GAS Journal of Clinical Medicine and Medical Research (GASJCMMR)

Volume 3 | Issue 8, 2026 Homepage: https://gaspublishers.com/gasjcmmr/ ISSN: 3049-1568

Molecular Adaptation to Radiation and Bioremediation Prospects in Deinococcus radiodurans

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Received: *02.08.2026* | ***Accepted:*** *20.08.2026* | ***Published:*** *24.08.2026*

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DOI: *10.5281/zenodo.22078060*

Abstract **Original Research Article**

The expression “radiation-eating bacteria” is frequently used in popular science to describe microorganisms that survive, interact with, or potentially benefit from high-radiation environments. Scientifically, however, the phrase is imprecise. The best-characterized bacterial example is Deinococcus radiodurans, an exceptionally radioresistant microorganism capable of surviving radiation doses far beyond those tolerated by most bacteria. Its extraordinary phenotype is not explained by consumption of ionizing radiation as a conventional metabolic substrate. Instead, survival arises from a coordinated system involving genome organization, protection of proteins from oxidative damage, manganese-associated antioxidant chemistry, stress-response regulation, and highly efficient DNA repair. Recent work has further identified specialized DNA-break recognition machinery, including DdrC that helps stabilize damaged DNA and facilitate repair. This review examines the distinction between radiation resistance and true radiotrophy, summarizes the cellular and molecular mechanisms that permit D. radiodurans to recover from severe irradiation, and evaluates its potential for environmental biotechnology. Particular attention is given to uranium biosorption and bioprecipitation, where engineered D. radiodurans strains have demonstrated substantial radionuclide-removal capacity. The evidence indicates that the most defensible scientific description is “extremely radiation-resistant bacterium,” while claims that the organism literally feeds on radiation require substantially stronger metabolic evidence. The field nevertheless provides an important platform for understanding stress biology, DNA repair, synthetic biology, and the treatment of radionuclide-contaminated environments.

Keywords: Deinococcus radiodurans; ionizing radiation; radiation resistance; DNA repair; oxidative stress; manganese; DdrC; uranium bioremediation; radionuclides; extremophiles.

Introduction

Ionizing radiation is energetic enough to remove electrons from atoms and molecules, producing direct molecular damage and secondary chemical reactions. In biological systems, water radiolysis and the subsequent formation of reactive oxygen species (ROS) can damage DNA, proteins, lipids, and other cellular components. For many microorganisms, sufficiently intense irradiation causes loss of viability. Deinococcus radiodurans is exceptional because it can remain viable after exposures that fragment its chromosomes extensively, making it one of the principal model organisms for radiation

biology and microbial stress resistance (Cox & Battista, 2005; Slade & Radman, 2011).

The popular phrase "radiation-eating bacteria" creates a conceptual problem. An organism may be highly resistant to radiation without using radiation as a source of metabolic energy. Radiation resistance describes survival; radiotrophy, by contrast, implies that radiation contributes directly to energy conservation or growth. The distinction is essential when interpreting experimental observations. D. radiodurans is strongly established as radioresistant, whereas direct radiation-powered growth is not the central explanation for its physiology.

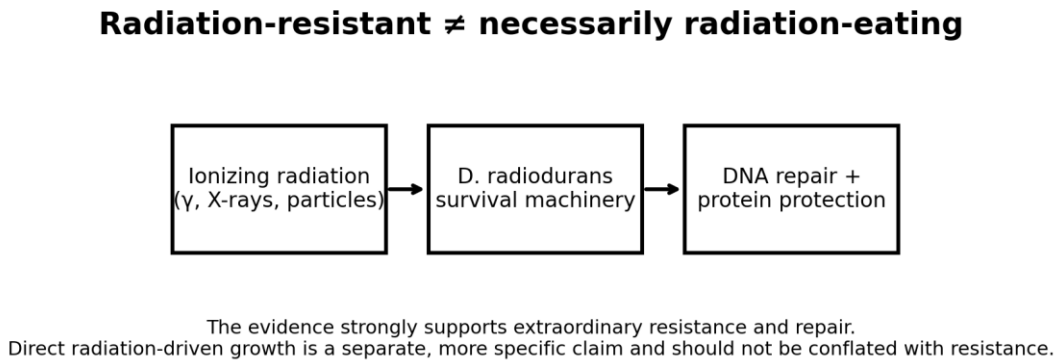

Figure 1. Conceptual distinction between radiation resistance and radiation-driven metabolism.

The scientific importance of D. radiodurans therefore lies less in the idea of a bacterium "eating" radiation and more in its ability to preserve functional proteins, maintain genomic information, and reconstruct extensively damaged chromosomes. Reviews have emphasized that resistance is multifactorial, involving both passive cellular architecture and active enzymatic systems (Cox & Battista, 2005; Daly, 2009).

Aim of the Review

This review synthesizes the established literature on D. radiodurans and related radiation-resistant microorganisms, with four objectives: (1) to define the scientific meaning of radiation-eating or radiotrophic bacteria; (2) to explain the molecular basis of extreme radiation resistance; (3) to summarize recent advances in DNA-break sensing and oxidative-stress protection; and (4) to assess the practical potential of radiation-resistant bacteria for radionuclide bioremediation.

2. Deinococcus radiodurans: Biological Characteristics

D. radiodurans is a non-spore-forming, Gram-positive bacterium belonging to the family Deinococcaceae. It is characterized by a distinctive cellular organization and a capacity to tolerate several environmental stresses, including ionizing radiation, ultraviolet radiation, desiccation, and oxidative insults. Its radiation resistance is not an isolated trait; rather, it reflects a broader stress-tolerance phenotype in which preservation and repair of macromolecules are tightly coordinated.

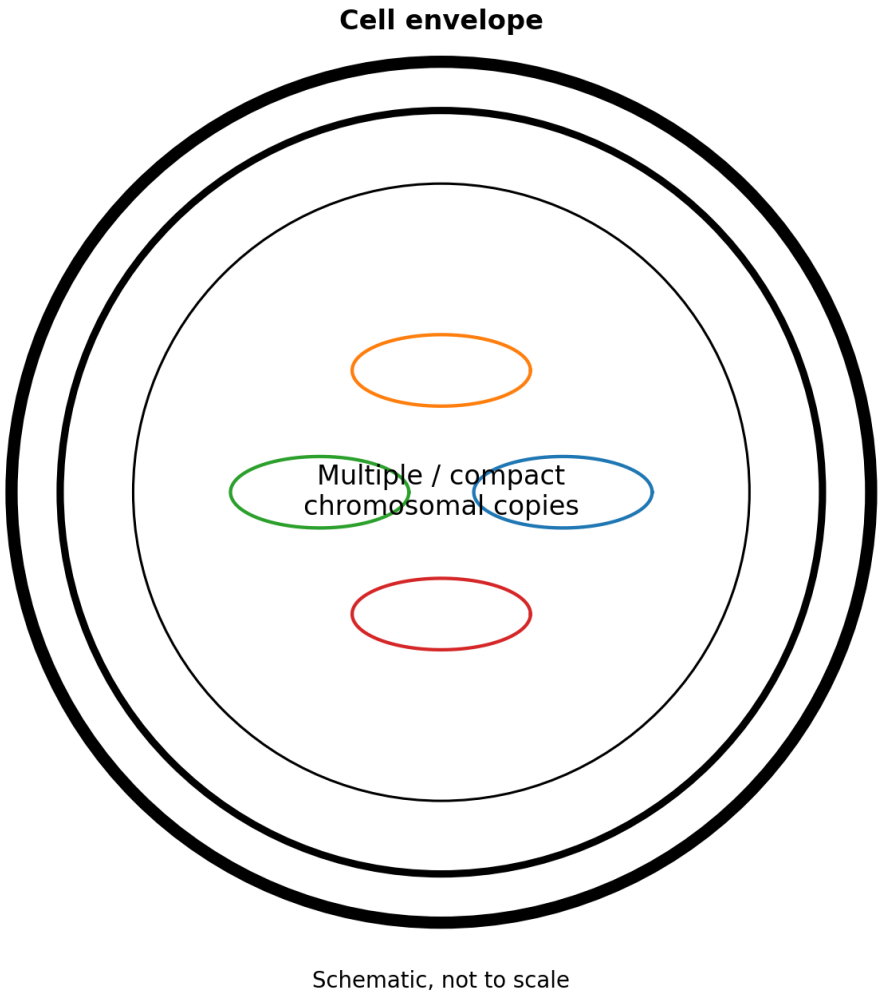

Figure 2. Simplified schematic of the cellular organization of D. radiodurans. The diagram is conceptual and not to scale.

A central feature is the presence of multiple genome copies and a compact nucleoid architecture. These features reduce the probability that irradiation-generated DNA fragments will diffuse away from one another and provide repeated sequence templates for recombinational repair. Classical studies demonstrated that extensive double-strand DNA breakage can occur after irradiation while the organism subsequently reconstructs functional chromosomes (Cox & Battista, 2005).

Importantly, the organism is not immune to radiation damage. Its DNA can be fragmented, and its proteins can be exposed to oxidative chemistry. The remarkable phenotype arises because the damage is tolerated and repaired more effectively than in radiation-sensitive organisms. This distinction is crucial: resistance is a property of the recovery system, not evidence that radiation causes no molecular injury.

Radiation Resistance across Microorganisms

Radiation resistance occurs in several microbial lineages, including multiple Deinococcus species and other extremophilic microorganisms. Comparative genomic work indicates that radiation-resistant Deinococcus species share broad strategies for oxidative-stress defense and DNA repair,

although individual species differ in the exact complement and regulation of resistance-associated proteins (Slade & Radman, 2011; Fuchs et al., 2018).

The ecological distribution of Deinococcus species across soils, water, deserts, and other environments suggests that radiation resistance may have evolved as part of adaptation to oxidative and desiccation stress rather than as a response to nuclear environments alone. This interpretation helps explain why the same molecular systems protect cells from several apparently unrelated stressors.

3. What Ionizing Radiation Does to a Bacterial Cell

Ionizing radiation interacts with biological matter through direct ionization and excitation as well as indirectly through reactive products generated in water. DNA damage includes base modifications, single-strand breaks, and double-strand breaks. Proteins and membrane components may also undergo oxidative modification. The cellular response must therefore address more than DNA alone.

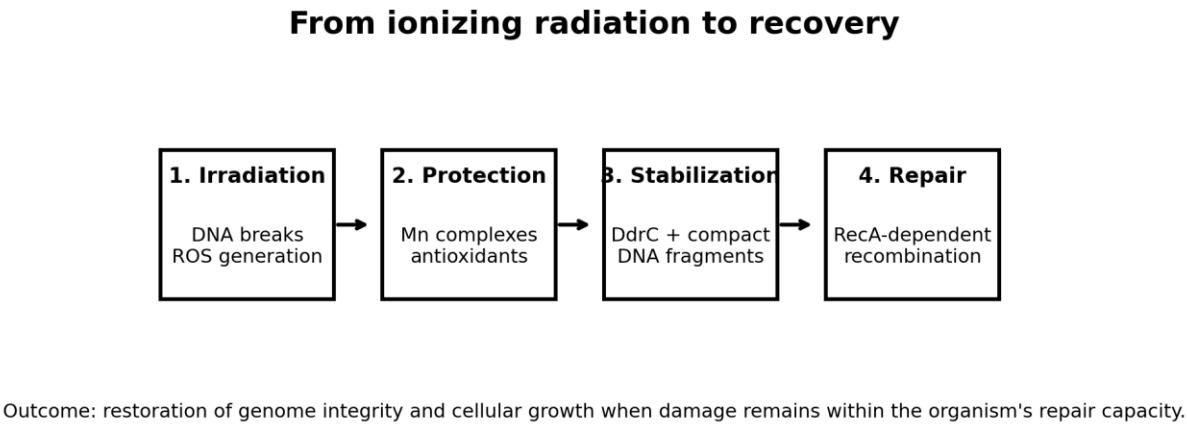

Figure 3. Simplified sequence from irradiation to cellular recovery in D. radiodurans.

A major conceptual advance in the field has been the recognition that protein oxidation is a critical determinant of radiation survival. Daly (2009) proposed that manganese-associated antioxidant chemistry can protect proteins required for DNA repair. Slade and Radman (2011) further reviewed evidence that D. radiodurans maintains lower levels of protein oxidation than radiation-sensitive bacteria despite suffering substantial DNA breakage.

This model changes the simplistic picture in which radiation kills cells primarily because DNA is broken. DNA damage is certainly severe, but a cell can survive if the repair machinery remains chemically functional. Consequently, preservation of repair proteins, antioxidant defenses, and metabolic recovery becomes a central component of radiation resistance.

Reactive Oxygen Species and Secondary Damage

ROS such as hydroxyl radicals and other oxidizing species can attack proteins, nucleic acids, and membrane components. Radiation-resistant bacteria appear to manage this secondary chemistry efficiently. Manganese ions and manganese-containing complexes have been associated with

antioxidant protection, while enzymatic systems such as catalases and superoxide dismutases contribute to ROS control. The combined effect is a cellular environment in which repair proteins remain active long enough to reconstruct damaged chromosomes.

This mechanism also explains why desiccation resistance and radiation resistance can be biologically linked. Both stresses can promote oxidative damage, meaning that selection for robust antioxidant and macromolecular-protection systems may provide cross-protection.

4. Molecular Mechanisms of Extreme Radiation Resistance

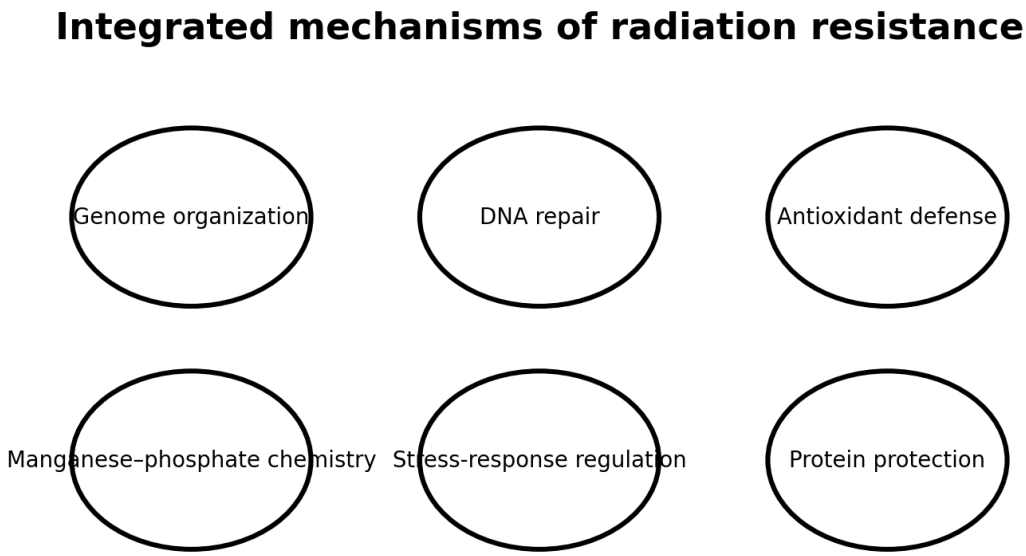

Figure 4. Major interacting mechanisms contributing to radiation resistance.

4.1 Genome Multiplicity and DNA Organization

Multiple genome copies provide homologous templates that can support reconstruction after chromosome fragmentation. Compact nucleoid organization can also reduce the physical dispersal of DNA fragments. Together, these features create favorable conditions for accurate recombinational repair.

4.2 DNA Repair Pathways

D. radiodurans uses several DNA-repair processes, including excision repair, homologous recombination, DNA synthesis, and specialized responses to double-strand breaks. RecA is a major component of recombinational repair. Historical work demonstrated that repair of extensive radiation-induced DNA fragmentation depends strongly on recombination functions (Cox & Battista, 2005).

4.3 Antioxidant and Protein-Protective Systems

The organism's antioxidant network limits oxidative modification of proteins and other macromolecules. Manganese-associated chemistry is particularly important because it can reduce the oxidative burden on proteins that are needed for recovery. The resulting synergy between antioxidant protection and DNA repair is one of the defining characteristics of the Deinococcus strategy (Daly, 2009; Slade & Radman, 2011).

4.4 Regulation of the Radiation/Desiccation Response

Deinococcus species possess specialized regulatory systems that coordinate expression of DNA-repair and stress-response genes. The IrrE–DdrO regulatory axis is a major example. Following damage, repression of appropriate repair genes is relieved, enabling rapid production of proteins required for recovery. This response differs in important respects from the canonical SOS response of many other bacteria.

4.5 DdrC and DNA-Break Stabilization

Recent structural and biochemical work has expanded the mechanistic picture. Szabla and colleagues reported in 2024 that DdrC recognizes DNA lesions and can bind pairs of single- or double-strand breaks, promoting DNA compaction and circularization of broken DNA fragments. This provides a plausible physical mechanism for stabilizing damaged DNA before subsequent repair steps (Szabla et al., 2024).

5. Is Deinococcus radiodurans Really "Radiation-Eating"?

The phrase "radiation-eating bacteria" is scientifically attractive but potentially misleading. In ordinary microbiological terminology, a microorganism "eats" or metabolizes a substrate when the substrate contributes materially to cellular energy or carbon metabolism. D. radiodurans does not fit this definition simply because it survives intense irradiation.

The strongest evidence supports radiation resistance: the organism survives high doses, repairs DNA, protects proteins, and controls oxidative stress. A separate question is whether ionizing radiation can be harvested as an energy source by a microbial metabolism. That question should be addressed using growth experiments, energy-balance measurements, isotope tracing where appropriate, and biochemical evidence demonstrating coupling between radiation exposure and ATP-generating processes.

Radiotrophy and Melanized Microorganisms

Research on melanized fungi has provided evidence that ionizing radiation can alter the electronic properties of melanin and, under experimental conditions, enhance growth of melanized fungi. These observations have led to the hypothesis that melanin may participate in energy transduction under irradiation. However, this literature primarily concerns fungi rather than D. radiodurans, and it should not be used as proof that a radioresistant bacterium consumes radiation for growth.

The distinction is particularly important in scientific communication. A defensible article should describe D. radiodurans as an "extremely radiation-resistant bacterium" and discuss radiotrophy as a separate research hypothesis. This wording avoids overstating the evidence while preserving the intriguing possibility that radiation-rich environments may influence microbial ecology in ways not yet completely understood.

Why the Distinction Matters

Confusing resistance with energy harvesting can lead to incorrect claims about nuclear-waste treatment, biotechnology, or microbial ecology. Radiation-resistant organisms may remain viable in radioactive environments without reducing radioactivity. A

bacterium can capture uranium ions or other radionuclides chemically without destroying their radioactivity. The radionuclide remains radioactive after biological immobilization; only its location, chemical form, or mobility changes.

For this reason, the practical value of D. radiodurans is currently better established in stress-resistant biotechnology and radionuclide capture than as a proven radiation-powered microorganism.

6. Uranium Biosorption and Bioprecipitation

One of the most promising applied areas for D. radiodurans is the treatment of uranium-containing solutions. The organism combines radiation resistance with cell-surface chemical groups capable of binding metals. This creates an unusual advantage: a biological system can remain functional in environments where radiation would damage many conventional microbial platforms.

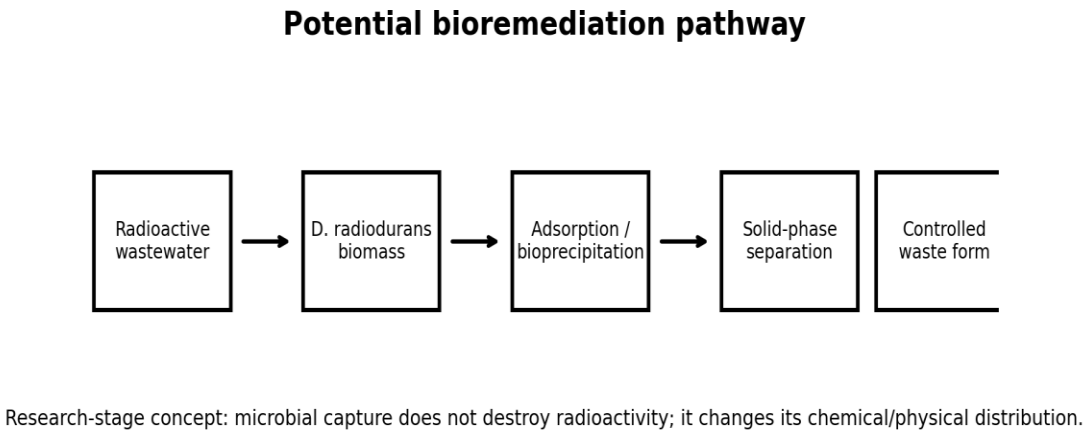

Figure 5. Conceptual workflow for microbial radionuclide capture. The process redistributes uranium; it does not destroy radioactivity.

Appukuttan et al. (2006) engineered D. radiodurans R1 to express PhoN, a nonspecific acid phosphatase. The recombinant organism precipitated more than 90% of uranium from a 0.8 mM uranyl nitrate solution within 6 h under the reported experimental conditions. This work demonstrated that radiation resistance could be combined with a designed biochemical function for radionuclide recovery.

Subsequent research expanded this concept. A recombinant D. radiodurans strain expressing an alkaline phosphatase (PhoK) achieved more than 90% uranium removal at 1 mM input concentration within 2 h and showed a reported maximum loading of approximately 10.7 g U per g dry biomass at 10 mM input uranium. The precipitated uranium was identified as a uranyl phosphate mineral, chernikovite, and immobilization in calcium alginate beads facilitated physical separation (Misra et al., 2013).

These results are significant because the bacterial system performs a chemical transformation that converts soluble uranium into a less mobile solid-associated form. The technology remains research-stage and must be evaluated against conventional

treatment systems for kinetics, selectivity, process control, waste handling, biosafety, and long-term stability.

Biosorption Mechanisms

Uranium can associate with cell surfaces through ion exchange and complexation involving functional groups such as carboxyl, phosphate, hydroxyl, and amide groups. Experimental studies using D. radiodurans have reported uranium association with the cell surface and spectral changes consistent with involvement of several chemical functionalities.

7. Genetic Engineering and Synthetic Biology Opportunities

The combination of extreme radiation resistance and genetic tractability makes D. radiodurans an attractive chassis for synthetic biology. Engineering strategies have focused on introducing genes that enhance radionuclide precipitation, metal reduction, biosorption, or stress-inducible responses.

The PhoN and PhoK examples illustrate a general design principle: a native stress-resistant host can be equipped with a heterologous enzyme that converts a soluble contaminant into a separable solid phase. This approach is conceptually different from “eating” radiation. The bacterium is functioning as a robust biological reactor whose resistance permits operation under harsh conditions.

Radiation-Inducible Expression

Radiation-responsive promoters provide another interesting strategy. Misra and colleagues reported a system using a radiation-inducible promoter to enhance uranium precipitation. Such systems could theoretically couple the presence of radiation-associated stress to expression of a remediation function, creating a biological response that is activated by the environmental condition being treated.

Potential Biosensor Applications

Radiation-responsive regulatory systems may also support biosensor development. A bacterial sensor does not need to metabolize radiation to detect it. Instead, radiation-induced molecular damage can activate a regulatory pathway, which is then connected to a measurable reporter. Such systems could potentially provide biological indicators of radiation exposure, although calibration, specificity, dynamic range, and environmental robustness must be rigorously characterized.

Engineering Constraints

Engineering radioresistant organisms for environmental deployment requires careful consideration of genetic stability, horizontal gene transfer, containment, ecological persistence, and downstream waste management. Laboratory performance does not automatically translate to field performance. In radioactive waste streams, pH, ionic strength, competing metals, organic matter, temperature, and radiation dose rate may all influence microbial activity and radionuclide chemistry.

For applied systems, the most important performance metric is not simply survival after irradiation but the integrated removal efficiency over time, selectivity for target radionuclides, resistance to competing contaminants, and ability to recover the captured radionuclide in a controlled waste form.

8. Comparative Perspective and Research Gaps

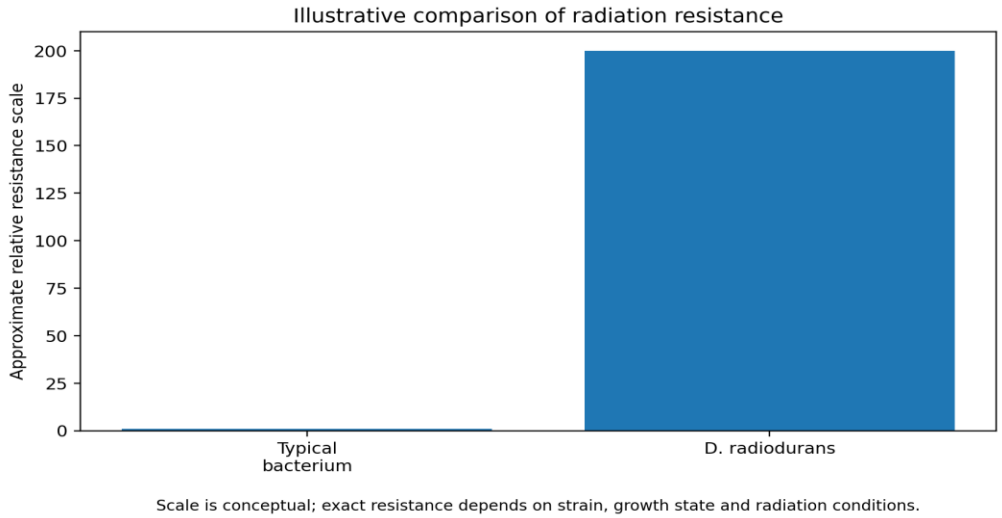

Figure 6. Illustrative comparison of radiation resistance. The scale is conceptual rather than a standardized quantitative dataset.

Feature	Radiation-sensitive bacteria	D. radiodurans	Melanized fungi
Primary advantage	Rapid growth under ordinary conditions	Extreme stress survival and repair	Melanin-associated stress tolerance
Radiation response	Loss of viability at comparatively lower doses	Very high survival after severe irradiation	Radiation response can include altered growth in some species
Key mechanism	Conventional repair and antioxidant systems	DNA repair + protein protection + Mn chemistry	Melanin and antioxidant mechanisms
Established radionuclide use	Limited / context-dependent	Uranium capture and engineered bioprecipitation	Research-stage

Major Research Gaps

First, the field needs clearer separation of three concepts: resistance, detection, and energy harvesting. A microorganism can be resistant without being a detector or an energy harvester. Second, the molecular basis of resistance continues to evolve as new proteins and regulatory components are characterized. DdrC is one example of how apparently specialized DNA-handling proteins can add mechanistic detail to the classical model.

Third, bioremediation studies need more realistic waste matrices. Many laboratory studies use controlled uranium solutions, whereas actual nuclear waste may contain mixtures of radionuclides, heavy metals, salts, complexants, and variable pH. Fourth, immobilized microbial systems deserve further study

because separation and containment are central engineering requirements.

Potential Research Directions

- Structure–function studies of DdrC and other DNA-break management proteins.
- Quantitative relationships among manganese, phosphate, ROS, and protein oxidation.
- Long-duration uranium capture in mixed-contaminant solutions.
- Immobilized or biofilm-based reactor configurations for controlled radionuclide capture.
- Radiation-responsive biosensors with quantitative reporter output.
- Standardized comparisons of radiation resistance using dose rate, growth state, and survival endpoints.

9. Environmental and Biotechnological Significance

The study of radiation-resistant bacteria extends beyond nuclear waste. The underlying biology offers a natural experiment in how living systems preserve information and function under extreme oxidative stress. DNA repair proteins, antioxidant chemistry, and stress-response regulation are relevant to microbiology, biotechnology, environmental engineering, and astrobiology.

Bioremediation

Microbial remediation can complement physical and chemical treatment by exploiting selective adsorption, precipitation, reduction, or complexation. For uranium, D. radiodurans has the additional advantage of remaining biologically robust in radiation-associated environments. Nevertheless, microbial remediation should be viewed as a radionuclide immobilization or recovery strategy, not radioactive decay. The final radioactive material still requires controlled handling and disposal.

Radiation Biology

D. radiodurans provides a model for understanding how cells prioritize repair after catastrophic molecular damage. The organism illustrates that survival can depend on protecting the repair machinery itself. This principle may inform the design of stress-resistant biological systems and the study of oxidative injury.

Synthetic Biology

A radiation-resistant chassis can be paired with genes for metal capture, biosensing, or biocatalysis. The engineering objective is not to make bacteria “eat” radiation, but to exploit their ability to remain functional while performing useful chemistry in harsh environments.

Astrobiology and Space Research

The ability of Deinococcus to withstand radiation and desiccation has made the genus relevant to questions about microbial survival under extreme planetary or space-associated conditions. Such studies do not imply that life evolved to consume cosmic radiation. Instead, they help define the physical limits of cellular persistence and the repair strategies that could support survival during prolonged environmental stress.

Scientific Communication

The phrase “radiation-eating bacteria” is useful as a popular entry point, but academic writing should immediately define what is meant. A scientifically precise formulation is: “radiation-resistant bacteria capable of surviving high ionizing-radiation exposure and, in engineered systems, participating in radionuclide capture.” This preserves the fascinating biology without turning a metaphor into a metabolic claim.

10. Conclusions

Deinococcus radiodurans is one of the most remarkable examples of microbial stress resistance known. Its extraordinary survival under ionizing radiation results from an integrated network rather than a single molecular feature. Genome multiplicity and organization help preserve repair templates; antioxidant systems, particularly manganese-associated chemistry, protect proteins from oxidative damage; regulatory pathways coordinate the stress response; and multiple DNA-repair mechanisms reconstruct damaged chromosomes.

The expression “radiation-eating bacterium” should therefore be used cautiously. The strongest evidence concerns radiation resistance, not radiation consumption as a metabolic substrate. Evidence from melanized fungi demonstrates that radiation can influence melanin chemistry and growth under some conditions, but these observations should not be generalized to D. radiodurans without direct metabolic evidence.

The applied literature provides a more concrete opportunity. Engineered D. radiodurans strains expressing phosphatases have demonstrated substantial uranium bioprecipitation and biosorption under laboratory conditions. These systems illustrate how radioresistant biology can be combined with synthetic biology to create microorganisms capable of radionuclide capture in harsh environments. However, the captured radionuclide remains radioactive, so biological treatment must be integrated with appropriate physical separation and radioactive-waste management.

Future research should focus on quantitative mechanistic studies, realistic mixed-contaminant matrices, immobilized-cell systems, long-term genetic stability, and standardized radiation-response measurements. The recent identification of specialized DNA-break recognition functions such as DdrC further demonstrates that the molecular biology of radiation resistance is still developing.

Final Scientific Statement

Based on the current evidence, D. radiodurans is best described as an extremely radiation-resistant bacterium rather than a bacterium that literally eats radiation. Its importance lies in its ability to survive, repair, and remain metabolically useful under conditions that are highly damaging to most microorganisms. This distinction strengthens rather than weakens the scientific significance of the organism: the real phenomenon—extraordinary cellular repair and protection—is already sufficiently remarkable.

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