage the photosynthetic apparatus and interfere with the normal functioning of plant cells. As photosynthesis declines, plants may produce less carbohydrate, which is required for the formation of roots, stems, leaves, flowers, fruits, and seeds. The resulting shortage of photosynthetic products can therefore slow plant growth and reduce biomass accumulation. Prolonged exposure to excessive radiation may also accelerate leaf deterioration, further reducing the surface area available for light absorption.

Chen et al. (2025) examined the effects of carbon-ion beam irradiation on soybean physiology, agronomic traits, and photosynthetic performance using 3-day-old seedlings exposed to 0, 5, 10, and 15 Gy. The researchers combined physiological measurements, agronomic assessments, and transcriptomic analysis to determine how radiation affected plant functioning. At 15 Gy, photosynthetic pigment contents decreased by 21.28–34.28%, while abnormalities in Photosystem II indicated compromised photosynthetic efficiency. The study concluded that high-dose carbon-ion radiation produces photosynthetic toxicity in soybean through alterations in photosynthetic pigments and related molecular pathways. In the same way, De Francesco et al. (2026) examined the physiological responses of *Salvia hispanica* microgreens to heavy-ion irradiation using carbon and iron ions at doses ranging from 0.3 to 25 Gy. The researchers assessed morphological, anatomical, biochemical, and photosynthetic characteristics to determine whether radiation impaired plant functionality under space-relevant conditions. The results showed that iron ions enhanced shoot growth, photosynthetic pigments, and soluble proteins, while carbon ions increased transpiration and mineral accumulation; importantly, net photosynthesis remained largely unaffected. The study concluded that chia microgreens demonstrate considerable physiological plasticity and can preserve photosynthetic performance under certain heavy-ion radiation conditions, suggesting potential suitability for space-based cultivation.

3.4. Poor Flowering and Fruit Formation

Poor flowering and fruit formation is defined as the reduced, delayed, or abnormal development of flowers and fruits in plants exposed to space radiation. Space radiation can adversely affect flowering and fruit formation by interfering with the reproductive processes required for successful crop production. Exposure to high-energy radiation may cause cellular and genetic damage in tissues involved in flower development, pollen production, pollination, and fertilization. When these reproductive processes are disrupted, plants may produce fewer flowers or develop flowers that are unable to complete normal fertilization. Radiation-induced stress can also affect pollen viability and the development of reproductive organs, thereby reducing the probability of successful seed and fruit formation. In crops that depend heavily on successful flowering and fertilization, such effects can have a direct influence on the quantity of harvestable products. Furthermore, radiation damage may alter hormonal and metabolic processes that regulate flowering time and fruit development. Fruits that develop under severe radiation stress may be fewer in number, smaller in size, or poorly developed. Reduced reproductive success can consequently decrease the number of fruits, grains, or seeds available at harvest.

Kantoğlu (2024) studied the effects of gamma irradiation on pollen viability, pollen-tube growth, fruit set, and embryo formation in tomato. The study exposed tomato pollen to 0, 50, 100, 200, 300, and 400 Gy of gamma radiation and evaluated pollen performance and fruit development after pollination. The results showed that increasing radiation doses reduced pollen viability and pollen-tube length, while 400 Gy prevented fruit set. The study concluded that excessive gamma irradiation can interfere with reproductive processes and consequently impair successful fruit formation in tomato. In the work by Cho et al. (2025) who assessed flowering time, gene expression, growth responses, and hydrogen-peroxide accumulation to determine the mechanisms underlying radiation-induced reproductive changes, it was observed that 125 Gy accelerated flowering through increased expression of the floral activator FT, whereas 250 Gy caused abnormal development and prevented reliable flowering assessment, while doses above 500 Gy resulted in plant mortality. The study concluded that ionizing radiation can substantially alter flowering regulation through photoreceptor, circadian-clock, and reactive-oxygen-signalling pathways, potentially disrupting normal reproductive development.

3.5. Reduced Seed Production

Reduced seed production is defined as a decrease in the number, viability, or quality of seeds produced by plants following exposure to space radiation. Space radiation can reduce seed production by affecting the reproductive tissues and biological processes involved in the formation of viable seeds. High-energy radiation can damage the DNA and cellular structures of reproductive cells, potentially interfering

with the development of pollen, ovules, and other reproductive tissues. Such damage may reduce pollen viability and decrease the likelihood of successful pollination and fertilization. Radiation exposure during critical reproductive stages may therefore result in fewer fertilized ovules developing into mature seeds. In addition, genetic damage caused by radiation can affect embryo development and reduce the proportion of seeds that remain viable. Plants experiencing severe radiation stress may also allocate fewer resources to reproduction because more energy is required for cellular repair and survival. Consequently, the number, size, and quality of seeds produced by exposed plants may decline. Reduced seed production can have implications beyond the immediate harvest because fewer viable seeds will be available for subsequent planting cycles.

As highlighted by Jahan et al. (2024) in their research where the applied different mutagenic treatments and evaluated germination, pollen fertility, growth characteristics, and yield-related traits across the resulting plant populations, a dose-dependent reduction in pollen fertility and other physiological parameters, although lower radiation doses improved some yield and yield-attributing characteristics in selected mutant lines. The study concluded that excessive radiation can impair reproductive performance and seed production, whereas carefully controlled low doses may generate useful genetic variation for crop improvement. Jhar et al. (2024) examined the effects of different gamma-irradiation doses on three sesame (*Sesamum indicum* L.) varieties to determine suitable doses for mutation breeding without severely compromising reproductive and yield performance. The researchers applied calibrated gamma-radiation treatments to seeds and evaluated germination, shoot and root development, capsule number, seed weight, and final seed yield under field conditions. The results demonstrated negative relationships between increasing radiation dose and several reproductive and yield traits, particularly capsule number, capsule length, 100-seed weight, and overall yield. It was concluded that excessive gamma irradiation can adversely affect seed production and yield components, while appropriate low doses may be useful for generating beneficial genetic variation in sesame.

3.6. Increased Plant Stress and Tissue Damage

Increased plant stress and tissue damage is defined as the physiological and cellular injury experienced by plants when exposure to space radiation exceeds their natural protective and repair mechanisms. Space radiation can increase physiological stress in plants by interacting with cellular molecules and generating reactive oxygen species that can damage important biological structures. Excessive radiation exposure can cause oxidative stress when the production of reactive oxygen species exceeds the plant's natural antioxidant defence capacity. These reactive molecules can damage proteins, lipids, cell membranes, DNA, and other components required for normal cellular functioning. As cellular damage increases, plants may experience physiological disturbances that affect water balance, nutrient utilization, metabolism, and overall growth. Radiation-induced tissue damage may become visible through symptoms such as leaf injury, reduced leaf development, tissue deterioration, or abnormal growth. Plants may respond by activating antioxidant systems and other protective mechanisms, but prolonged or intense exposure can overwhelm these defence responses. The energy and resources diverted toward repairing radiation damage may also reduce the resources available for growth and reproduction. Consequently, stressed plants may develop more slowly and produce less biomass, fewer reproductive structures, and lower crop yields.

Mokhtari et al. (2025) reviewed the effects of space-driven oxidative stress on biological systems, with particular attention to plants cultivated under space conditions and exposed to cosmic radiation. The authors synthesized evidence on how galactic cosmic rays and solar particle events generate reactive oxygen species (ROS) that can damage DNA, proteins, lipids, and other cellular components. The review showed that increased ROS production can overwhelm antioxidant defence mechanisms, resulting in persistent oxidative stress and disruption of normal plant physiological processes. The work concluded that radiation-induced oxidative stress represents an important mechanism of cellular and tissue damage that may compromise plant health and the safety and quality of crops produced during space missions.

Similarly, Abozahra et al. (2025) examined the molecular, biophysical, and biochemical responses of maize seeds exposed to gamma radiation using different gamma-ray sources. The researchers evaluated radiation-induced changes in biochemical and molecular characteristics of irradiated seeds to determine the biological effects of ionizing radiation on plant tissues. Their findings demonstrated measurable radiation-induced alterations in biochemical and molecular properties, confirming that gamma radiation interacts with seed cellular components and produces physiological stress. The authors concluded that radiation exposure can modify important cellular and biochemical processes in

maize, demonstrating the potential for tissue damage and stress responses following ionizing-radiation exposure.

3.7. Genetic Mutations and Abnormal Growth

Genetic mutations and abnormal growth is defined as the alteration of plant genetic material and the resulting development of physical or physiological characteristics that differ from normal growth. Space radiation can induce genetic mutations in plants because high-energy particles can interact directly with DNA and cause alterations in the genetic material. When DNA is damaged, plants may attempt to repair the affected genetic sequences, but some damage can remain unrepaired or be incorrectly repaired. Such changes can produce mutations that influence important characteristics such as plant height, leaf development, root formation, flowering, and reproductive performance. In some cases, radiation-induced mutations may have little visible effect, while others can result in abnormal or undesirable plant characteristics. Plants may therefore develop distorted leaves, weak stems, irregular roots, delayed development, or other growth abnormalities following substantial radiation exposure. Genetic alterations can also affect physiological processes that determine how efficiently plants obtain nutrients, carry out photosynthesis, and respond to environmental stress. When these changes interfere with normal development, the plant may produce less biomass and fewer harvestable products. Mutations occurring in reproductive cells may also be transmitted to subsequent generations, potentially affecting the characteristics and productivity of future crops. Although controlled radiation exposure can sometimes generate useful genetic variation for crop improvement, excessive or uncontrolled exposure is more likely to produce harmful effects. According to Huang et al. (2026), high doses (≥2,000 Gy) severely reduced seed viability and fresh weight while producing large-fragment deletions and mutations in genes associated with DNA repair and plant metabolism. The authors went further to state that excessive gamma radiation can cause substantial genomic instability and abnormal plant development, whereas lower doses can generate manageable genetic variation for crop improvement. Khan et al. (2026) investigated the effects of different gamma-radiation doses on six hexaploid wheat genotypes using 0, 100, 150, 200, and 250 Gy treatments. The researchers evaluated 18 traits covering early growth, phenology, plant development, and yield characteristics to determine genotype-specific responses to radiation. Their findings showed that the highest dose of 250 Gy negatively affected all evaluated traits, while radiation-induced mutants displayed abnormal characteristics including dwarfism, double spikes, increased tillering, and altered spike architecture. The researchers concluded that gamma radiation can induce substantial genetic and morphological variation in wheat, with excessive doses producing detrimental abnormalities while optimized doses can generate useful mutants for crop improvement.

3.8. Reduced Crop Quality

Reduced crop quality is defined as a deterioration in the physical, nutritional, biochemical, or commercial characteristics of fruits, grains, vegetables, seeds, and other harvested agricultural products following radiation exposure. Space radiation can affect crop quality by altering the physical, physiological, and biochemical characteristics of agricultural products produced by exposed plants. Radiation-induced cellular damage can interfere with normal development of fruits, grains, seeds, leaves, and other harvested plant materials. As a result, crops may exhibit reduced size, lower weight, abnormal shape, or other undesirable physical characteristics. Radiation stress can also influence the accumulation of carbohydrates, proteins, vitamins, minerals, pigments, and other compounds that contribute to the nutritional and commercial quality of crops. Damage to plant tissues may further reduce the ability of crops to maintain their normal structure and physiological condition during development. In some circumstances, radiation exposure may alter the timing of maturation, causing crops to develop unevenly or fail to reach their expected quality at harvest. The quality of seeds may also decline when radiation affects embryo development, viability, or genetic stability. These effects can reduce the economic and nutritional value of agricultural products even when the exposed plants remain capable of producing a harvest. The severity of quality reduction depends on radiation dose, duration of exposure, crop species, developmental stage, and environmental conditions. Therefore, assessing the effects of space radiation requires consideration not only of the quantity of crops produced but also of the quality and usability of the harvested products.

Fagbemi et al. (2024) investigated the effects of gamma irradiation combined with hydrothermal treatment on the nutritional and physicochemical quality of African bush mango seeds and their extracted oil. The researchers treated the seeds with different gamma-radiation doses and evaluated proximate composition, minerals, antinutritional factors, amino-acid profile, and oil-quality characteristics. The results showed dose-dependent changes in protein content, amino-acid composition, tannins, iodine value, and free fatty acids, although

several nutritional and functional properties were retained. The study concluded that irradiation can modify important nutritional and quality characteristics of crop seeds, demonstrating that radiation dose is an important determinant of the final quality of agricultural products.

Related work was carried by Nithimethachoke et al. (2026) who investigated gamma-irradiation-induced metabolic changes in eight Thai rice cultivars to evaluate radiation tolerance for potential space agriculture. The researchers exposed rice seeds to 150, 300, and 900 Gy of gamma radiation and assessed germination, shoot and root development, together with metabolomic changes in selected radiation-tolerant plants. The results showed that although germination remained above 90% across treatments, increasing radiation caused dose-dependent inhibition of shoot and root elongation and substantial tissue-specific metabolic reprogramming. The study concluded that radiation can alter the metabolic stability and developmental quality of crop plants even when seed viability remains high, highlighting the importance of evaluating crop quality beyond germination alone.

4. Conclusion

The work on examining the the effects of space radiation on crop yields and the implications for sustainable crop production in long-duration space exploration missions has been carried out, using the review research method. The review established that space radiation can significantly influence crop production through interconnected physiological, reproductive, cellular, and genetic mechanisms. The major effects identified include reduced crop yield, restricted plant growth and biomass accumulation, impaired photosynthetic performance, and disruptions in flowering and fruit formation. Radiation exposure may also reduce seed production, increase oxidative stress and cellular or tissue damage, induce genetic mutations, and alter the quality and nutritional characteristics of harvested crops. It was also observed that the severity and extent of these effects are influenced by several factors, including radiation dose, duration of exposure, and that recent studies indicates that some crop species possess adaptive and protective mechanisms that enable them to mitigate, or partially recover from radiation-induced stress. This suggests that plant responses to space radiation are not uniform and may vary considerably among species and growing conditions. Therefore, improving the feasibility of crop production during future space missions will require greater attention to the development of radiation-tolerant crop varieties, effective radiation shielding, and controlled-environment cultivation systems.

5. Recommendations

From the review, it is recommended that future research should prioritize long-duration experiments using space-relevant radiation types and doses to establish reliable crop-yield thresholds. Also, we recommend that radiation-tolerant crop varieties should be identified through physiological, genetic, metabolomic, and breeding approaches for lunar, Martian, and deep-space agriculture.

References

[1] Abozahra, M. S., Amin, M. A., Sarker, T. C., Abd-ElGawad, A. M., and 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*, 9340.

[2] Arantes, J. H. B., Lopes, M. A., and Fávero, A. P. (2025). Microgravity and ionizing radiation on plant development in space. *Ciência e Agrotecnologia, 49*, e012025.

[3] Chen, J., Du, Y., Feng, Z., Long, J., Wang, L., Liu, X., Kang, G., Ding, J., Li, Z., Jin, W., and Zhou, L. (2025). Physiology, agronomic traits, and transcriptome jointly revealed the radiation toxicity effect and response mechanism of carbon ion beam irradiation on soybean. *Plant Physiology and Biochemistry, 227*, 109999.

[4] Cho, S. W., Lee, W., Lee, S. S., Kim, J. I., and Song, Y. H. (2025). Photoreceptors and circadian clock regulators control growth and flowering under ionizing radiation stress. *Journal of Plant Biology, 68*(6), 515–523.

[5] De Francesco, S., Amitrano, C., Vitale, E., Costanzo, G., Tinganelli, W., Pugliese, M., Arrichiello, C., Muto, P., Durante, M., De Pascale, S., Arena, C., and De Micco, V. (2025). Radiation quality matters: Morphological and biochemical responses of *Brassica rapa* microgreens to X-rays, C-ions, and Fe-ions. *Planta, 262*(5), 118.

[6] De Francesco, S., Le Disquet, I., Pereda-Loth, V., Tisseyre, L., De Pascale, S., Amitrano, C., Carnero Diaz, E., and De Micco, V. (2025). Combined effects of microgravity and chronic low-dose gamma radiation on *Brassica rapa* microgreens. *Plants, 14*(1), 64.

[7] De Francesco, S., Amitrano, C., Vitale, E., Tinganelli, W., Durante, M., De Pascale, S., Arena, C., and De Micco, V. (2026). Morpho-anatomical and biochemical plasticity of chia

(*Salvia hispanica* L.) microgreens following heavy-ion seed irradiation. *Plant Physiology and Biochemistry, 237*, 111517.

[8] Fagbemi, S. A., Asunni, A. O., Olorunnusi, J. O., Okeji, M. A., and Enujiugha, V. N. (2024). Combined gamma irradiation and hydrothermal treatments did not adversely affect the nutritional characteristics of African bush mango (*Irvingia gabonensis*) seeds and the oil quality. *Journal of Agriculture, Food Technology and Sustainability, 1*(1), 26–35.

[9] Geras'kin, S. (2024). Plant adaptation to ionizing radiation: Mechanisms and patterns. *Science of the Total Environment, 916*, 170201.

[10] Huang, Y., Zhao, Y., Ou, X., and Lu, G. (2026). Dose-dependent γ-radiation effects on seed vigor and genomic mutation patterns in Shuidong mustard (*Brassica juncea* var. *multiceps*). *BMC Genomics, 27*, 676.

[11] Jahan, R., Raina, A., Malik, S., Khan, S., and colleagues. (2024). Gamma rays and sodium azide induced variations in bio-physiological and agronomical traits in linseed (*Linum usitatissimum* L.). *Heliyon, 10*(11), e31329.

[12] Jhar, A., Sabbagh, S., Alkhattab, E., Abrak, S., Hatipoğlu, H., and Brennan, A. C. (2024). Optimising gamma irradiation seed treatment of sesame (*Sesamum indicum* L.) varieties for potential future application in mutation breeding. *Crop Breeding, Genetics and Genomics, 6*(3), e240004.

[13] Kantoğlu, K. Y. (2024). Influence of gamma irradiation on pollen viability, pollen tube growth, and fruit development in tomato (*Solanum lycopersicum* L.). *The Horticulture Journal, 93*(2), 169–175.

[14] Khan, N. U., Nisa, B. T., Ullah, I., Law, D., Tan, D. K. Y., Elmenofy, W., Arif, M. A. R., and Yasin, M. (2026). Irradiation of hexaploid wheat (*Triticum aestivum* L.) seeds with varying doses of gamma radiation leads to novel mutants. *Cereal Research Communications, 54*(2), 907–921.

[15] Maffei, M. E., Balestrini, R., Costantino, P., Lanfranco, L., Morgante, M., Battistelli, A., and Del Bianco, M. (2024). The physiology of plants in the context of space exploration. *Communications Biology, 7*(1), 1311.

[16] Mishra, S., Duarte, G. T., Horemans, N., Ruytinx, J., Gudkov, D., and Danchenko, M. (2024). Complexity of responses to ionizing radiation in plants, and the impact on interacting biotic factors. *Science of the Total Environment, 924*, 171567.

[17] Mokhtari, M., Reinsch, S. S., Barbero Barcenilla, B., Ziyaei, K., and Barker, R. J. (2025). Space-driven ROS in cells: A hidden danger to astronaut health and food safety. *npj Microgravity, 11*, 52.

[18] Nithimethachoke, T., Tantraphongsathon, K., Sooksaksun, K., Srisombat, P., Krobthong, S., Yingchutrakul, Y., Moung-ngam, P., Orpong, P., Picha, R., and Tulyananda, T. (2026). Gamma irradiation-induced metabolic reprogramming as a determinant of radiation tolerance in Thai rice germplasm for space agriculture. *Plant Growth Regulation*.

[19] Zhang, Y., Richards, J. T., Meyers, A. D., Dixit, A., Massa, G. D., Spencer, L. E., and Levine, H. G. (2024). *Impact of space radiation with other combined space environmental factors on plant seeds and plant development: From Arabidopsis thaliana to crops*. NASA John F. Kennedy Space Center.