



Effects of space radiation on cereal seeds

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Abstract. This mini-review synthesizes current evidence regarding the effects of space radiation on cereal seeds, with emphasis on viability, germination, genetic integrity, and implications for extraterrestrial agriculture. Available data indicate that prolonged exposure to space radiation—particularly under low-shielding conditions—generally reduces seed viability and germination capacity, with marked interspecific variability, rice being more sensitive than barley or wheat. However, responses are heterogeneous, as some cereals exhibit enhanced germination under specific exposure scenarios, highlighting the complex interaction between radiation dose, quality, genotype, and environmental conditions. At the genomic level, space radiation induces DNA damage, chromosomal aberrations, and structural variation, supporting its application in mutation breeding programs. Orbital experiments aboard Mir and the International Space Station demonstrate that cereals can complete their life cycle in microgravity, although reproductive success is constrained by multiple interacting stressors, including atmospheric composition and system engineering limitations. For deep-space agriculture, current evidence remains insufficient, as low-Earth orbit (LEO) conditions do not fully replicate the radiation environment beyond Earth's magnetosphere. Emerging studies suggest that sustainable extraterrestrial crop production will require integrated strategies combining biological adaptation and physical radioprotection. Overall, space radiation represents both a risk factor for seed performance and a potential tool for crop improvement in future space-based agricultural systems.

Keywords: germination, mutation breeding, DNA damage, extraterrestrial agriculture, International Space Station, plant stress biology, radioprotection, crop adaptation.

Introduction. Space radiation alters cereal seed viability, mutational load, and later crop performance, but the direction and magnitude of the effect depend strongly on species, exposure duration, shielding, and the surrounding spaceflight environment (Mohanta et al., 2021; Richards et al., 2025). In cereals, the most direct evidence comes from wheat, barley, rice, and triticale, while mechanistic interpretation still relies partly on broader plant datasets because true deep-space cereal experiments remain sparse (Richards et al., 2025).

The aim of this mini-review is to critically evaluate the current state of knowledge on the effects of space radiation on cereal seeds, focusing on key biological endpoints including viability, germination performance, and genetic stability. Additionally, the study seeks to contextualize these effects within the broader framework of space-based agriculture by examining experimental evidence from orbital platforms and simulation studies. A further objective is to assess the potential of space radiation both as a constraint on crop productivity and as a tool for mutation breeding, while identifying major knowledge gaps that limit extrapolation to deep-space environments such as lunar and Martian systems.

Viability and Germination. The clearest cereal signal is that prolonged exposure matters more than simple flight history. Seeds exposed outside the ISS environment for many months showed substantial viability losses, especially rice, which appears more sensitive than barley under comparable exposure histories (Richards et al., 2025). By contrast, some shorter or more shielded seed-storage studies in non-cereal crops found

delayed germination without loss of final germination, reinforcing that shielding and mission architecture modify risk (Richards et al., 2025).

At the same time, cereal germination outcomes are not uniformly negative. A comparative review of space breeding reports that wheat, barley, and triticale sometimes show significantly higher germination than both ground controls and gamma-irradiated seeds, whereas rice often shows little change and some other crops decline (Mohanta et al., 2021). This heterogeneity indicates that "space radiation effect" is not a single phenotype but a composite outcome of dose, dose rate, radiation quality, seed water status, and genotype (Richards et al., 2025) (Table 1).

Table 1

Strength of evidence on cereal seed germination effects

<i>Evidence strength</i>	<i>Claim</i>
Strong (8/10)	Longer external space exposure reduces cereal germination, with a 13-month exposure associated with a 16% germination decrease in barley and a 48% decrease in rice, and a 20-month rice exposure associated with a 73% decrease (Richards et al., 2025).
Moderate (7/10)	Responses differ by cereal species and genotype: wheat, barley, and triticale showed higher germination than ground controls in one spaceflight dataset, whereas rice and millet showed no difference, and sorghum showed reduced germination potential (Mohanta et al., 2021).
Moderate (6/10)	Seeds that do germinate after exposure do not always show large biomass penalties, as post-flight barley and rice seedlings showed no significant change in growth pattern or biomass despite lower germination success (Richards et al., 2025).

The score was calculated based on the following information: the number of available studies, sample sizes, and the reproducibility of the results.

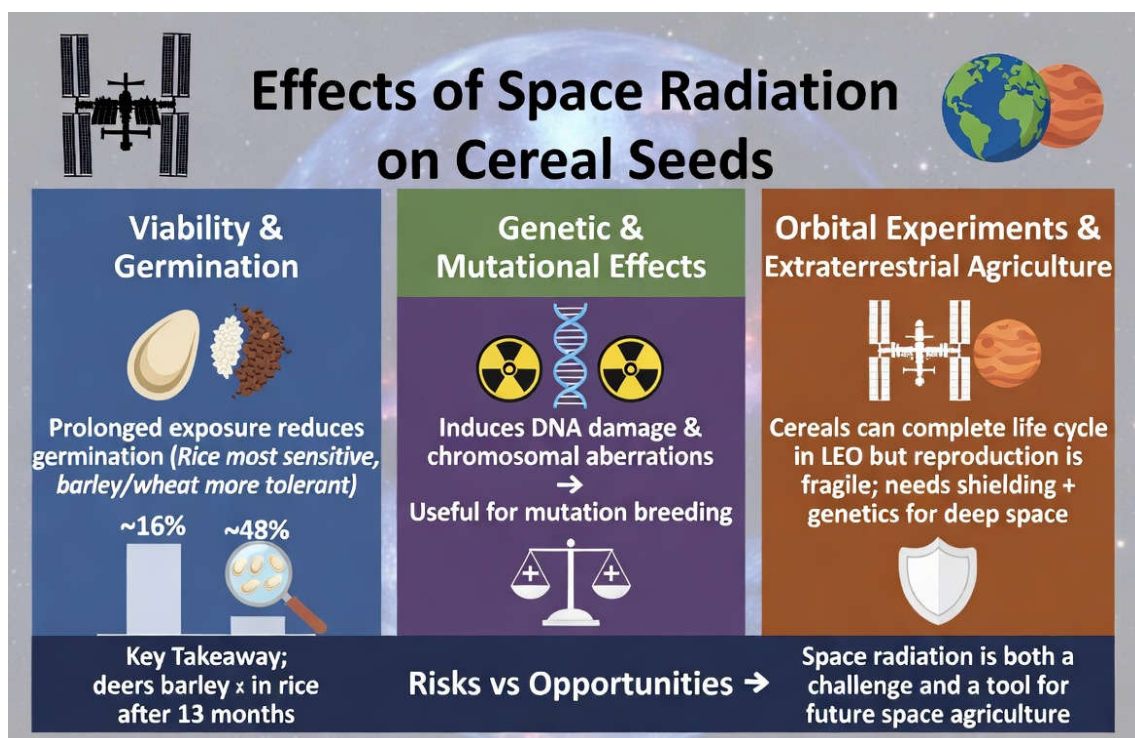


Figure 1. Space radiation impacts on cereal seeds and implications for extraterrestrial farming.

Mutational and Genetic Effects. Space exposure induces DNA damage, chromosomal aberrations, and structural genomic variation, which is the main basis for using spaceflight as a mutation-breeding environment (Mohanta et al., 2021; Califar et al., 2018) (Figure 1). Across plant systems, mitotic activity tends to decline while chromosomal aberrations rise after exposure to space conditions, and these effects have been described as broadly recurrent across species (Mohanta et al., 2021).

The mechanistic literature also shows that radiation quality matters. Simulated galactic cosmic ray exposure caused dose-dependent activation of DNA repair pathways, while heavier ions produced more severe developmental damage than lower-LET exposures in seed and seedling experiments (Dixit et al., 2023; Zhang et al., 2022; Richards et al., 2025). Earlier flight work further showed that radiation damage depends on the biological endpoint measured and on shielding conditions within the spacecraft, which is critical when extrapolating from low-Earth orbit to lunar or Martian agriculture (Kranz, 1986).

For cereals specifically, the breeding interest lies in whether induced variation can be harnessed rather than merely tolerated. Space breeding has already been pursued operationally, with China reporting roughly 200 plant varieties developed through space-radiation-associated breeding programs, and recent reviews place this strategy within the broader continuum of radiation mutation breeding used to expand whole-genome diversity for crop improvement (Mohanta et al., 2021; Ma et al., 2021).

ISS and Orbital Cereal Experiments. ISS and Mir experiments show that cereal seeds can be produced in orbit, but they also show why radiation cannot be interpreted in isolation. Early Mir work on super-dwarf wheat reported strong reductions in vegetative growth and mineral balance, followed by partial reproductive success after return to Earth (Mashinsky et al., 1994). Later ISS work overcame some cultivation barriers and obtained wheat seeds directly under flight conditions, indicating that cereal reproduction in low-Earth orbit is feasible when hardware and cultivar choice are optimized (Baranova et al., 2019).

Those orbital studies also identify confounders that matter as much as radiation for productivity. Excess ethylene in spacecraft plant chambers impaired the generative sphere and fertility in wheat, and limited volume forced reliance on dwarf or super-dwarf ideotypes (Baranova et al., 2019). Accordingly, observed seed or yield changes in flight are best read as outcomes of combined stress exposure involving microgravity, atmosphere management, and radiation rather than as pure radiobiology (Ngwoke et al., 2023; Cui et al., 2023; Safirescu et al., 2024; Zhang et al., 2022; Păpuc, 2023; Richards et al., 2025; Moldovan & Bordea, 2025; Arantes et al., 2025) (Table 2).

Table 2

Orbital evidence on wheat reproduction and seed traits

<i>Study context</i>	<i>Cereal finding</i>	<i>Implication</i>
Mir seed-to-seed wheat	Vegetative indices were 2–2.5-fold lower than controls, and one returned head was sterile, but 28 seeds matured on Earth and most produced normal progeny (Mashinsky et al., 1994)	Wheat can complete a life cycle in principle, but reproduction is fragile.
ISS wheat “seed-to-seed” program	Repeated ISS experiments eventually produced the first wheat seeds in space flight conditions (Baranova et al., 2019)	Stable cereal reproduction in orbit is technically achievable.
ISS wheat kernel morphology	Space-grown wheat grains had altered birsh hair length and kernel-coat cell arrangement, yet these differences did not prevent production of full offspring (Baranova et al., 2019)	Subtle developmental changes can occur without immediate loss of seed function.

<i>Study context</i>	<i>Cereal finding</i>	<i>Implication</i>
Mir/ISS engineering constraints	Dwarf wheat was selected for space systems, and low yields plus ethylene-related reproductive impairment were major constraints (Carillo et al., 2020; Baranova et al., 2019)	Orbital cereal performance depends on the whole habitat, not radiation alone.
ISS farming strategy	Staple cereals are viewed as more suitable for longer lunar or Martian greenhouse systems than for near-term ISS food supply (Carillo et al., 2020)	Cereal deployment is more plausible in planetary agriculture than current station operations.

Extraterrestrial Agriculture. For extraterrestrial agriculture, the central issue is not whether cereal seeds can survive some radiation, but whether they can sustain multigenerational, seed-to-seed productivity under chronic exposure beyond Earth's magnetosphere (Richards et al., 2025). Current evidence supports guarded optimism for low-Earth orbit cultivation, yet it remains insufficient for deep-space prediction because ISS radiation is strongly shaped by shielding and differs substantially from unshielded or planetary-transit radiation fields (Richards et al., 2025).

Recent simulation studies reinforce that chronic radiation interacts with other space factors. Under Mars-relevant chronic low-dose gamma radiation combined with altered gravity, seedlings showed moderate growth reduction and oxidative stress concentrated in roots, while other studies found that low-LET irradiation can sometimes increase antioxidant production without obvious growth penalties (De Francesco et al., 2024; De Francesco et al., 2023). This suggests that future cereal systems may require both biological tolerance traits and physical shielding, rather than relying on inherent seed robustness alone (De Francesco et al., 2024; Kunal et al., 2025).

Protective strategies are beginning to emerge. Melanin-based shielding nearly fully preserved survival in heavily gamma-irradiated seeds in recent experiments, supporting the broader idea that seed storage and propagation modules for lunar or Martian agriculture should be designed as radioprotective infrastructure (Kunal et al., 2025). For crop selection, reviews of ISS farming argue that staple cereals such as dwarf wheat are unlikely to be central to current station menus but remain strong candidates for larger bioregenerative systems on the Moon or Mars, where caloric return and closed-loop life support become more important (Carillo et al., 2020).

Conclusions. The available body of evidence demonstrates that space radiation exerts multifaceted effects on cereal seeds, with outcomes that depend strongly on exposure duration, radiation type, and species-specific sensitivity. While prolonged exposure generally reduces germination and viability, certain conditions may produce neutral or even stimulatory effects, underscoring the non-linear nature of plant responses to ionizing radiation. At the molecular level, radiation-induced genomic alterations provide a mechanistic basis for both deleterious effects and beneficial variation exploitable in breeding programs.

Findings from orbital experiments confirm that cereal crops can reproduce under spaceflight conditions, but also reveal that radiation cannot be considered in isolation, as microgravity, atmospheric factors, and engineering constraints play equally critical roles. Importantly, current low-Earth orbit data are not fully representative of deep-space radiation environments, limiting predictive capacity for long-term extraterrestrial agriculture.

Future progress in this field will depend on integrating biological resilience with technological solutions, particularly advanced shielding strategies and optimized growth systems. Consequently, successful deployment of cereals in extraterrestrial settings will require a systems-level approach that combines plant genetics, space engineering, and radiobiology.

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