

**IONIZING RADIATION IN AGRICULTURE: PHYSICAL, BIOLOGICAL AND
ONTOLOGICAL APPROACHES**

**RADIAÇÃO IONIZANTE NA AGRICULTURA: ABORDAGENS FÍSICAS,
BIOLÓGICAS E ONTOLÓGICAS**

**RADIACIÓN IONIZANTE EN LA AGRICULTURA: ENFOQUES FÍSICOS,
BIOLÓGICOS Y ONTOLÓGICOS**

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ABSTRACT

Ionizing radiation has been present in agricultural and biological sciences for more than seven decades. Beyond its classical role in mutation breeding and food preservation, radiation has gained renewed attention as a tool for physiological stimulation at sublethal doses (a phenomenon known as radiohormesis). This chapter presents an integrative overview of the use of ionizing radiation in agriculture, addressing the physical principles, biological effects, and agronomic applications from a multidisciplinary perspective. Emphasis is placed on low-dose physiological responses, mechanisms of stimulation, and recent advances in digital knowledge systems that structure and disseminate information on radiobiological processes. The discussion aims to bridge traditional nuclear agronomy with modern approaches in ontology engineering and artificial intelligence for decision support.

Keywords: Ionizing Radiation. Agriculture. Mutation Breeding. Radiohormesis. Ontologies. Seed Physiology. Reproducibility.

RESUMO

A radiação ionizante tem estado presente nas ciências agrícolas e biológicas há mais de sete décadas. Além de seu papel clássico no melhoramento genético e na preservação de alimentos, a radiação tem recebido atenção renovada como ferramenta de estimulação fisiológica em doses subletais (fenômeno conhecido como radiohormese). Este capítulo apresenta uma visão integradora do uso da radiação ionizante na agricultura, abordando os princípios físicos, os efeitos biológicos e as aplicações agrônomicas em uma perspectiva multidisciplinar. Dá-se ênfase às respostas fisiológicas de baixa dose, aos mecanismos de estimulação e aos avanços recentes em sistemas digitais de conhecimento que estruturam e disseminam informações sobre processos radiobiológicos. A discussão procura conectar a agronomia nuclear tradicional às abordagens modernas em engenharia ontológica e inteligência artificial voltadas ao apoio à decisão.

Palavras-chave: Radiação Ionizante. Agricultura. Melhoramento por Mutação. Radiohormese. Ontologias. Fisiologia de Sementes. Reprodutibilidade.

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RESUMEN

La radiación ionizante se ha utilizado en las ciencias agrícolas y biológicas durante más de siete décadas. Más allá de su papel clásico en la mejora genética y la conservación de alimentos, ha recibido renovada atención como herramienta para la estimulación fisiológica a dosis subletales (un fenómeno conocido como radiohormesis). Este capítulo presenta una visión integradora del uso de la radiación ionizante en la agricultura, abordando los principios físicos, los efectos biológicos y las aplicaciones agronómicas desde una perspectiva multidisciplinar. Se hace hincapié en las respuestas fisiológicas a bajas dosis, los mecanismos de estimulación y los avances recientes en sistemas de conocimiento digital que estructuran y difunden información sobre procesos radiobiológicos. El análisis busca conectar la agronomía nuclear tradicional con los enfoques modernos de la ingeniería ontológica y la inteligencia artificial, centrados en el apoyo a la toma de decisiones.

Palabras clave: Radiación Ionizante. Agricultura. Mejora por Mutación. Radiohormesis. Ontologías. Fisiología de las Semillas. Reproducibilidad.

1 INTRODUCTION

Ionizing radiation has played an important role in modern agronomy and plant biology since the mid-twentieth century. From the pioneering experiments of the early nuclear age, when controlled irradiation was first applied to crop seeds, scientists have explored radiation not only as a source of genetic variability but also as a physical agent capable of modifying metabolic and physiological processes in plants (VOSE, 1980). What began as an extension of atomic research into agriculture soon became one of the most productive intersections between physics and biology, giving rise to the field now known as *nuclear agronomy*.

Throughout the 1950s and 1960s, national and international programs (particularly those coordinated by the Food and Agriculture Organization (FAO) and the International Atomic Energy Agency (IAEA)) standardized the use of cobalt-60 and cesium-137 irradiators for seed treatment, mutation induction, and sterilization of pests. The FAO/IAEA joint division, established in 1964, became the main institutional driver for developing methodologies, dosimetry standards, and safety regulations (SPENCER-LOPES et al., 2018). Under this framework, hundreds of laboratories accross the world adopted irradiation as a practical technique for mutation breeding, phytosanitary treatment, and food preservation.

The agricultural applications of radiation evolved under two complementary paradigms that remain conceptually distinct yet mechanistically related: the *genetic paradigm* and the *physiological paradigm*. The genetic paradigm focuses on mutation breeding: the deliberate induction of heritable genetic variation through exposure to high or moderate doses of radiation, usually in the range of 100–400 Gy for most crops (SAVOV, 1989). This approach seeks to expand the genetic base of cultivated species, offering plant breeders new sources of allelic diversity that can be fixed by conventional selection and crossing. Over 3,400 officially released mutant varieties of cereals, legumes, ornamentals, and fruits have been developed worldwide using this method (FAO/IAEA, 2018).

The physiological paradigm, by contrast, deals with the short-term and (very) often non-heritable effects of low-dose irradiation on living tissues, particularly seeds and seedlings. In this context, radiation functions as a mild abiotic stressor capable of triggering adaptive responses at the molecular and cellular levels. When carefully calibrated, sublethal doses (typically below 20 Gy for most plant species) can accelerate germination, promote uniform emergence, and stimulate early biomass accumulation. This biphasic response, in which low doses enhance performance while higher exposures inhibit it, defines the phenomenon of *radiohormesis* (VILLEGAS et al., 2023). Although the term derives from the

broader toxicological concept of hormesis, it has specific implications for plant physiology, suggesting that radiation may act as a priming factor that enhances vigor and stress resilience.

From a scientific perspective, these two paradigms represent different temporal and mechanistic scales of response. The genetic paradigm addresses changes in DNA sequence, chromosomal rearrangements, and mutation frequency: processes that require multiple generations of selection and stabilization. The physiological paradigm, on the other hand, operates on a much shorter timescale, modulating gene expression, antioxidant metabolism, and enzymatic activity without necessarily altering the genome. Yet both paradigms depend on the same fundamental interaction between ionizing energy and biological matter: the ionization of water molecules and the subsequent formation of reactive oxygen species (ROS), such as hydroxyl radicals, superoxide anions, and hydrogen peroxide (VOSE, 1980). These molecules, traditionally regarded as damaging agents, are now understood to function as key signaling intermediates when present in low concentrations.

The mechanistic link between oxidative signaling and beneficial physiological responses has been repeatedly demonstrated in controlled experiments. Sublethal irradiation doses generate transient increases in ROS, which in turn activate redox-sensitive transcription factors, mitogen-activated protein kinase (MAPK) cascades, and hormonal cross-talk pathways involving auxins, abscisic acid, and cytokinins (GENG et al., 2019). The activation of these pathways leads to faster mobilization of storage reserves, enhanced cell expansion, and earlier root and shoot initiation. When exposure exceeds the capacity of cellular antioxidant systems, however, oxidative stress dominates, resulting in lipid peroxidation, protein oxidation, and DNA strand breaks. This delicate balance between activation and inhibition defines the hormetic dose–response curve.

Empirical evidence for radiohormesis has accumulated across diverse species. Studies on cereals, legumes, and solanaceous crops report that gamma irradiation in the range of 5–15 Gy enhances germination rate, uniformity, and seedling vigor, while doses above 20 Gy generally suppress these traits (VILLEGAS et al., 2023). Controlled laboratory experiments with *Nicotiana tabacum* L. confirmed these trends, revealing varietal differences in sensitivity and optimum stimulation doses (ALVES et al., 2026). In those studies, low-dose gamma exposure (approximately 10–15 Gy) significantly advanced germination kinetics and increased early biomass, with the most responsive genotypes exhibiting up to 100% gains in fresh weight compared with non-irradiated controls. Importantly, the stimulatory window

varied among cultivars, emphasizing that genetic background influences the balance between beneficial and deleterious outcomes. These findings corroborate earlier hypotheses proposed by (VOSE, 1980) that low-level radiation may serve as a developmental cue, analogous to mild temperature or osmotic stresses, capable of enhancing seed metabolic activity without structural damage.

Beyond its physiological effects, the use of radiation in agriculture intersects with broader questions of data standardization, reproducibility, and interdisciplinary knowledge management. For decades, experimental results on plant irradiation were disseminated through disparate sources (agronomy journals, radiobiology reports, and institutional bulletins) often using inconsistent terminology for dose units, biological endpoints, and material descriptions. As a result, integrating findings across species, laboratories, and irradiation conditions remains difficult. The emergence of ontological and digital knowledge frameworks seeks to address this fragmentation by providing formal structures to represent entities such as radiation source, dose range, and observed effect. Ontologies (machine-readable vocabularies that define relationships among concepts) enable interoperability between experimental databases and decision-support systems, paving the way for more systematic use of radiation data in agricultural research (ALVES et al., 2026).

Two complementary ontologies illustrate this trend. The first, OnTop, models the entire tobacco production lifecycle, integrating environmental, soil, and management factors relevant to agricultural decision support (ALVES et al., 2025). Although not limited to irradiation, it provides the conceptual foundation for integrating radiation effects within broader agronomic processes. The second, OnSIR (Ontology of Seed Irradiation), explicitly formalizes the domain of seed irradiation and plant radiobiology, capturing entities such as *StimulatoryDose*, *MutagenicRange*, and *SterilizationThreshold* (ALVES et al., 2026). By aligning radiation-related concepts with ontology engineering, OnSIR facilitates semantic queries such as “Which radiation ranges induce hormetic responses in *Nicotiana tabacum* for such-and-such variety?” or “What is the mutagenic range for dry soybean seeds?” This structured approach transforms experimental observations into machine-actionable knowledge, allowing integration with artificial intelligence systems for agricultural decision support.

From a historical standpoint, the institutionalization of radiation use in agriculture has followed a curious, quasi-Schopenhauerian cyclical pattern of enthusiasm and caution. The early decades emphasized mutation breeding and food sterilization, leading to notable

achievements but also to public concern about radiation safety. Subsequent years witnessed a shift toward more conservative applications and stricter regulatory oversight. In recent years, however, advances in dosimetry, controlled facilities, and biological understanding have renewed interest in the beneficial uses of low-dose irradiation, supported by a clearer differentiation between ionizing radiation as a process and radioactivity as a property of matter. The adoption of rigorous safety protocols and the availability of compact gamma irradiators have made the technique accessible to agricultural research centers worldwide, including those in developing regions (FAO/IAEA, 2018).

The integration of classical radiobiological experimentation with modern data infrastructures marks a new phase in nuclear agronomy. Traditional studies provided invaluable empirical evidence on dose–response relationships and varietal sensitivity; contemporary ontological frameworks extend this legacy by ensuring that such knowledge remains discoverable, comparable, and reusable. The combined perspective (from the field experiment to the semantic model) encapsulates the evolution of radiation use in agriculture: from empirical observation to standardized science, and now to intelligent data-driven practice.

Therefore, the purpose of this chapter is to offer a comprehensive synthesis of these intertwined dimensions. It revisits the physical and biological foundations of ionizing radiation, surveys its classical and emerging agricultural applications, discusses the physiological basis of hormesis, and explores how semantic technologies and artificial intelligence can enhance knowledge integration and decision making in this field. By bridging the historical, experimental, and digital aspects of radiation agronomy, we aim to contextualize the enduring relevance of nuclear techniques in addressing contemporary agricultural challenges: productivity, sustainability, and scientific reproducibility.

2 PHYSICAL AND BIOLOGICAL FUNDAMENTALS OF IRRADIATION

2.1 NATURE OF IONIZING RADIATION

Ionizing radiation refers to any type of energy emission capable of removing electrons from atoms or molecules, generating ions and free radicals. It encompasses both electromagnetic waves of high frequency, such as gamma rays and X-rays, and particle radiation, such as electrons, protons, neutrons, or heavy ions. In agricultural applications, the predominant sources are gamma emitters derived from cobalt-60 (^{60}Co) and cesium-137

(^{137}Cs), as well as electron-beam accelerators used for low-penetration treatments (VOSE, 1980).

The suitability of each radiation type depends on penetration depth, dose rate, and interaction pattern. Gamma radiation offers high penetration and energy uniformity, allowing large sample volumes (such as seed batches or packaged products) to receive homogeneous exposure. Electrons, by contrast, have shallower penetration and are more appropriate for surface sterilization or thin biological materials. Ion beams and X-rays, while less common in agronomic settings, are important in experimental radiobiology for investigating high linear energy transfer (LET) effects and mutation spectra (SPENCER-LOPES et al., 2018).

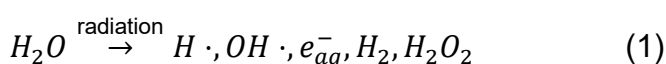
From a physical standpoint, the absorbed dose (D) quantifies the amount of energy deposited per unit mass of material, expressed in gray (Gy), where $1\text{Gy}=1\text{Jkg}^{-1}$. However, dose alone does not fully describe biological impact; dose rate (Gy h^{-1}) and radiation quality (LET) are equally relevant. Low-LET radiation, such as gamma and X-rays, distributes ionizations sparsely, generating predominantly indirect effects mediated by reactive oxygen species (ROS). High-LET particles, such as alpha particles (particles identical to Helium nuclei) or heavy ions, produce dense ionization tracks, resulting in localized clusters of DNA damage (VOSE, 1980). These distinctions underlie the different biological responses observed among exposure types.

In agricultural facilities, dose uniformity and reproducibility are achieved through standardized geometries and calibration with dosimeters such as Fricke, ceric–cerous, or alanine systems. The FAO/IAEA protocols emphasize traceability of dose measurement, ensuring that each exposure is accompanied by detailed metadata including source strength, distance, temperature, and seed moisture content (FAO/IAEA, 2018). Such precision is essential when small variations in dose can shift a treatment from stimulatory to inhibitory.

Radiation in agriculture must also be understood as a controlled physical process, distinct from radioactivity in the sense of contamination. The energy delivered during exposure does not render the biological material radioactive, as the interaction involves energy transfer without nuclear transmutation (VOSE, 1980). This distinction, frequently misunderstood outside scientific circles, is crucial for public acceptance and regulatory approval of irradiated seeds or food products.

2.2 INTERACTION WITH BIOLOGICAL MATERIAL

The biological action of ionizing radiation begins with the absorption of energy by cellular components, especially water. In most plant tissues, water represents over 70% of the mass, making it the principal target of radiation. The ionization and excitation of water molecules produce a cascade of short-lived species (hydroxyl radicals ($OH\cdot$), hydrated electrons (e_{aq}^-), hydrogen atoms ($H\cdot$), hydrogen peroxide (H_2O_2), and molecular hydrogen (H_2)) collectively known as the products of water radiolysis (VOSE, 1980). The general sequence can be expressed as:



These reactive intermediates diffuse within microseconds and interact with biomolecules such as lipids, proteins, and nucleic acids. Two main pathways of biological damage are recognized: (i) the *direct effect*, where radiation energy is deposited directly in macromolecules, causing ionization or excitation of the target itself; and (ii) the *indirect effect*, in which radicals generated in surrounding water react chemically with biomolecules. In hydrated tissues, indirect effects dominate, while in dry seeds, where free water is limited, direct energy deposition in the solid matrix becomes more significant (VOSE, 1980; SPENCER-LOPES et al., 2018).

At the cellular level, these reactions lead to a complex interplay of damage and signaling. Hydroxyl radicals can abstract hydrogen atoms from membrane lipids, initiating lipid peroxidation that alters membrane fluidity and permeability. Hydrogen peroxide, although less reactive, can diffuse through membranes and serve as a secondary messenger in redox signaling. In the nucleus, double-strand breaks (DSBs) in DNA are critical lesions that, if misrepaired, lead to mutations or chromosomal aberrations. However, at sublethal doses, the transient ROS burst acts as a signal that upregulates antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidases (POD), as well as DNA repair pathways (GENG et al., 2019). This paradoxical activation of defense and repair systems explains how mild irradiation can improve physiological performance.

A recent study by the authors on *Nicotiana tabacum* L. provides a quantitative illustration of this balance. When seeds were exposed to incremental doses between 0 and 20 Gy, stimulation of germination and biomass was observed in the 10–15 Gy range, whereas inhibition starts to appear beyond 15 Gy. The interpretation aligns with the radiolytic

mechanism: within the stimulatory window, ROS concentrations are sufficient to activate metabolism but below the threshold of irreversible damage. As doses rise, ROS accumulation surpasses antioxidant capacity, leading to delayed germination and reduced growth. The study further confirmed that this dynamic differs among genotypes, underscoring the interaction between intrinsic radiosensitivity and oxidative metabolism (ALVES et al., 2026).

Radiation also affects the physical state of seed structures. In embryonic tissues, ionization can weaken cell wall cross-links and alter membrane potentials, facilitating water uptake during imbibition. Low doses may increase membrane permeability and stimulate respiratory activity, as evidenced by higher oxygen consumption rates in irradiated seeds (VOSE, 1980). Conversely, excessive ionization disrupts membranes, causing electrolyte leakage and impaired germination. In chloroplasts, gamma irradiation at the seedling stage influences pigment biosynthesis and photosynthetic efficiency, which can either enhance or reduce growth depending on dose and developmental timing.

2.3 DETERMINANTS OF RADIOSENSITIVITY

Radiosensitivity (the degree to which a biological system responds to a given radiation dose) varies widely among plant species, tissues, and physiological states. Several determinants govern this variability, encompassing physical, biochemical, and genetic factors (VOSE, 1980; SPENCER-LOPES et al., 2018).

1. Water Content and Physiological State.

Water content represents the most fundamental determinant. Dry seeds are considerably more resistant to irradiation than germinated or hydrated tissues because indirect damage mediated by water radiolysis is minimized. Under desiccated conditions, radicals formed within the solid matrix recombine locally before diffusing to sensitive targets. This explains why doses as high as 400 Gy can be used for mutation induction in dry seeds of cereals, whereas hydrated tissues exhibit lethal effects at one-tenth that level (VOSE, 1980). Conversely, in studies focused on physiological stimulation, partial hydration is often desirable, as a limited presence of free water enhances ROS-mediated signaling without reaching damaging concentrations (ALVES et al., 2026).

2. Genotype and Cellular Composition.

The genetic constitution of the plant determines baseline antioxidant capacity, DNA repair efficiency, and chromatin architecture, all of which influence radiation response. Varieties rich in phenolic antioxidants or possessing high SOD and CAT activity show

extended hormetic windows. The *Nicotiana tabacum* varieties tested in controlled experiments exemplify this diversity: the Dark genotype exhibited maximal stimulation near 12.7 Gy, while the Burley and Virginia genotypes responded at slightly higher doses with lower amplitude. These distinctions likely arise from varietal differences in ROS metabolism and hormonal regulation (ALVES et al., 2026).

3. Dose Rate and Temporal Pattern.

The same total dose delivered at different rates can produce distinct biological outcomes. Low dose rates allow partial repair during exposure, whereas acute delivery generates higher instantaneous radical concentrations. FAO/IAEA guidelines recommend characterizing both absorbed dose and dose rate when reporting experiments to ensure comparability (SPENCER-LOPES et al., 2018). In mutation breeding, dose rates around 100–300 Gy h⁻¹ are typical, while in radiohormesis experiments, much lower rates (1–10 Gy h⁻¹) are often employed to favor metabolic adaptation. This is one of the reasons why even "old" sources (i.e. sources where many half-lives have passed) are useful for hormesis research.

4. Chromatin and Cell Cycle Stage.

The structural organization of chromatin influences the accessibility of DNA to damage and repair enzymes. Cells in active division, especially during G2 and mitosis, exhibit higher sensitivity due to chromatin condensation and lack of homologous repair templates. In multicellular plant tissues, meristematic regions are therefore the most radiosensitive. This principle guides practical irradiation protocols: dormant seeds or pollen are chosen for mutation breeding to reduce lethality, whereas sprouting tissues are targeted when the goal is to study metabolic stimulation (VOSE, 1980).

5. Environmental Modifiers.

Oxygen concentration, temperature, and the presence of chemical protectors or sensitizers modulate radiation effects. The so-called *oxygen enhancement ratio* (OER) quantifies how oxygen amplifies biological damage by stabilizing free radical species. Under hypoxic conditions, radical recombination is favored, reducing effective dose. Conversely, high oxygen availability enhances peroxidation and increases radiosensitivity (AVAKYAN et al., 1977). Temperature affects both radical diffusion and repair kinetics, with moderate heat accelerating enzymatic repair but excessive heat exacerbating stress.

6. Biological Endpoint and Measurement Criteria.

The interpretation of radiosensitivity also depends on the endpoint measured. For example, a dose that reduces final germination percentage may still improve germination rate

or seedling vigor. Kinetic parameters such as the time to 50% germination (T_{50}) and the area under the germination curve (AUC) provide more sensitive indicators of hormetic stimulation than categorical survival data (ALVES et al., 2026). Understanding which physiological parameter best represents the desired effect is essential for consistent evaluation.

Integrating Physical and Biological Dimensions

The study of radiation effects in agriculture sits at the intersection of physics, chemistry, and biology. The absorbed dose, dose rate, and LET describe the physical side; the formation of radicals, antioxidant balance, and repair pathways describe the biological side. Bridging these domains requires a quantitative framework that links measurable exposure parameters to observable physiological outcomes. In this sense, recent ontological initiatives such as OnSIR formalize the connection between radiation physics and plant response by defining classes and relations like *Exposure*, *DoseCategory*, *BiologicalOutcome*, and *Radiosensitivity* (ALVES et al., 2026). These semantic structures translate empirical knowledge into computable form, enabling reasoning over diverse datasets.

The combined evidence from traditional radiobiology and contemporary data modeling converges on a coherent view: radiation acts as a modulator of biological systems whose effects depend on the fine balance between physical energy deposition and biochemical resilience. Understanding this duality is essential for designing irradiation treatments that are safe, reproducible, and beneficial. As emphasized by VOSE (1980, pp. 34–35), “the biological effect of radiation depends not only upon the total energy absorbed but upon the physical conditions of exposure and the physiological condition of the material irradiated,” and later (p. 146) he reiterated that “interpretation of plant responses to radiation must take into account both the physical characteristics of the exposure and the state of the organism at the time of treatment.” These statements remain as relevant today as when they were written, serving as a guiding principle for all subsequent research in nuclear agriculture.

2.4 CLASSICAL AGRICULTURAL APPLICATIONS

The use of ionizing radiation in agriculture emerged as an important component of post-war research into peaceful applications of atomic energy. Among its early successes were the induction of beneficial mutations in crops, the sterilization of insect pests for area-wide control programs, and the extension of food shelf life through inhibition of microbial growth and physiological decay. These practical outcomes established radiation as a versatile tool for both pre- and post-harvest stages of agricultural production. Despite being

developed in the mid-twentieth century, these applications remain scientifically and economically relevant, forming the foundation for more recent studies on radiohormesis and precision irradiation (VOSE, 1980; FAO/IAEA, 2018).

2.5 MUTATION BREEDING

Mutation breeding represents the oldest and most institutionalized agricultural application of ionizing radiation. The principle is straightforward: exposing seeds, pollen, or vegetative tissues to a controlled dose of radiation increases the frequency of mutations, thereby generating novel genetic variability. In the end of the day, it is just the acceleration, "a little help", we may say, to the process Nature already does in evolution. This variability can then be exploited by conventional breeding techniques to select superior lines exhibiting desirable agronomic traits (SAVOV, 1989).

Historically, mutation induction was first demonstrated in 1927, when H. J. Muller showed that X-rays could produce heritable changes in *Drosophila*. By the 1930s, similar experiments on barley and maize had confirmed the mutagenic potential of radiation in plants. After the second World War, large-scale mutation programs were launched under the auspices of national atomic energy commissions and, later, through the FAO/IAEA Joint Division of Nuclear Techniques in Food and Agriculture. These initiatives standardized irradiation protocols, dosimetry methods, and breeding procedures, leading to the development of thousands of mutant cultivars across the globe (SPENCER-LOPES et al., 2018). They also helped rehabilitate nuclear science after the terrible crimes committed against Hiroshima and Nagasaki.

Typical doses for mutation breeding range from 100 to 400 Gy for dry seeds, depending on species radiosensitivity. The objective is to identify the so-called *semi-lethal dose* (LD₅₀), where about half the treated individuals survive and show a useful mutation frequency without excessive lethality (VOSE, 1980). In cereals such as rice and barley, LD₅₀ usually lies between 200 and 300 Gy; in legumes, around 150–250 Gy; and in vegetatively propagated crops, even lower doses may be required. Mutations are typically point changes or small deletions, although chromosomal rearrangements and translocations can also occur. The resulting phenotypic diversity is enormous: altered plant architecture, modified seed color, enhanced disease resistance, or improved abiotic stress tolerance may occur.

By 2018, the FAO/IAEA Mutant Variety Database listed more than 3,400 officially released mutant varieties worldwide, including major staples such as rice, wheat, barley, and

soybean, as well as fruits and ornamentals (FAO/IAEA, 2018). The global impact is substantial: in China, mutation breeding contributed to more than one million hectares of improved rice cultivars; in Japan, the famous “Reimei” rice, derived from gamma-irradiated material, marked a milestone in food security; and in Latin America, radiation-induced mutants of beans and groundnuts have shown enhanced yield stability under semi-arid conditions.

Methodological refinements have expanded the range of mutagenic materials and target tissues. Beyond seeds, scientists now use in vitro culture systems (such as callus, somatic embryos, and micropropagated shoots) allowing greater control over mutation spectrum and chimerism. The advent of molecular markers and genomic sequencing has also enabled the identification of specific mutations and the mapping of radiation-induced alleles, thereby improving selection efficiency. These molecular approaches confirm Vose’s (1980) prediction that radiation, as a tool of mutation induction, will achieve its greatest potential when combined with biochemical and genetic screening techniques.

Mutation breeding programs follow a structured sequence: (1) determination of radiosensitivity curve and optimal dose, (2) mass irradiation of seeds or tissues, (3) cultivation of the M_1 generation to identify surviving plants, (4) selection of variants in subsequent generations (M_2 – M_4), and (5) agronomic evaluation and stabilization of promising mutants. Each step requires careful record keeping of irradiation parameters, emphasizing dose rate, seed moisture, and post-irradiation storage conditions. Recent ontological models, such as the OnSIR framework, formalize this workflow, defining classes like *ExposureProcess*, *MutationInduction*, and *PhenotypicScreening*, which help integrate diverse experimental datasets into consistent digital repositories (ALVES et al., 2026).

While mutation breeding relies on relatively high doses, the biological mechanisms involved share continuity with those operating at lower doses. Both rely on the initial ionization of cellular components and the activation of repair and signaling pathways. In fact, the threshold between mutagenic and hormetic responses may depend more on repair fidelity and dose accumulation than on qualitatively different processes. Thus, mutation breeding and radiohormesis can be viewed as opposite ends of a continuous spectrum of radiation–plant interactions.

2.6 PHYTOSANITARY TREATMENT

Beyond its use for genetic improvement, ionizing radiation provides a powerful means of controlling pests and pathogens in agricultural commodities. The concept of using radiation for disinfestation was introduced shortly after its application in mutation breeding. The method exploits the differential radiosensitivity between microorganisms and the treated product: doses sufficient to eliminate (or inactivate in the case of spores) insects or fungi are far below those that could damage plant tissue or alter food quality (VOSE, 1980).

Phytosanitary irradiation involves exposing harvested commodities (grains, fruits, nuts, spices, or leaves) to doses typically ranging from 200 to a few thousand Gy. The biological effects include inhibition of cell division in insects, sterilization of reproductive organs, and suppression of fungal sporulation. The process leaves no chemical residues and does not significantly increase product temperature, making it environmentally safe and compatible with international trade standards (WARKE et al., 1999). Usually, also, organoleptic characteristics are maintained after processing.

Radiation-based pest control operates through several mechanisms. In insects, gamma irradiation induces dominant lethal mutations, preventing reproduction. In fungi and bacteria, DNA strand breaks and oxidative damage inhibit replication. Because the treated commodities are metabolically quiescent, such doses cause negligible structural or biochemical alterations in the host tissues. The FAO/IAEA and the International Plant Protection Convention (IPPC) recognize phytosanitary irradiation as an approved method for quarantine treatment, allowing countries to meet biosecurity requirements without relying on methyl bromide or phosphine fumigation (FAO/IAEA, 2018).

An illustrative example is the use of gamma irradiation for the control of storage pests such as *Sitophilus oryzae* (rice weevil) and *Callosobruchus maculatus* (cowpea beetle). Doses of 300–600 Gy effectively sterilize adult insects without affecting grain viability or nutritional value. In the tobacco industry, irradiation has been successfully employed to reduce microbial contamination and insect infestation in processed leaves, improving hygienic quality while preserving organoleptic characteristics (WARKE et al., 1999). This approach aligns with sustainable production goals and consumer safety, as no pesticide residues are involved.

Modern advances extend these concepts to integrated pest management (IPM) strategies, combining irradiation with biological control agents and environmental monitoring. For instance, sterile insect technique (SIT) programs employ radiation to sterilize male insects

before release into target populations, reducing reproduction rates in pest species such as fruit flies and tsetse flies. These programs illustrate how radiation can serve not merely as a disinfestation method but as a relevant part of ecological pest control, reducing chemical dependence and environmental impact.

Ontological frameworks such as OnTop contribute to the management of phytosanitary data by structuring information about pest species, treatment parameters, and environmental conditions (ALVES et al., 2025). Within such systems, the concept of *ManagementAction* encompasses activities like irradiation, fumigation, or thermal treatment, allowing interoperability between datasets from different regulatory and experimental sources. This digital structuring of phytosanitary knowledge enhances traceability, compliance verification, and the optimization of treatment protocols.

Food Preservation

A third major application of ionizing radiation in agriculture and food science is the preservation of perishable products. While mutation breeding and phytosanitary control operate at relatively higher doses, food preservation relies on comparatively low exposures (generally between 50 and 150 Gy) sufficient to inhibit sprouting, delay ripening, and suppress enzymatic activity without altering sensory or nutritional attributes (FAO/IAEA, 2018).

The physiological processes leading to spoilage or deterioration are largely enzymatic or hormonal in nature. After harvest, tubers such as potatoes and onions may sprout, consuming stored carbohydrates and reducing market value. Similarly, enzymatic browning in fruits and microbial growth in spices compromise appearance, taste and safety. Ionizing radiation interrupts these processes by inhibiting cell division in meristematic tissues and inactivating oxidative enzymes like polyphenol oxidase (PPO) and peroxidase (POD). The result is prolonged shelf life and improved product uniformity.

Radiation preservation differs fundamentally from thermal or chemical methods. Because the absorbed energy is low and evenly distributed, temperature rise during treatment rarely exceeds 1–2°C, avoiding the loss of volatile compounds and vitamins. Moreover, unlike chemical preservatives, radiation leaves no residues and requires no additives, an advantage for health-conscious consumers. The FAO and WHO have repeatedly affirmed the safety of irradiated foods when processed under recommended guidelines (FAO/IAEA, 2018).

Numerous case studies demonstrate these benefits. In potatoes, doses around 100 Gy inhibit sprouting for several months without affecting cooking quality. In onions, similar doses prevent sprouting and extend storage life by 4–6 months. Mangoes and papayas irradiated with 100–200 Gy maintain firmness and color longer during export, reducing post-harvest losses. In spices such as pepper and cardamom, gamma irradiation at 5–10 kGy ensures microbial decontamination while preserving aroma and flavor. Although higher than the doses used for physiological preservation, such treatments remain well below thresholds that induce chemical or nutritional degradation (VOSE, 1980).

From an operational standpoint, food irradiation requires precise dosimetry and validation. Factors such as packaging material, product density, and moisture content influence dose distribution. To ensure compliance, dosimeters are placed at minimum and maximum dose locations within the product lot, and absorbed doses are verified against established standards. International guidelines specify labeling requirements and recommend the use of the “Radura” symbol to identify irradiated foods, promoting transparency and consumer confidence.

The integration of food preservation data into digital frameworks further exemplifies the evolution of radiation technology toward smart agriculture. By linking parameters like dose, temperature, and microbial load within an ontological model, researchers can build predictive systems to optimize treatment schedules and logistics. For example, a knowledge graph could relate *IrradiationDose* to *ShelfLifeExtension* and *MicrobialReduction*, enabling automated reasoning about ideal storage conditions and trade routes (ALVES et al., 2025).

Broader Significance and Legacy

The classical applications of radiation (mutation breeding, phytosanitary control, and food preservation) collectively illustrate the versatility of ionizing energy in addressing diverse agricultural challenges. They also exemplify the transition from empirical experimentation to standardized technological practice. Each application involves the same fundamental physics but distinct biological targets: in mutation breeding, DNA within developing embryos; in phytosanitary treatments, the reproductive cells of pests and pathogens; and in food preservation, the metabolic enzymes of harvested tissues. The range of effective doses across these applications spans nearly four orders of magnitude, from a few tens to several thousand gray, underscoring the importance of precise dosimetry and contextual interpretation (VOSE, 1980).

These achievements paved the way for contemporary investigations into low-dose effects and radiohormesis. As noted in recent studies on *Nicotiana tabacum*, physiological stimulation occurs at doses an order of magnitude lower than those used for mutation induction but within the same conceptual framework of radiation–biomolecule interaction (ALVES et al., 2026).

Furthermore, the classical applications demonstrate that radiation can be a sustainable technology when integrated responsibly. Unlike chemical fumigants or thermal sterilization, irradiation consumes relatively little energy, produces no greenhouse gases, and generates no hazardous waste. It aligns with the United Nations Sustainable Development Goals (SDGs), particularly those concerning responsible consumption, zero hunger, and climate action. In this sense, the legacy of the early nuclear agronomy programs continues to evolve: from the initial promise of atomic progress to the modern vision of intelligent, low-impact agriculture.

Table 1

Summary of ionizing radiation dose ranges and their main agricultural purposes, aligned with mechanistic interpretation and ontological classes.

Effect Application	Typical Range (Gy)	Dose	Purpose Biological Effect	Consistency and Mechanistic Notes
Hormesis (Low-dose Stimulation)	Below 20, optimum 5–15		Enhances germination, vigor, antioxidant activity (SOD, CAT, POD), and early biomass. Acts as seed priming via mild ROS signaling and hormonal modulation.	Consistent with <i>N. tabacum</i> optima ($\approx 12.5\text{Gy}$) and FAO/IAEA reports (5–15 Gy). Represented in OnSIR: StimulatoryDose . (VOSE, 1980; ALVES et al., 2026; VILLEGAS et al., 2023)
Mutagenesis (Breeding)	100–400 seeds)	(dry	Induces heritable variation for selection (yield, stress resistance).	Aligned with VOSE (1980) and FAO/IAEA (2018) values: cereals 200–300, legumes

Effect Application	Typical Range (Gy)	Dose	Purpose Biological Effect	Consistency and Mechanistic Notes
			Used to determine LD ₅₀ .	150–250. Mechanism: DNA double-strand breaks and imperfect repair. OnSIR: MutagenicRange. (SAVOV, 1989)
Phytosanitary Sterilization	200–1000 (pests); 5–10 kGy (spices)		Eliminates insects, fungi, bacteria; replaces fumigants for quarantine and microbial safety.	Mechanisms: dominant lethal mutations, inhibition of sporulation. Consistent with VOSE (1980), WARKE et al. (1999). OnSIR: SterilizationThres hold.
Food Preservation	50–150		Inhibits sprouting and enzymatic browning; prolongs shelf life of tubers and fruits.	FAO/IAEA (2018): potatoes, onions, mangoes, papayas. Mechanism: inhibition of mitosis in meristematic tissues. OnSIR: InhibitoryDose.
Industrial Sterilization	10–25 kGy		Complete microbial inactivation (media, medical/food).	Above physiological range; causes macromolecule degradation. Retains relevance for in vitro seed sterilization. OnSIR: HighDoseRange.

Low-Dose Effects and Radiohormesis

At sublethal doses (typically 1–20 Gy), ionizing radiation may stimulate metabolic activity, accelerate germination, and enhance early seedling performance. This biphasic dose–response relationship (where low doses produce beneficial stimulation and higher doses inhibit or damage) is termed *radiohormesis*. The concept, long debated in toxicology, has gained renewed attention in plant sciences as a possible tool for sustainable crop improvement (VOSE, 1980; VILLEGAS et al., 2023).

Radiation hormesis represents a paradoxical biological response: the same agent capable of inducing DNA damage and growth inhibition at high intensities can, at lower levels, activate protective and adaptive mechanisms that ultimately improve vitality. The recognition of this phenomenon in plants has transformed how agronomists interpret radiation effects (from strictly deleterious to potentially regulatory) and has opened a new frontier in seed technology, stress physiology, and digital agronomy (ALVES et al., 2026).

Physiological Basis

The physiological basis of radiohormesis lies in the interplay between stress perception and adaptive response. Ionizing radiation interacts with plant cells primarily through the radiolysis of water, producing reactive oxygen species (ROS) such as hydroxyl radicals, superoxide anions, and hydrogen peroxide. At high doses, these radicals accumulate to cytotoxic levels, causing membrane peroxidation, enzyme inhibition, and DNA strand breaks. At low doses, however, the transient increase in ROS serves as a signal that activates redox-sensitive transcription factors, enzymatic defense systems and hormonal pathways (VOSE, 1980).

Experimental evidence indicates that the ROS burst following low-dose irradiation functions similarly to the oxidative signaling observed during seed priming with osmotic or vernalization treatments. The elevated redox potential triggers NADPH-dependent enzymes, increases ATP turnover, and mobilizes reserve compounds. Enzymes such as amylase, peroxidase, and catalase exhibit enhanced activity within hours after exposure, facilitating faster energy release for germination (GENG et al., 2019). The upregulation of superoxide dismutase (SOD) and catalase (CAT) ensures rapid neutralization of excess radicals, preventing oxidative damage while maintaining a mild stress signal.

At the subcellular level, mitochondria and chloroplasts play critical roles in this adaptive response. Low doses of radiation have been shown to increase mitochondrial respiration rates and chlorophyll biosynthesis in young seedlings. Such responses suggest a temporary

enhancement of metabolic flux, consistent with the “overcompensation” model of hormesis proposed by Calabrese and Baldwin (2003), in which mild stress elicits compensatory processes that exceed basal levels of function.

Hormonal modulation further contributes to the stimulatory effects. Studies in *Nicotiana tabacum* and other species show that low-dose gamma irradiation elevates auxin and cytokinin levels while transiently suppressing abscisic acid (ABA), thereby promoting cell division and elongation (VOSE, 1980). Irradiation also influences calcium signaling, a key mediator in stress perception, which in turn regulates antioxidant enzyme gene expression. The cumulative effect of these pathways manifests as enhanced germination rate, improved uniformity, and increased early biomass accumulation.

Recent insights suggest that radiohormetic signaling may involve epigenetic mechanisms as well. DNA methylation, histone modification, and microRNA regulation have all been implicated in the adaptive memory induced by mild radiation stress (ALVES et al., 2026). Such modifications can persist across cell divisions, offering a plausible explanation for the sustained improvement in vigor observed in irradiated plants beyond the immediate treatment phase.

Experimental Evidence

Over seven decades of experimentation have established radiohormesis as a reproducible though dose-sensitive phenomenon. Early observations by VOSE (1980) described enhanced germination and growth in barley and lettuce irradiated at 5–10 Gy, followed by inhibition above 20 Gy. Subsequent FAO/IAEA trials across multiple species confirmed that the stimulatory window generally falls between 5 and 15 Gy for dry or semi-dry seeds (FAO/IAEA, 2018). Within this range, germination speed, seedling height, and chlorophyll content often surpass those of non-irradiated controls.

Controlled experiments with *Nicotiana tabacum* L. have provided one of the most detailed analyses of this effect. In a recent study by the authors, three commercial varieties (Burley, Dark and Virginia) were exposed to graded doses from 0 to 20 Gy using a ^{60}Co gamma source. Measurements included germination kinetics, seedling dry mass, and growth rate over two and four weeks. Results revealed clear varietal differences in sensitivity: the Dark variety exhibited maximal stimulation near 12.5 Gy, with biomass increases exceeding 100% relative to control, while BY and VA showed smaller yet significant gains around 10 Gy. Above 15 Gy, growth declined, confirming the narrowness of the hormetic window (ALVES

et al., 2026). The main germination kinetics and biomass parameters are presented in Table 2.

Table 2

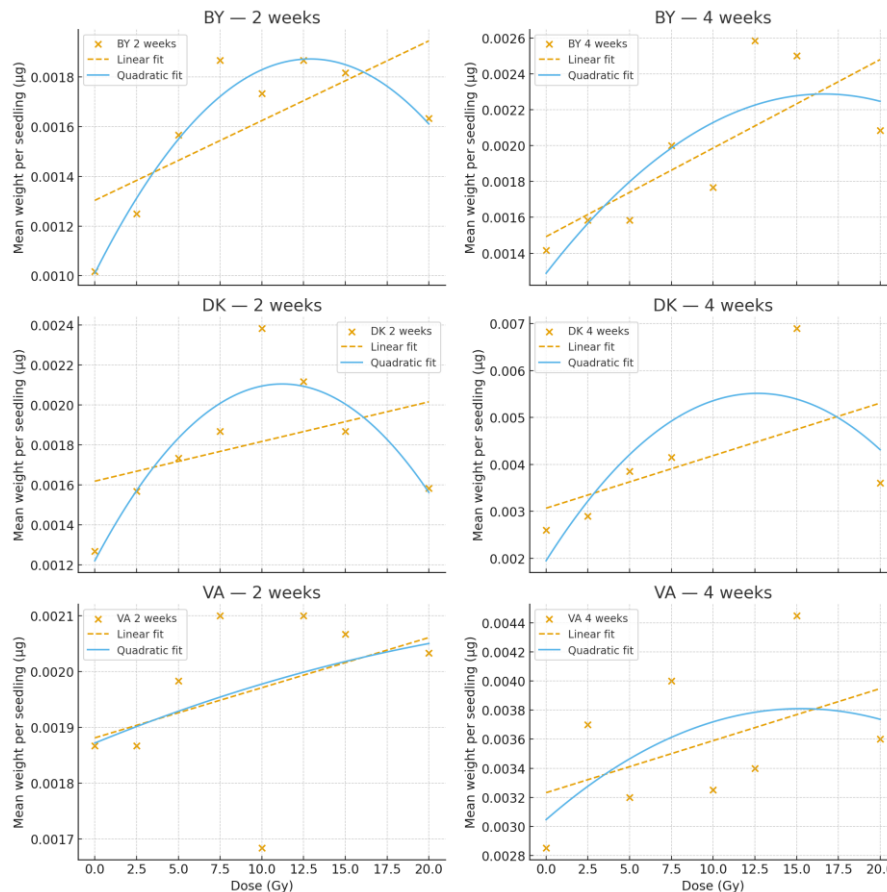
Mean germination and biomass parameters for three Nicotiana tabacum varieties exposed to graded doses of gamma radiation. Adapted from ALVES et al. (2026).

Variety	Dose (Gy)	T ₅₀ (days)	AUC (a.u.)	Biomass
				Change (%)
Burley (BY)	0–20	3.8–3.1	92–110	+45
Dark (DK)	0–20	4.0–2.9	88–121	+112
Virginia (VA)	0–20	3.6–3.2	95–107	+38

As shown in Figure 1, the dose–response curves for seedling biomass exhibit a distinct biphasic pattern: growth enhancement up to 15 Gy followed by a decline at higher exposures. This figure illustrates the quantitative transition from stimulation to inhibition, reinforcing the concept that radiosensitivity and adaptive repair capacity define the effective range of radiohormesis in plants (ALVES et al., 2025).

Figure 1

Dose–response curves for seedling biomass in three Nicotiana tabacum varieties after gamma irradiation. The range 10–15 Gy corresponds to the stimulatory window identified experimentally.



Source: From ALVES et al. (2026).

Kinetic analyses based on time-to-50% germination (T_{50}) and area under the germination curve (AUC) provided quantitative indicators of stimulation. Low doses reduced T_{50} by up to 30%, signifying faster emergence, and increased AUC values, reflecting more uniform population establishment. These physiological improvements correlated with increased antioxidant enzyme activities and higher soluble sugar concentrations in the cotyledons, supporting the hypothesis that mild oxidative stress accelerates reserve mobilization.

Other species exhibit similar biphasic patterns. In cowpea and soybean, irradiation at 5–10 Gy enhanced germination percentage and vigor index, whereas doses beyond 20 Gy reduced root and shoot lengths (GENG et al., 2019). In wheat, stimulation of seedling height and chlorophyll content occurred at 8 Gy, with inhibition above 25 Gy. In tomato, low-dose

gamma irradiation improved early growth and photosynthetic efficiency but delayed flowering when exposure exceeded 15 Gy (WIENDL, 2010). Such consistency across taxa supports the generality of the hormetic model in plants, although the optimal dose varies by genotype, seed moisture and dose rate.

The reproducibility of radiohormesis depends critically on dosimetric precision and environmental control. Small deviations in absorbed dose or humidity can shift the stimulatory range. The FAO/IAEA recommends that researchers characterize the full dose–response curve for each species under well-defined conditions, including seed moisture content, oxygen availability, and post-irradiation storage time (FAO/IAEA, 2018). These parameters determine the balance between ROS generation and antioxidant capacity, which ultimately dictates whether stimulation or inhibition occurs.

Ontological frameworks such as OnSIR formalize this relationship by defining explicit classes like *LowDoseRange*, *StimulatoryDose*, and *InhibitoryDose* (ALVES et al., 2026). Through logical relations such as $\text{LowDoseRange} \subseteq \text{hasEffect some (StimulatesGrowth or EnhancesGermination)}$, the ontology enables computational reasoning about experimental outcomes. Aligning these formal definitions with data from radiation facilities, the system supports meta-analyses across species and dose categories, facilitating the identification of generalized hormetic thresholds.

Mechanistic Insights

Understanding why plants exhibit hormesis requires reconciling molecular events with whole-organism outcomes. Three complementary hypotheses dominate current explanations.

First, the *adaptive repair hypothesis* posits that low-dose irradiation activates DNA repair systems more robustly than they are required at baseline. The transient activation of these pathways not only corrects minor damage from the exposure itself but also preconditions the cell against future stress. Enhanced activity of enzymes involved in base excision repair (BER) and nucleotide excision repair (NER) has been documented in irradiated seedlings (VOSE, 1980).

Second, the *metabolic stimulation hypothesis* suggests that mild radiation acts as an energy catalyst by accelerating respiratory metabolism. Measurements of oxygen consumption and dehydrogenase activity show short-term increases after low-dose exposure, leading to greater ATP availability for cell division and elongation (GENG et al.,

2019). The increase in metabolic rate, however, declines after several days, indicating that the stimulation is transient and self-limiting.

Third, the *signaling balance hypothesis* integrates ROS and hormonal signaling into a unified model. According to this view, ROS generated by radiolysis serve as primary messengers that modulate calcium influx and activate protein kinases. These signals, in turn, alter transcriptional networks governing antioxidant defenses and growth regulation. The resulting dynamic equilibrium produces enhanced physiological performance without lasting oxidative damage.

Epigenetic studies provide additional evidence for a “memory effect” of low-dose irradiation. Methylation-sensitive markers reveal temporary changes in DNA methylation patterns following sublethal exposure, some of which persist through early development. Such reversible epigenetic reprogramming may underlie the enhanced vigor observed in seedlings derived from irradiated seeds (ALVES et al., 2026).

Agronomic Implications

The recognition of radiohormesis has significant agronomic implications. Low-dose irradiation can be regarded as a form of *physical seed priming*, analogous to hydropriming or osmopriming but achieved through energy transfer rather than chemical or osmotic gradients. The method offers unique advantages: uniform treatment of large seed batches, independence from water quality, and compatibility with existing gamma facilities used for mutation breeding (FAO/IAEA, 2018).

Potential applications include:

- *Enhancement of germination under stress:* Irradiated seeds often show improved emergence in saline, drought, or temperature-stressed soils. The pre-activation of antioxidant systems increases tolerance to oxidative stress encountered during germination.
- *Synchronization of seedling establishment:* More uniform germination leads to homogenous crop stands, facilitating mechanized management and reducing yield variability.
- *Stimulation of early vigor:* Accelerated growth at the seedling stage can improve competitiveness against weeds (an often overlooked advantage) and contribute to better resource use efficiency.

However, practical implementation requires rigorous standardization. Unlike mutation breeding, where small variations in dose can be tolerated, radiohormetic effects depend on

precise calibration. Environmental factors such as relative humidity, oxygen concentration, and storage period between irradiation and sowing can modulate outcomes dramatically. Excessive delay between treatment and planting may allow ROS-related signaling effects to dissipate, reducing stimulation (VOSE, 1980).

To address these challenges, FAO/IAEA protocols recommend detailed reporting of physical and biological parameters. Ontological data models now incorporate such metadata under standardized properties like *hasDoseRate*, *hasMoistureCondition*, and *hasPostTreatmentInterval*, ensuring that future analyses can compare results reproducibly (ALVES et al., 2026). The use of semantic frameworks is thus instrumental for transforming radiohormesis from a qualitative observation into a quantitatively predictable process.

In the broader context of sustainable agriculture, radiation-induced seed priming aligns with the goals of reducing chemical inputs and enhancing resilience. It requires no additives, generates no waste, and can be performed in facilities already available for food irradiation. Furthermore, when integrated with digital monitoring and decision-support systems, radiohormesis data can feed into predictive models that optimize planting schedules based on environmental conditions and seed vigor (ALVES et al., 2025). This synthesis of physical treatment, biological response, and digital reasoning exemplifies the evolution of nuclear techniques into components of intelligent agronomy.

Challenges and Perspectives

Despite compelling evidence, several challenges limit the broader adoption of radiohormesis in agricultural practice. The first is *variability*. Results often differ among laboratories due to small deviations in dose measurement or seed condition. This variability underscores the need for harmonized methodologies and inter-laboratory calibration campaigns, similar to those established for mutation breeding (FAO/IAEA, 2018).

The second challenge is *mechanistic uncertainty*. Although the involvement of ROS signaling is well supported, the precise molecular events linking radiation exposure to developmental acceleration remain incompletely understood. Integrating omics approaches (transcriptomics, proteomics and metabolomics) with traditional physiology could possibly clarify these pathways. Ontological modeling provides a formal framework for organizing such complex, multiscale data.

A third challenge concerns *public perception*. The term “radiation” continues to evoke apprehension despite the absence of induced radioactivity or chemical residues in irradiated materials. Effective science communication, emphasizing safety and environmental benefits,

is essential to foster acceptance among producers and consumers. The historical success of food irradiation programs demonstrates that these concerns can be overcome through transparency and regulatory oversight.

Looking forward, advances in precision dosimetry, automated irradiation systems, and AI-driven experimental design promise to enhance reproducibility and scalability. The combination of low-dose gamma irradiation with other priming techniques (for instance, hydropriming, vernalization or magnetic field treatment) may yield synergistic benefits. From a data perspective, the linkage of radiation exposure parameters with agronomic outcomes through semantic databases will allow predictive modeling of hormetic windows for diverse species and environments (ALVES et al., 2026).

Digital and Ontological Approaches in Radiation Agronomy

Need for Knowledge Integration

Although the use of ionizing radiation in agriculture dates back more than seventy years, the accumulated knowledge in plant radiobiology remains dispersed across thousands of reports, theses and localized experiments. Many of these studies were conducted independently, using different experimental setups, units of measurement, and biological descriptors. As a result, comparative synthesis and meta-analysis are often difficult or impossible. For example, two laboratories might report “seed stimulation” at 10 Gy in distinct species but measure outcomes with incompatible metrics: one as germination percentage, another as biomass gain. Without shared standards for terminology and metadata, cross-study interpretation remains largely qualitative (FAO/IAEA, 2018).

This fragmentation reflects a historical pattern in agricultural research, where local adaptation of methods and terminology evolves faster than formal standardization. In the specific field of plant irradiation, the problem is amplified by interdisciplinary complexity: physics defines exposure in terms of absorbed dose and linear energy transfer, while agronomy expresses results through growth indices, yield or stress tolerance. Bridging these vocabularies requires an explicit mapping between physical and biological parameters, a task that cannot rely solely on narrative description.

In recent years, the convergence of agricultural informatics, data science, and ontology engineering has provided new tools for solving this integration gap. An ontology, in its simplest sense, is a structured representation of knowledge: a vocabulary of concepts and relationships formalized so that humans and computers can interpret data consistently. In radiation agronomy, this means formally representing entities such as *radiation source*, *dose*

category, *biological material* and *observed effect* (ALVES et al., 2026). Ontological models allow the results of field or laboratory experiments to be described not as isolated text, but as standardized data points linked to a conceptual framework. Once structured this way, data can be reused, compared, and analyzed automatically.

The motivation for such integration is practical. Modern agricultural research increasingly relies on data sharing among institutions, long-term monitoring, and meta-analytical modeling. Precision agriculture and climate-smart farming already employ semantic databases to integrate information on soil, weather, and crop management. Extending this digital infrastructure to encompass radiation effects ensures that the empirical foundation of nuclear agronomy becomes interoperable with the broader agricultural knowledge ecosystem. By connecting radiation response data to soil fertility, climate, and management practices, scientists can explore questions such as: “Under which climatic conditions is low-dose irradiation most beneficial for germination?” or “How does seed moisture interact with radiation to affect field emergence?” Such questions require structured, multi-dimensional data that only semantic frameworks can consistently support.

Ontologies as Semantic Infrastructure

Ontologies differ from simple databases because they represent not only data but also meaning. Each concept in an ontology belongs to a hierarchy, has defined properties, and is linked to others through explicit relationships such as *is a type of*, *has dose*, *causes effect* or *occurs in species*. This structure enables machines to perform reasoning (to infer new information from existing statements) and allows humans to interpret complex datasets without ambiguity (ALVES et al., 2026).

In radiation agronomy, several conceptual layers must be integrated. At the physical level, irradiation is described by parameters such as energy, dose, and dose rate. At the biological level, outcomes are classified as mutation, stimulation, or inhibition. Between them lies an intermediate layer of experimental context: species, variety, tissue type, water content, and environmental conditions. Ontologies provide the scaffolding to connect these layers, enabling queries such as:

“Which species exhibit stimulatory effects between 5 and 10 Gy of gamma radiation when seed moisture is below 12%?”

Such a query requires the ontology to know that *gamma radiation* is a subclass of *ionizing radiation*, that 5–10 Gy corresponds to a *low-dose range*, and that *seed moisture* is

an environmental modifier of radiosensitivity. Without this semantic infrastructure, answering such a question would require manual review of dozens of papers.

The Ontology for Seed Irradiation (OnSIR) was designed to formalize exactly this type of knowledge (ALVES et al., 2026). OnSIR represents the conceptual domain of seed irradiation through classes such as *Exposure*, *DoseCategory*, *RadiationSource*, *BiologicalMaterial*, and *Outcome*. It distinguishes categories like *StimulatoryDose*, *MutagenicRange*, and *SterilizationThreshold*, allowing precise annotation of experimental data. In this framework, the 10–15 Gy range that stimulates germination in *Nicotiana tabacum* L. is formally defined as a subclass of *LowDoseRange* that has the property *induces* some *EnhancedGermination*. This formalization transforms a qualitative observation into a structured assertion that can be queried or compared automatically.

Another layer of semantic modeling is provided by the Ontology of Tobacco Production (OnTop), which focuses on the agronomic side of the crop system (ALVES et al., 2025). OnTop models entities such as *ClimateCondition*, *SoilCondition*, *ManagementAction*, and *YieldOutcome*. When linked to OnSIR, it allows radiation treatments to be interpreted within the broader production cycle: for instance, how seedbed irradiation affects subsequent field growth or curing quality. Through such linkage, ontologies act as bridges between laboratory radiobiology and real-world agricultural management.

Beyond individual ontologies, the principle of interoperability is central. Agricultural research increasingly adopts shared, ensuring that new domain-specific vocabularies can communicate with existing ones. OnSIR follows this approach, aligning its classes with higher-level categories like *Process*, *MaterialEntity*, and *Quality*. As a result, its data can interact with environmental and crop ontologies without semantic conflict, promoting the integration of radiation effects into global agricultural data infrastructures.

For agricultural scientists, the value of such semantic infrastructure lies not in abstract logic but in practical benefits: reproducibility, discoverability, and decision support. When radiation experiments are described using standardized ontological terms, other researchers can reproduce treatments with confidence, knowing exactly what dose range, environmental condition and biological material were used. Moreover, digital repositories indexed by ontological terms allow future studies to build on existing results without redundancy (something that every researcher in this field has encountered).

Application in Agricultural Research and Extension

The agricultural implications of ontology-based systems extend beyond the laboratory. In breeding programs, radiation is used not only to induce mutations but also to evaluate stress tolerance. Ontological data models can document the full experimental workflow, from irradiation to field performance, capturing metadata such as irradiation facility, date, dose rate, variety name, and observed trait. This structured documentation becomes invaluable when evaluating long-term responses or correlating radiation treatments with climatic variability (ALVES et al., 2025).

In extension and production systems, semantic databases can assist in knowledge transfer. For example, an agricultural advisor might query a digital platform for recommended irradiation doses to stimulate germination in tobacco or cowpea under specific moisture conditions. The system, drawing from ontologically structured data, can provide evidence-based guidelines along with safety and operational parameters. By embedding radiation knowledge into the digital tools already used in precision agriculture, ontologies make nuclear techniques accessible to practitioners who may have no formal training in radiobiology.

Another promising application is the integration of irradiation data with environmental and phenological monitoring. Linking OnSIR concepts like *DoseRate* and *ExposureTime* to OnTop entities such as *Temperature*, *Humidity*, or *SoilMoisture* allows researchers to model how environmental variables modulate radiation effects. For instance, the same 10 Gy dose may produce stronger stimulation under moderate humidity than under arid conditions, due to differences in ROS diffusion and seed hydration. By embedding these relationships into an ontology, the system can generate hypotheses and guide future experiments.

Integration with Artificial Intelligence

While ontologies provide the formal backbone of knowledge, artificial intelligence (AI) tools offer the reasoning capacity to make this knowledge operational. Large Language Models (LLMs), when integrated with ontological data, can generate coherent explanations and recommendations that combine symbolic precision with linguistic flexibility. In practice, this means that an AI system trained on agricultural data can understand user questions like “What is the optimal irradiation dose for stimulating tobacco seed germination at such-and-such latitude and longitude for such-and-such variety at such-and-such time of the year?” and consult structured ontological knowledge to refine its answer (ALVES et al., 2026).

This hybrid approach was tested in experimental evaluations where an LLM was provided with and without access to ontologies, with promising results.

From an agricultural viewpoint, AI–ontology integration offers practical advantages. It can support decision-making in seed technology, quality assurance, and training. In seed processing facilities, an AI assistant equipped with OnSIR data could recommend irradiation settings according to crop type and moisture level. In extension services, digital platforms could answer farmer queries about the safety and benefits of irradiated seeds, ensuring accurate information dissemination and reducing misconceptions about radiation use in agriculture.

Importantly, the goal of such systems is not to replace expert judgment but to complement it. Ontologies capture consensus knowledge, while AI provides interpretative flexibility. Together, they can democratize access to complex scientific information, bridging the gap between nuclear research centers and agricultural communities. This synergy aligns with the FAO’s vision of “digital transformation of agriculture” and supports the integration of nuclear techniques into broader frameworks of sustainable intensification (FAO/IAEA, 2018).

Ethical and Practical Considerations

As digital systems increasingly mediate agricultural knowledge, ethical and practical considerations arise. Data governance is essential: irradiation experiments involve not only physical parameters but also biological materials that may have intellectual property implications. Ontological repositories should therefore incorporate metadata on data ownership, licensing, and privacy. The use of open licenses, such as Creative Commons Attribution, ensures that ontological content remains accessible to researchers while protecting contributors’ rights.

Training and accessibility are equally important. For many agronomists, the terminology of ontologies and artificial intelligence remains unfamiliar. Educational initiatives that translate these concepts into practical agricultural examples can encourage adoption. Ontologies like OnTop and OnSIR were designed with this pedagogical dimension in mind, using intuitive hierarchies and clear definitions rather than abstract formalism (ALVES et al., 2025; ALVES et al., 2026).

Finally, digital infrastructures must be aligned with physical capacity. Ontological reasoning and AI-based recommendations depend on the availability of well-calibrated irradiation facilities and accurate experimental data. For many developing countries, this implies investment not only in digital tools but also in physical laboratories and training programs. The synergy between technological infrastructure and human expertise is what will ultimately determine the success of digital radiation agronomy.

Future Perspectives

The convergence of nuclear techniques and digital agriculture heralds a new phase in the evolution of agronomic science. In the past, the emphasis was on discovering radiation effects experimentally; today, the challenge is to integrate, standardize, and predict them. Ontologies provide the language, while AI provides the logic. Together, they can enable predictive modeling of radiation outcomes, optimizing doses for each species and environment.

One promising direction is the creation of international ontological registries for plant radiobiology, analogous to genetic databases. Such registries would store dose–response curves, seed parameters, and environmental metadata in standardized formats, accessible to both scientists and policymakers. Combined with climate and soil datasets, they could inform large-scale strategies for sustainable intensification, using radiation as a safe and precise input technology.

The broader vision is that every radiation experiment conducted in agriculture contributes not only to local knowledge but also to a shared, evolving digital ecosystem. When described through ontological standards, even small studies gain global relevance. This democratization of data aligns with the open-science principles endorsed by FAO and UNESCO, ensuring that the benefits of radiation research reach all regions, including those most in need of resilient agricultural solutions.

In summary, digital and ontological approaches do not replace the traditional methods of radiation agronomy: they amplify them. They transform scattered results into structured, accessible and actionable knowledge.

Perspectives and Conclusions

Ionizing radiation continues to provide valuable tools for sustainable agriculture. From mutation breeding to physiological stimulation, its effects depend critically on dose, context and biological material. Future progress will hinge on the convergence between traditional experimentation and digital knowledge infrastructures. Standardized data, interoperable ontologies and intelligent reasoning systems can transform isolated findings into actionable insights. Through this integration, radiation agronomy may evolve from an empirical field into a predictive and data-driven science, aligning nuclear techniques with the broader goals of sustainable and intelligent agriculture.

Historical Reflection and Scientific Continuity

The trajectory of ionizing radiation in agriculture mirrors the broader evolution of agricultural science: it began as an experimental curiosity, matured into a set of standardized practices, and now moves toward data integration and intelligent decision support. During the 1950s and 1960s, the prevailing optimism surrounding nuclear energy fostered extensive experimentation with gamma irradiation in plant breeding, pest control and food preservation. This early period of nuclear agronomy, characterized by unbounded confidence in scientific progress, remains an enduring source of inspiration. Researchers such as Peter B. Vose, extensively cited throughout this chapter and with whom one of the authors had the opportunity to collaborate during his stay at the Center for Nuclear Energy in Agriculture, systematized the methodology and established a coherent theoretical foundation that demonstrated how radiation could serve as a controlled and reproducible variable in biological research. That pioneering period produced not only mutant varieties and improved post-harvest technologies but also a distinctive scientific ethos.

Today, that same ethos reemerges under different technological conditions. Where earlier researchers relied on analog dosimeters and field notebooks, modern scientists operate with automated irradiators, spectrophotometers and digital data loggers. The challenge, however, remains essentially the same: understanding how a physical process (the deposition of energy in matter) translates into a biological response that can be useful for agriculture. The continuity between past and present underscores the durability of radiation as an agricultural tool and the foresight of early nuclear agronomists who saw in it not a transient innovation but a permanent addition to the scientific toolkit.

The empirical knowledge accumulated during the twentieth century provides the empirical backbone for contemporary developments in radiohormesis and digital agronomy. The experimental design principles introduced by VOSE (1980) (control of seed moisture, calibration of source geometry, and replication under field conditions) remain valid today. What has changed is the capacity to measure, record and analyze these parameters at scales unimaginable to earlier generations. The rise of computational modeling and ontological representation brings to fruition the very ideal those pioneers anticipated: a precise and quantitative understanding of how radiation interacts with living systems.

From Empirical Observations to Predictive Models

Historically, the use of radiation in agriculture followed an empirical trajectory: researchers exposed plant material to a range of doses and observed the outcomes. The

resulting dose–response curves were plotted manually and compared across experiments. While effective for identifying general trends, this approach could not easily capture the multitude of interacting variables (seed physiology, dose rate, oxygen concentration or genetic background) that shape the biological effect.

Contemporary data science changes this paradigm. By digitizing and semantically annotating experiments, scientists can construct predictive models that relate physical parameters to biological outcomes. For instance, integrating dose, dose rate and moisture content within an ontology allows statistical and machine-learning algorithms to identify patterns that would be invisible in narrative reports. Instead of stating that “10 Gy stimulated germination,” researchers can now compute probabilistic thresholds: under defined conditions, a given dose has a quantifiable likelihood of producing stimulation rather than inhibition.

Such predictive capability has practical importance. In mutation breeding, it enables more efficient determination of LD₅₀ values without extensive preliminary trials. In radiohormetic seed priming, it allows optimization of treatment protocols for specific cultivars. And in phytosanitary irradiation, predictive models can balance microbial inactivation with organoleptic characteristics preservation. The transition from empirical observation to predictive analytics thus represents a natural continuation of the discipline’s maturation.

Reproducibility, Standardization and the Role of Ontologies

A persistent challenge in radiation agronomy has been the difficulty of reproducing results across laboratories. Slight variations in seed storage, humidity or dose measurement can shift outcomes dramatically. The introduction of ontologies addresses this problem by enforcing standardized descriptors for all relevant parameters. When experiments are annotated using shared concepts (*hasMoistureContent*, *hasDoseRate*, *usesSourceType*, *hasObservedOutcome*) their metadata become interoperable, allowing results from different regions to be compared directly.

The OnSIR ontology exemplifies this principle. It formalizes key entities, each defined by quantitative and qualitative attributes. By assigning persistent identifiers to these concepts, OnSIR ensures that the term “low dose” means the same thing in every dataset. Similarly, the OnTop ontology standardizes agronomic contexts (soil condition, management action, or yield outcome) enabling cross-domain integration. Together, these ontologies create a shared language for describing radiation experiments in agriculture, bridging the gap between physical measurement and biological interpretation (ALVES et al., 2025; ALVES et al., 2026).

Reproducibility is not merely a methodological virtue, it is a prerequisite for practical application. Farmers and seed companies will only adopt irradiation-based technologies if their effects are consistent and predictable. Standardized data models provide the foundation for this reliability.

Integration into Sustainable Agricultural Systems

Radiation technology aligns with many of the objectives of sustainable agriculture. It reduces chemical inputs, extends food shelf life and enhances genetic diversity without transgenic modification. When applied responsibly, it leaves no residues and consumes minimal energy. Yet the sustainable implementation of radiation requires coordination among physical facilities, agronomic institutions and regulatory frameworks.

In seed technology, low-dose irradiation offers a clean alternative to chemical seed treatments. Instead of fungicides or growth regulators, a short exposure to gamma rays can achieve similar effects in terms of vigor and germination speed. In post-harvest management, irradiation reduces food waste (a critical aspect of sustainability) by preventing spoilage and extending shelf life. The FAO and IAEA continue to support the establishment of irradiation facilities in developing countries, recognizing their potential to strengthen food security and reduce post-harvest losses (FAO/IAEA, 2018).

Sustainability also involves knowledge sustainability: the ability to preserve and transmit scientific information across generations. Ontological frameworks contribute to this dimension by making radiation data findable, accessible, interoperable and reusable (the FAIR principles). A radiation experiment conducted today, if properly annotated, could remain interpretable decades later, regardless of personnel changes or software evolution. This continuity ensures that the cumulative investment in nuclear agricultural research continues to yield benefits.

Interdisciplinary Synergy: Physics, Biology and Computer Science

Radiation agronomy exemplifies the interdisciplinary nature of modern agricultural research. It brings together the precision of physics, the complexity of biology and the interpretive power of data science. Each discipline contributes essential insights: physics provides the quantitative framework for energy deposition, biology reveals the pathways of stress and adaptation, informatics integrates both into predictive systems.

The success of this interdisciplinary approach depends on mutual literacy among disciplines. Physicists must understand the biological relevance of dose, while agronomists must appreciate the constraints of dosimetry and safety. Data scientists, in turn, must

translate biological complexity into structured models without oversimplification. Training programs and collaborative projects are therefore vital. Universities and international agencies could develop multidisciplinary curricula that combine nuclear science, plant physiology and information management, preparing a new generation of “digital nuclear agronomists.”

Public Perception, Safety, and Communication

Despite decades of safe use, public perception of radiation in agriculture remains ambivalent. Misunderstanding arises mainly from the conflation of irradiation (by energy exposure) with radioactivity (by nuclear contamination). Educational outreach must therefore emphasize that irradiated seeds or foods do not become radioactive; they merely absorb a controlled amount of energy that modifies biological processes without leaving residual radioisotopes (VOSE, 1980).

Public communication should highlight the comparative safety and environmental benefits of irradiation relative to chemical or thermal alternatives. In phytosanitary control, for instance, irradiation replaces fumigants that deplete the ozone layer. In food preservation, it avoids chemical preservatives that may pose health concerns. Moreover, unlike genetic modification, mutation breeding via irradiation relies on natural repair mechanisms and does not introduce foreign DNA. Transparency in labeling and certification, supported by international standards, can further enhance consumer confidence.

Digital technologies can assist in communication by providing accessible, ontology-based information outlets. Farmers and consumers could query these systems for explanations of terms like “gamma treatment,” “low dose,” or “hormetic effect,” receiving scientifically validated but non-technical descriptions. In this way, digital infrastructure not only serves researchers but also becomes a tool for science education and public trust.

Economic and Institutional Dimensions

The economic viability of radiation applications depends on cost efficiency, infrastructure and institutional support. Establishing and maintaining irradiation facilities requires significant investment, but the long-term returns can be substantial when facilities are shared across multiple sectors (agriculture, food industry and medical sterilization). Regional centers of excellence, coordinated by agencies like the IAEA, can provide services to surrounding countries, optimizing utilization and reducing costs.

At the institutional level, the integration of nuclear and digital agriculture demands coherent governance. Regulations must ensure safety without creating unnecessary barriers

to innovation. Harmonized licensing procedures, common dosimetry standards and mutual recognition of certifications would facilitate international trade of irradiated seeds and products. Moreover, policies encouraging open data and ontology-based reporting can enhance transparency and collaboration. Through the Atoms4Food initiative, the FAO and IAEA are exploring digital and irradiation-based approaches for sustainable agrifood systems (IAEA, 2023).

Scientific Frontiers: Low-Dose Mechanisms and Systems Biology

From a scientific perspective, the frontier lies in elucidating the mechanisms of low-dose effects. While the biphasic dose–response pattern is well established empirically, its molecular underpinnings remain incompletely understood. Advances in systems biology, particularly omics technologies, provide new opportunities to explore these mechanisms at multiple levels.

Integrating omics data with radiation parameters could reveal how specific pathways respond to low-dose exposure. For example, transcriptomic analysis might identify genes involved in oxidative stress response, DNA repair or hormone signaling that are transiently upregulated after irradiation. Metabolomics could detect shifts in primary metabolites indicating enhanced energy metabolism. When mapped within an ontological framework, these molecular responses can be linked to macroscopic traits such as germination speed or biomass accumulation, completing the chain from physics to phenotype.

Regional Opportunities and Global Cooperation

Developing countries stand to gain disproportionately from advances in radiation agronomy. Many already possess basic irradiation infrastructure for medical or industrial use, which can be adapted for agricultural applications. Low-dose seed priming could help overcome germination challenges in arid or saline environments, while mutation breeding could generate locally adapted varieties without the high cost of genetic engineering. Furthermore, food irradiation can reduce post-harvest losses in tropical climates, contributing directly to food security.

Global cooperation, facilitated by FAO/IAEA programs, plays a pivotal role. Shared ontological frameworks and open data platforms ensure that results from one country inform practices in another. A study on hormesis in tobacco conducted in Brazil, for example, can be compared with data on groundnut or maize from Africa or Asia, using standardized descriptors. Such interoperability fosters equitable scientific participation, ensuring that innovations are not confined to a few technologically advanced nations.

3 VISION FOR THE NEXT DECADES

Looking ahead, the integration of nuclear and digital technologies promises to change the landscape of agricultural research. The coming decades are likely to witness the emergence of three interrelated trends:

1. Predictive Radiation Agronomy.

Combining empirical data with ontological modeling and machine learning will allow the prediction of radiation outcomes under specific environmental and biological conditions. Researchers will be able to input parameters such as dose, moisture and seed variety and obtain probabilistic forecasts of germination, growth, or mutation frequency. Such predictive tools will save resources, reduce experimental redundancy and enhance precision.

2. Autonomous Irradiation Systems.

Automation and robotics could enable fully controlled seed treatment facilities where dosimetry, exposure and post-irradiation handling are regulated by digital feedback loops. Sensors measuring temperature, humidity and seed moisture would adjust irradiation parameters in real time, maintaining optimal conditions for desired effects. Data from each batch would be automatically uploaded to a centralized ontology-based database, ensuring traceability.

3. Integrated Decision Support Platforms.

Digital agriculture platforms that currently manage irrigation, fertilization and pest control will eventually incorporate radiation modules. These modules will advise on whether irradiation should be applied, at what dose and in which growth stage. The recommendations will draw upon accumulated ontological data, environmental monitoring and predictive models. Farmers could access such systems via mobile applications, bringing the benefits of nuclear science directly to the field.

Concluding Remarks

The history of ionizing radiation in agriculture is a story of transformation: from experimental curiosity to established practice, from empirical observation to predictive modeling, from isolated results to interoperable knowledge. Each phase built upon the previous one, expanding not only technical capacity but also conceptual depth.

Today, as agriculture faces unprecedented challenges (pollution, soil degradation and food insecurity in times of abundance) the insights of radiation agronomy acquire renewed significance. The same physical principles that once yielded mutant varieties and preserved foods can now contribute to precision farming, stress tolerance and data-driven sustainability.

By merging the rigor of nuclear physics with the adaptability of biological systems and the connectivity of digital technologies, the field offers a model for scientific integration.

In practical terms, this integration demands three commitments. First, to maintain experimental excellence. Second, to ensure data interoperability through standardized ontologies and open repositories. Third, to communicate transparently with the public, reaffirming the safety and benefits of nuclear techniques. These commitments will ensure that radiation remains a trusted and innovative component of agricultural science.

Ultimately, the future of radiation agronomy will depend not on isolated breakthroughs but on cumulative, collaborative progress. Each experiment, each dataset and each ontology contributes to a global mosaic of knowledge. The synergy of physics, biology, agronomy and digital intelligence could illuminate the pathways of plant life with unprecedented clarity.

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