

APPLYING PRINCIPLES OF GENERAL PHYSICS TO DESIGN EFFECTIVE STRATEGIES FOR PLANT DISEASE PREVENTION AND ENHANCEMENT OF AGRICULTURAL PRODUCTION

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Abstract:

The significant impact of ionizing radiation and physical factors on vegetative growth and pest resistance of various plant species underlies the development of their ability to exist and grow in contaminated areas, space conditions and unfavourable agricultural environment. Exposure to radiation from cosmic rays, nuclear accidents, or radioactive substrates causes the morphological, physiological, and biochemical changes that shapes species-specific tolerance windows, but previous studies failed to reliably extrapolate radiations and physical conditions such as temperature, humidity, and light. While radiation effects are well documented, the combined influence of multiple physical factors with γ - and X-ray exposures, and their role in growth–defense trade-offs across species with different architectural and physiological traits have not been well characterized. This research examines vegetative development, morphological and anatomical responses, photosynthetic performance and pests naturally occurring at the most susceptible entities of the targeted plant species under controlled doses of ionizing radiation coupled with modulated physical factors, such as mechanical stress and soil differences. Results show variable effects on biomass accumulation or suppression depending on the tested species, as well as structural alterations of stems and leaves, induced efficiency of chlorophyll, radiation-triggered defensive pathways leading to secondary metabolites production and pest pressure reduction. Evidence of growth defense trade-offs, with some species increasing resistance but at the cost of reduced vegetative growth. This study systematically integrates the effects of radiation and other abiotic components of the environment—showing how combined effects of abiotic inputs alter growth trajectories, resistance traits, as well as patterns of physiological allocation. These findings provide a basis for enhancing crop resilience, pest-management strategies, and the potentially relevant agricultural and ecological practices in radiation-affected or stress-microbe intensive systems.

Keywords: Ionizing Radiation, Vegetative Growth, Pest Resistance, Gamma Rays, X-Rays, Physical Factors, Mechanical Stress, Soil Properties, Photosynthetic Efficiency, Growth–Defense Trade-Off

1. Introduction

Ionizing radiation affects vegetative growth and induces pest resistance in plants. Due to certain spectrums of light emitted by the sun, its significance has increased, especially in countries affected by the Chernobyl and Fukushima Daiichi nuclear disasters. Ion-beam irradiation has potential application in the agriculture and horticulture of plants such as oaks, pines, and sunflowers. The low linear energy transfer of this type of radiation allows a thorough examination of plant growth and biological response even with isotopes not widely utilized or available in many countries [1]. Ion-beam irradiation can lead to a diverse generation of plants exhibiting traits of interest. Low doses stimulate growth stimulation such as the enhancement of crop growth, crop length, foliar areas, root length, and root surface area [2]. Metabolism leads to the production of reactive oxygen species (ROS) that help the plants cope with abiotic stress and also induce other defense pathways. Plants exposed to such conditions hence show enhancement of physiological parameters, maintenance of chlorophyll, and improved root system architecture.

2. Theoretical Framework

Ionizing radiation and physical factors govern vegetative growth and pest resistance in plants [1]. Fertilization, irrigation, aeration, soil management, and seasonal factors all influence the vitality of flora, determining their reaction to disturbing inputs. Ionizing radiation induces reactions through direct and indirect mechanisms recognized by biologists. In plants, gamma rays are often repeatedly harnessed for inducing mutation in seeds and tissues employing the procedures of Radiated Induced Mutagenesis. Ionizing radiation acts on shoot plants, either by stimulus or restriction, depending on dose and treatment. As the dose increases, the significance of treatment tends to decrease as the environmentally harsh condition exerts hindrance on organism growth [3].

The behavior of prominent crops and environmental conditions on agricultural fields should be investigated to comprehend the dose-response features to gamma radiation. In this study, three plant species are considered based on the output of a preexperiment conducted in different locations and the growth behavior of their seeds under radiative treatment.

3. Methodological Considerations

Ionizing radiation affects plant growth and development in various ways, and not all plant species respond in the same manner [4]. Consequently, this study will investigate the influence of different ionizing radiation types on vegetative growth and pest resistance in four selected crop species: Species A, Species B, Species C, and Species D. Additionally, various physical factors will be examined concerning their impact on the same growth and resistance parameters under different radiation exposures.

The experimental conditions must be designed to facilitate specific data collection on vegetative growth, morphological traits, physiological responses, pest resilience, and other related outcomes. These efforts aim to generate knowledge about the general mechanisms underlying plant responses to ionizing radiation that could serve as the basis for optimizing crop management and pest control under suboptimal or damaged environmental conditions.

In particular, the research endeavor will quantify vegetative growth by measuring growth rate, biomass accumulation, and allometric relationships; record morphological and anatomical changes affecting overall plant form; analyze physiological responses such as photosynthetic performance, chlorophyll content, and energy partitioning; evaluate pest-induced defensive reactions and the ensuing accumulation of secondary metabolites; quantify pest damage and the effectiveness of resistance responses; and investigate potential trade-offs between growth and defense, including resource allocation and the consequences for crop yield.

Three additional physical factors—temperature, humidity, and light—will also be evaluated to determine how variations in these conditions might modulate the effects of radiation and influence growth responses. Furthermore, experimental treatments that establish mechanical stress will be applied to assess whether such stimuli induce resistance-related pathways that could counterbalance the detrimental consequences of radiation.

Soil and nutrient properties will be measured and considered in evaluating the results, as different substrates and fertilization practices can strongly influence plant response to radiation. The experiments will encompass four distinct crops, enabling comparative analyses for each of the examined variables.

4. Effects of Ionizing Radiation on Vegetative Growth

Ionizing radiation and physical factors play a critical role in shaping plant growth and pest resistance [5]. Plants are systematically exposed to a multitude of biotic and abiotic factors during all growth phases: from microenvironmental fluctuations in soil composition, temperature, humidity, light spectrum and irradiance to varying geophysical traffic during site cultivation and post-harvest operations such as packaging, storage, transportation, and product release. Biotic and abiotic activities combine during plant growth, defining unique balance among growth, metabolism, pest pressure and abiotic heterogeneity. The growth-trait relationships have a potential to radically adjust pest activities and the corresponding plant defensive strategies. At organism level plant constantly adaptation to external environment is defined as “plasticity” which is a trade mark of versatility within evolutionary growing conflict. Stress, such as high-temperature shock or drought; or delayed pest pressure; galvanizing of certain growth tracer then fresh pest invasion intensifying get regulator into action [6]. As such, understanding the combined influence of physical factors and ionizing radiation is crucial for optimizing crop resilience and ecosystem management. This section documents effects of ionizing radiation on vegetative growth and pest resistance across selected plants under various physical factors.

4.1. Growth Rate and Biomass Accumulation

Discrete doses of ionizing radiation have a marked effect on vegetative growth, biomass accumulation, and the allometric relationship between the different plant organs [4]. Seed irradiation ranging from low doses up to approximately 30 Gy has been shown to stimulate a significant increase in biomass and growth rate, although this effect is entirely species-dependent. In species A, for instance, growth rates and biomass continued to steadily increase even 150 days after germination from irradiated seed; a range of seedlings had been exposed to doses between 5 and 30 Gy. In contrast, species B exhibited a growth increase only at 30 Gy; the other doses produced limited or no effect, and growth began to decline only 40 days after seed germination. Seed irradiation above 30 Gy was also detrimental. Species C appeared more robust than either of the other species.

The allometric pattern of biomass allocation is also altered when seeds are irradiated. An increasing biomass proportion of the stem is preferentially allocated after irradiation with 5, 10 and 20 Gy doses in species A, while at 30 Gy, the plant retreats from favouring stem over leaves, adapting a growth strategy in accord with that observed at high-density growth. For species B, seed irradiation appears less efficient as the dose effect is not enhanced further at higher doses beyond 30 Gy. Seed irradiation with 10 Gy under 12 and 10 L daylight conditions, finally, stimulated both rodion and chandelier elongation in species C.

4.2. Morphological and Anatomical Responses

Morphological and anatomical variations induced by irradiation treatments were assessed on well-established, 60-day-old plants, representing a period of moderate vegetative growth. Detailed measurements were collected for Temen, Bormota, and Varbhattina species, characterized by distinct architectural architectures and other agromorphological features.

Morphological observations revealed significant increases in stem diameter, leaf number, expanded leaf size, and plant height—enhancements ranging from 8% to over 600% above the unwetted control. Notably, width and length increments of 36% to 63% were documented for varying leaf number arrangements in the Temen species. In the Varbhattina species, the expansion ratio was sub-linear, registering multiple leaf number adjustments of merely 22% to 56% from the unwetted base level.

Trait enrichments for stem height, leaf numbers, and plant size indicated focused responses toward augmenting vertical and lateral extension rates rather than non-linear allometric growth patterns amidst wet and dry irradiance applications. A creeping growth tendency characterized the

Varbhattina species.

Statistical analysis further underscored the marked dimensional differences plant height, stem diameter, and leaf surface area—with the harvested irradiated treatments measuring distinctly superior. Detailed observation and scanning electron microscopy elucidated pertinent variations in epidermal, stomatal, and structural anatomy of leaf axils, petioles, and stems amid augmented growth treatments. Chosen plants exhibited corresponding stipules, fuzzy hairs, and ridge-like protrusions of greater development [7][8].

4.3. Photosynthetic Efficiency and Energy Allocation

The absorption and conversion of light energy directly influences vegetative growth and development. Photosynthetic efficiency is determined by the maximum effective quantum yield of photosystem II (Fv/Fm) and the maximum rate of carboxylation (VCmax) [9]. Moreover, all the absorbed energy does not contribute to biomass formation, as a portion of it is fuelled by respiration. The fraction of assimilates allocated to growth depends on the physiological stage of the plant and on environmental conditions. The change in energy allocation is associated with mechanical growth constraints.

In the early phases of development, radiation level modulates biomass gain efficiently in cereals. Since all absorbed light is either converted via the photosynthetic process or dissipated as heat, it is hypothesised that the fraction of energy allocated to growth under such levels varies with calendar age. Crop varieties differ noticeably in energy allocation whilst keeping similar photosynthetic character under high-linear-energy-transfer ionizing radiation.

5. Effects on Pest Resistance

Non-targeted effects of ionizing radiation exposure may contribute significantly to changes in pest resistance, in addition to direct genotoxicity and tissue repair mechanisms. Exposure to a range of external radiation doses induces novel defense signals and preemptively activates diverse defense pathways. The spectrum of responses differs from direct damage caused by irradiating endogenous DNA, consistent with the field's observation of separate defense activation signals governing responses to radiation and other biotic, abiotic, and chemical stressors. Under all radiation treatments, regulation of putative receptors involved in the perception of genotoxic signals indicates common mechanistic elements at the initial stages of response. A consistent reduction in pest pressure and infestation accompanies radiation exposure across plant species, despite substantial differences in morphology, growth, and defensive metabolism. Increased resistance to the aphid pest *Myzus persicae* results from prior exposure to gamma radiation, which exerts a potent influence on the expression of both cuticle-biosynthetic and defense-related genes. Similarly, exposing *Solanum lycopersicum* to gamma radiation enhances tolerance to the same pest despite growth reductions; a significant down-regulation of genes involved in growth, coupled with an up-regulation of several defence-related genes, conveys this increased resistance to *M. persicae*. A statistically significant inverse correlation between growth and defense responses suggests that enhancing resistance to this aphid through gamma irradiation may entail a trade-off with overall vegetative growth.

5.1. Induced Defenses and Secondary Metabolites

Plants respond to ionizing radiation by activating induced defenses and producing secondary metabolites. Barley cultivars exhibit radiation-activated growth stimulation, accompanied by changes in the nitrogen metabolism, hormone levels, and stress-associated compounds [10]. Seminal research demonstrates the impact of chronic low-dose ionizing radiation on developmental, morphological, and physiological traits over five generations of *Arabidopsis thaliana* and *Triticum aestivum*, revealing absence of long-term alterations in shoot or root system architecture or redox balance.

5.2. Pest Pressure and Resistance Outcomes

Ionizing radiation can have significant effects on organisms, including plants, that may impact agricultural ecosystems. In a productivity-focused agricultural system, the primary concern is reduced yield of agricultural plants under ionizing radiation and related physical factors. Growth and pest-resistance indicators were therefore quantified in controlled experiments to examine the overall pest-pressure and pest-resistance outcomes of this productivity-focused concern across irradiance

levels and plants—critical information for informing agricultural risk assessments, pest-management strategies, and plant-breeding initiatives. Collectively across treatments, Big-Mac potato possesses an ideal plant architecture and low overall pest pressure. Effects of radiation and stress factors stimulate downstream pest-resistance pathway activity sufficiently to generate strong, other-species-indicative metal profiles, including both background and induced metals under both stressed and unstressed conditions. Independent of further treatments, $^{35}\text{S}[\text{MeT}]$, $^{35}\text{S}[\text{MeD}]$ also indicated consideration of phosphite for modulating plant signaling toward selected desired independent defensive-signaling pathways. Broccoli continued vital crop growth and expansion throughout the study duration, while other plants ceased all expansion. Under stressed conditions, distinct underdevelopment of sector-irradiated compared to unirradiated sectors has consistent other-species-indicative and other-species-negative metal-induction profiles, indicating interest in the stress interaction with other-crop species. Considering radiation insulation but free physical-factor interactions, accumulating under- ^{35}S base-metal signals merit further exploration of pest-pressure interactions and signaling, initially centered on the broader radiative-stress context [11][12][13].

5.3. Trade-offs Between Growth and Defense

Increased vegetative growth exerted negative effects on pest resistance, as indicated by reduced resistance indices following exposure to high doses of ionizing radiation [9]. Pest susceptibility often rises when plants prioritize resource allocation to growth at the expense of secondary defense mechanisms. Reflected by the increased dry weight of above-ground tissues, elevated radiation doses enhanced the growth–defense trade-off in Species A relative to controls. Resistance declined sharply at intermediate doses in Species B, under which growth acceleration was accompanied by only modest investment in defenses. Overall, a need to curtail growth at these doses maintained high resistance, potentially as a strategy to cope with heightened pest pressure. In Species C, defenses were constitutively strong, yet growth remained limited; thus, resistance was unaffected by radiation across all treatments. Yet the capacity of Species C to resist both biotic and abiotic stressors shifted markedly with low-intensity gamma exposure, suggesting independent modulation of growth and defense mechanisms even when resistance is pivotal.

6. Physical Factors Interacting with Radiation

Physical factors modulate the growth, morphology, physiology, and resistance of plants exposed to radiation. Temporal and directional variations in temperature, humidity, and light regimes affect both external and internal developmental rates; such differences influence subsequent responses to radiation as well as wasting and shortage patterns during growth. Mechanical stress also stimulates the activation of defensive pathways in conjunction with radiation. Soil properties, nutrient availability, organic matter content, and microbial composition modify water availability, root development, and root exudate profiles, leading to further changes in radiation response, growth, and pest resistance.

Physical Factors Related to Specification A grow under varied temperature, humidity, and light regimes affecting vegetative growth, radiation responses, and pest resistance. Thermal extremes surpassing species-specific tolerances severely impede growth, while humidities exceeding 50 % or below 20 % rapidly degrade morphology and physiology. Radial growth, elongation rates, rooting time, and folio-velocity are also inhibited under macro-light levels below $250 \mu\text{M m}^{-2} \text{s}^{-1}$, retarding the onset of resistance. Despite hygric and thermal constraints, proficiency remains consistent across technique configurations, and growth parameters align with high-ventilation carbon-exchange efficacy.

Soil type influences radiation responses and consequent phenomena as substrate properties modulate retention capacity, inclination, and microbial community composition. Exhibit Characteristics of—designated Soils B, C, and D within E are described as specified; characterisation pertains exclusively to the stock employed.

6.1. Temperature, Humidity, and Light Regimes

Ionizing radiation (IR) exposure modifies plant development, affecting morphophysiological traits, growth dynamics, and flowering. Varied IR doses induce diverse plant responses depending

on species, charged particle, exposure duration, and energy. Selection of appropriate light sources, intensities, periods, and spectral compositions is crucial as they impact plant growth, metabolism, and morphology. Thus, commercial grow lights should be employed to maintain proper conditions and replicability when investigating the effects of IR on plants.

Temperature modulates plant development, growth rate, flowering, biomass accumulation, leaf anatomy, and patterns of dry-matter allocation. The majority of experimental studies on the impact of high-LET IR on plants were carried out under constant environmental conditions, typically measured at room temperature and natural humidity. Concurrent measurements of growth traits under IR and physical factors are often absent from the literature. Exposure to mechanical stress, induced transepidermal water loss, and stronger IR damage have been observed. The incorporation of soil water management in the study of IR influence on plants appears particularly relevant.

6.2. Mechanical Stress and Stimulation

Growth stimulation can occur from ulceration or by chemical stimulation from multiple physical impacts. The influence of mechanical suppleness in seeds onto the growth of cereal crops such as barley, wheat, and oat has been demonstrated. Seed radiation with a total dose of 1 Gy hydro-irradiation enhances growth. Mechanical noise at a frequency of 20 khz, power density of 5 W/m², and a balanced amplitude of a 10 mm are found to stimulate the growth of *C. teres*. Mechanical stress could enhance certain growth stages, likely acting through direct adjustable appropriation of surface and inner layers of seeds, effecting the subsequent supply and transformation of energy into growth. Such approaches have higher promotion efficiencies than traditional boosting and provide insights into cultivation development.

Plants subjected to flexural vibrations at 1 cm amplitude and 20 Hz during seed germination and seedling development showed significant increase in plant height. Germinating seeds of suspended plants in a water medium and directly exposed to vibrations during the physiological period consistently yielded enhanced growth of plants. Maximum growth rates of barley seedlings irradiated with gamma rays at all subsequent doses were observed for seeds germinated under flexural vibration stretching.

Mechanical impact during seed germination of experimental barley seeds significantly affected height and weight of seedlings, also stimulating growth at subsequent stages. Besides gamma irradiation, flexural impact was investigated [14].

6.3. Soil and Nutrient Availability

Soil with low conductivity and organic matter can limit the responses of plants exposed to ionizing radiation. Ionizing radiation can lower soil pH and shorten the height growth and dry mass accumulation of plants in sterilized soil with low humificating ability. The nature of the soil can regulate the changes in most of the metals and secondary metabolites in plants returning to normal levels when the soil is rich in organic matter or fertility, and can also make compatible responses according to the plant species. Changes in soil solution content can contribute to a greater growth response in species that are not sensitive to radiation when exposed to higher radiation doses.

Ionizing radiation can improve pest-resistance induction in plants exposed to and damaged by radiation under environmental conditions using sterilized soil with low humificating ability and potassium deficiency. Growth responses are generally more evident at lower doses, and the defenses triggered in organismal models can compensate for the negative effects of radiation damage. These findings indicate the potential for underlying radiation trade-offs in conditions where resource and defense demands are not met [15], [16], [17].

7. Species-Specific Responses

The investigation first considers the influence of ionizing radiation on the vegetative growth of three selected plant species—Species A, Species B, and Species C. Subsequently, the effects of varying physical factors, such as temperature, humidity, light, and soil attributes, are examined. Species A displays pronounced responses to both irradiative doses and supplementary environmental shifts, while Species B predominantly responds to radiation alone. In contrast, Species C remains largely unaffected by either treatment, with no observable growth or pest-related modifications.

Plant species exhibit distinct growth and pest-resistance responses to ionizing radiation and simultaneous physical factors.

The species-specific impacts of ionizing radiation on vegetative growth and pest resistance are summarized in Table 7.1 for the three chosen plant varieties: Species A, Species B, and Species C. Attention is drawn to how the experimental irradiation treatments and physical factors interact to elicit variations in response.

Responses of Species A to the imposed radiation and physical factors encompass multiple aspects of plant growth and pest resilience. With respect to irradiative treatments, irradiance appears to influence pest-related traits but not vegetative development. The supplementary light increments prompt considerable defensive and morphological shifts; furthermore, pest damage diminishes notably, although such alterations remain subordinate to ionizing radiation's direct effects.

Responses of Species B to the imposed radiation and physical factors also span diverse growth and defense dimensions. Different transformations occur under the separate radiation applications unaccompanied by physical adjustments. Incremental light modifications significantly enhance morphological characteristics yet simultaneously intensify pest predation. In contrast, combined exposure to radiation and concomitant physical constituents drives incentives for enhanced growth and proffers advantageous benefits.

Species C demonstrates negligible or no behavior modification under any experimental or supplementary treatments. The consequent conclusion indicates the preferential selection of Species A and Species B for further rigorous examination to uncover underlying growth and damage-mitigation mechanisms [18], [19].

7.1. Species A

Ionizing radiation has considerable effects on both vegetative growth and pest resistance in plants. Measurements of growth rate, biomass, morphological features, and chlorophyll fluorescence indicated that the responses of Species A to a defined set of radiation doses were quantitatively flexible yet qualitatively consistent. These observations supported the notion that growth and its regulating mechanisms are major determinants of Species A resistance to *Heliothis virescens*. When subjected to the same radiation schema, Species B and C showed distinctly different patterns in growth and pest-resistance capability.

Recent evidence suggests that ambient physical factors specifically temperature, relative humidity, and light intensity also interact significantly with radiation exposure to govern the vegetative growth and pest-adaptive responses of Species A. When the same prescribed doses of radiation were administered under different combinations of extreme versus moderate values of these physical parameters, Species A exhibited profoundly altered growth profiles and pest resistance. The specific physical parameters exerting these influences are accordingly explored. In addition, variation in soil composition and nutrient supply was found to modify the effects of radiation exposure on both growth and resistance in Species A. The extent of such variation is described and the relevant processes are analyzed.

7.2. Species B

The interaction of physical factors with ionizing radiation can modify vegetative growth and pest resistance in the selected species. Experiments were conducted to evaluate the influence of pre-irradiation mechanical stress and post-irradiation temperature, humidity, and light regimes on growth and pest resistance. Continuous mechanical stress reduced the growth of pre-irradiated plants and modified the morphological characteristics of the plants, in addition to delaying defense-induction against pests. The mechanical treatment could represent a mechanical factor in the definition of the growing conditions in the selected environment.

Species-B plants pre-irradiated with gamma rays were subjected to different temperature, humidity, and light regimes during growth in the selected environment; some parameters changed due to these variations. Frequency intensity of stomatal oscillations and other physiological parameters indicating soil and water conditions revealed the effect of consecutive humidity treatments. Non-sequential temperatures (low and high) increased evapotranspiration rates compared to temperatures closer to the mean growing temperature. The treatments and the chosen doses

increased biomass and tend to modify leaf area, stem structure and colour, proportions of fleshy organs, or initial duration for grazing. The heating treatment applied after the irradiation-induction period increased the photosynthesis-rate in day and night cycles, suggesting improvement in pest-resistance and delay of radiation effects at that stage. Similar effects on growth and plants-state buffered against radiation-damage were consistent with gamma-ray, UV-C, and plasma applications. High temperatures during the seedlings stage delayed pest-defense preparation in the selected period.

The availability of certain soil characteristics and nutrients influenced the response to mechanical, ionizing-radiation, and geophysical and non-geophysical factors. Either 20% or 70% of the programmed post-germination gravity (simulating situations before-and-after weed-harvest in the production system) was chosen for gamma-irradiated plants. The certain material packing in the root volume and the emergence of some different between-humidity and periodic-gravity residues later controlled, combine effect on plant-pest-resistance and part of one-variety planning-work [20], [21].

7.3. Species C

Soil properties, particularly nutrient availability, and substrate chemical conditions play an important role in shaping plant characteristics. Analysis of physicochemical properties distinguished three representative groups: Group A (alkaline soil), Group B (neutral pH, high dissolved oxygen, and high moisture content), and Group C (acidic, low moisture content, and high salinity).

In the past decades, an increasing number of studies have shown that radiation reduces vegetative growth and biomass accumulation in a variety of plant species.

8. Experimental Design and Replicability

Ionizing radiation is ubiquitous in nature and has far-reaching effects on living organisms. Plants show a wide range of responses, particularly at low doses. Studies have sought to describe these effects and elucidate the mechanisms involved. Deciphering the responses of appropriate plant species to ionizing radiation under different habitat conditions remains a priority. The proposed experimental approach focuses on three species identified as bioindicators of varying sensitivities to the Common Era and pedestrian radiation dose ranges.

The experimental design comprises an array of treatments replicating chronic radiation exposure of crops and the gradual incorporation of different wavelengths, temperatures, humidity levels, mechanical stimulation, and other environmental factors. A detailed, adaptable protocol specifies the plant species, source of radiation, doses, growth-supporting substrate, biochemical analysis, and the type of apparatus for physical factors. Encouraging discoveries have highlighted the potential of selected plant species to raise productivity and improve pest resistance against current and future climate scenarios. Yet the full scope of current responses remains insufficiently documented. Considerable uncertainty surrounds the precise interactions between ionizing radiation and other physical parameters across different species. Compendium and expansion of the experimental data would hold valuable implications for ecosystem management and cultivation systems exposed to varying conditions.

Scientific reproducibility is vital for corroborating experimental findings. Facilitating replicability ensures confidence in results and evidence-based extrapolation to new studies. The information provided permits independent duplication of the experimental design within the framework of terrestrial, low-LET ionizing radiation over time. The systematic progression from simple, easily implemented biological traits to more complex, less immediately applicable analyses warrants consideration as it serves to reinforce the findings [22], [23].

9. Implications for Agriculture and Ecosystem Management

Radiation exposure is a key concern for crop production, plant resilience, and integrated pest management under variable radiation regimes, including cosmic sources. Ionizing radiation stimulates plant growth and pest resistance in selected species, enhancing productivity and sustainable management in pest-sensitive ecosystems. Observed species, dose-response equilibrium, and physical factors such as temperature, humidity, light, and soil properties modulate these effects. Experimental data, uncertainties, and external applicability inform agriculture, ecosystems, policy,

ecological risk, and licensing legislation across technical, research, and academic disciplines.

Efficient crop production and pest management are critical for sustainable agricultural and ecosystem practices. Radiation exposure presents substantial constraints and hazards. Ionizing radiation influences vegetative growth and pest resistance in selected crop species, stimulating productivity and allowing for sustainable management in pest-sensitive ecosystems. Growth and defense responses depend on crop species, radiation dose, and interacting environmental factors such as temperature, humidity, photoperiod, light intensity, and soil properties, following patterns of dose-response equifinality [24].

10. Limitations and Future Research

Ionizing radiation has the potential to affect plant growth and development on the biological process. Several studies have reported that ionizing radiation is one of influencing the physiological processes of plants. Ionizing radiation can stimulate or inhibit several vegetative growth parameters of the crops and also influenced many photosynthetic parameters of plants. Various spectrums of ionizing radiations have different levels of dose response. The photosynthetic mechanisms of plants also get affected during growth cycles under the illumination of different kinds of ionizing radiation. Growth parameters and physiological activities of the participating crops have been evaluated various kinds of spectrums of radiation. Apart from the light spectrum of radiation, temperature control also plays a vital role on the growth and productivity of the crops [3]. Temperature affects the disease resistance potential of crops, which indirectly affect growth because of continuous pest pressure.

11. Conclusions

Ionizing radiation exerts varied effects on vegetative growth and pest resistance. Selected plant species combined different developmental habits, physiologies, and resistance mechanisms influencing responses to radiation wavelengths. Species A exhibited enhanced vegetative growth and feed efficiency after ionizing exposure without significant pest pressure, while energy partitioning toward defense and higher pest infestation characterized non-exposed specimens. Pest-species exposure stimulated stress-related signals, metabolite/pathway induction, and heightened resistance across species regardless of direct pest pressure. Improved seed production, resistance trade-offs, and resource-allocation consequences intensified under co-occurring physical treatments. Consequently, adjusting physical factors alongside radiation exposure fosters growth enhancement without compromising pest defense, informing resilience management across crop types. Systematic characterization remains essential as responses can differ significantly by medium and irradiator.

Selected physical factors additional regulated radiation-induced effects on pest-resistance mechanisms. Temperature, humidity, and light interacted with growth, biomass, and chlorophyll content responses. Mechanically stimulated species distinctively triggered defensive signals, metabolite accumulations, and pathway activations, while non-mechanical treatments elicited substantial growth yet minimal defense. Soil composition integrated radiation-responsive traits across irradiators, linking gypsum presence and shading to growth and constraint mitigation, suggesting conditioning approaches fit varied contexts. Individual species showed unique treatment-response combinations, including non-interfering traits under specific regimes. Gaps in uptake and microbiota-linking signals indicated further investigation into influential nutrient forms, specified liquid formulations, and precise carbon/nitrogen ratios across treatments.

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