

## Life in high radiation/radioactive environments

*Daddy: Why do I need to wear sunscreen when I go outside?*



Photo by Kindel Media: <https://www.pexels.com/photo/sun-drawing-sunscreen-on-child-s-back-photo-8276909/>

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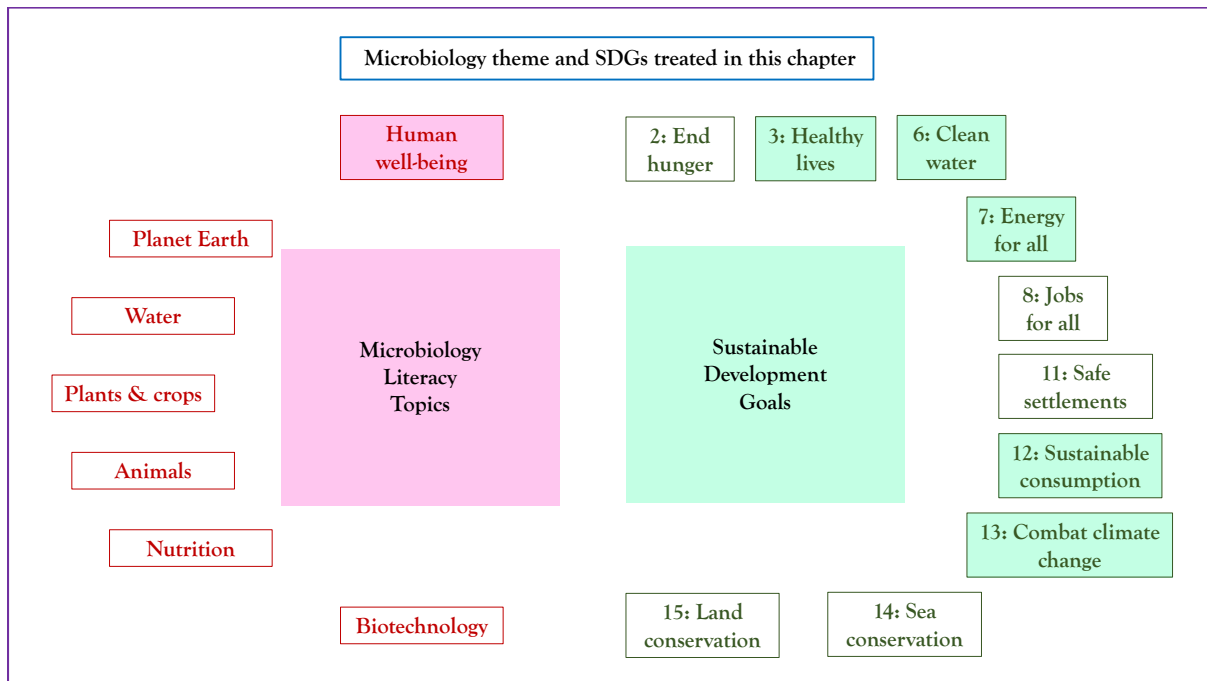
## Life in high radiation/radioactive environments

### Storyline

Most organisms cannot live under high levels of radiation; however, some have evolved to survive or even thrive under these extreme conditions. These organisms are considered **radioresistant**. While some of these organisms are complex and multicellular, such as tardigrades (colloquially known as “water bears”), many are microbes, which are simple, single-celled organisms too small to be seen by the naked eye. For example, the bacterium *Deinococcus radiodurans*, which was originally found in irradiation-sterilized canned meat, can withstand a 1000-fold stronger dose of radiation than humans. Understanding and utilizing the mechanisms of these organisms’ survival under such high radiation conditions has led to improvements in medicine, waste disposal, energy, and more.

### The Microbiology and Societal Context

*The microbiology:* radiation and radioactivity; radiation-resistant microbes: melanin; applications of radioresistant microbes. *Sustainability issues:* health; water contamination; energy, bioremediation; global warming.



### Life in High Radiation/Radioactive Environments: the Microbiology

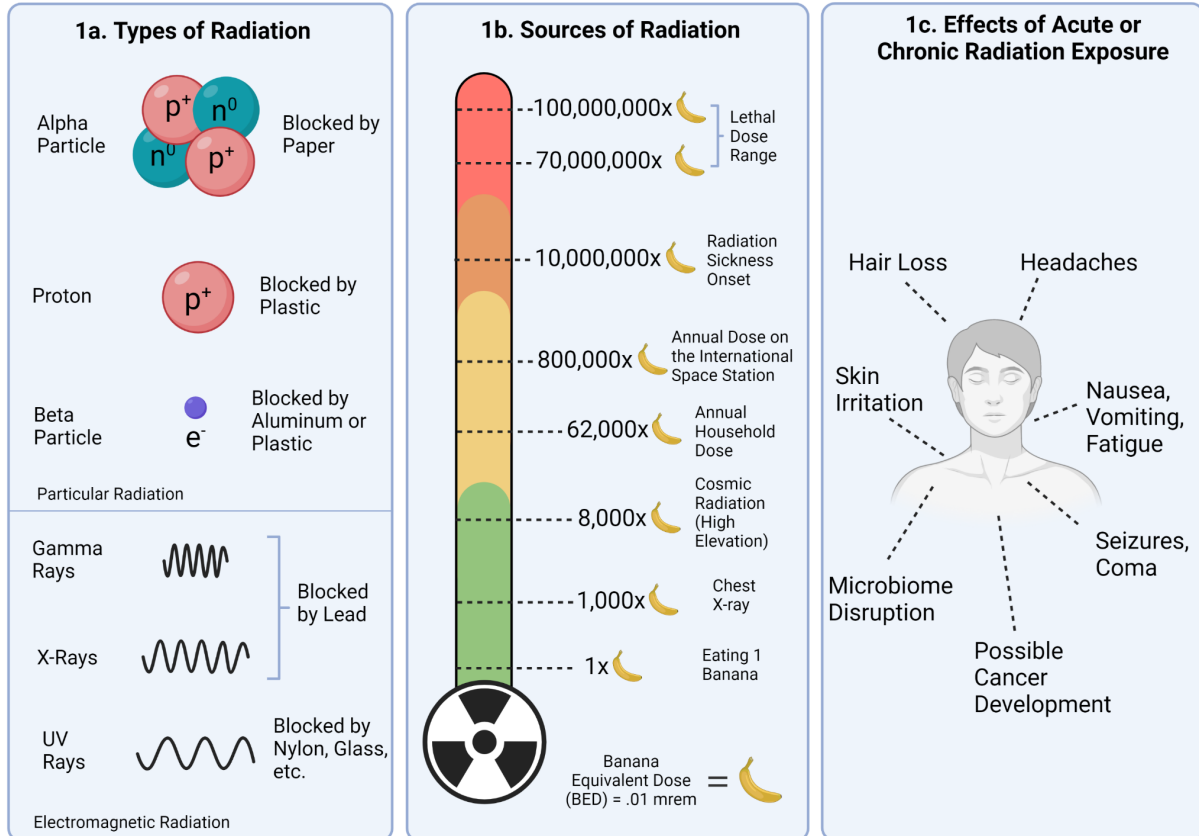
1. *What is radiation?* Humans are capable of great things. They can build societies in all types of environments. Yet, highly **radioactive** environments pose particular challenges for all living organisms, including humans. Media portrayal of radiation is typically extreme, with exposure leading to either superpowers (as in Spiderman after being bitten by a radioactive spider, or the Hulk after surviving a gamma bomb blast), or to immediate death. This has led to some misconceptions about how we typically encounter radiation and its prevalence in our everyday lives.

Radiation is a natural form of energy that is emitted in the form of waves or high-speed particles. There are two types of radiation, **ionizing** and **non-ionizing**. **Ionizing radiation** is defined by having such high energy that it can change **atoms** into **radicals**, a type of highly reactive molecule that can significantly damage other molecules. Ionizing radiation results from certain parts of the **electromagnetic spectrum**, such as ultraviolet light (**UV**), **x**, and **gamma rays**, as well as from **subatomic particles**, such as **protons** and **alpha** and **beta particles** emitted by **radioactive isotopes**, and **radioisotopes**. In a living cell, **radicals** bump into biological molecules, the downstream effects of which are discussed. Although radiation can be a health risk, we will discuss in subsequent sections how ionizing radiation can also be used in medicine or as a source of energy. As the focus of this topic framework is on ionizing radiation, we will subsequently refer to this as simply “radiation.”

Forms of non-ionizing radiation (not covered in this chapter) include visible light and radio waves; these radiation forms do not have the ability to create radicals and are typically safe or less harmful to the body than ionizing radiation.

2. *There are several natural sources of radiation, but most do not cause significant harm to people.* Some natural sources of radiation include UV rays from the sun (which is why we need to wear sunscreen when we go out on sunny days), **gamma rays** from stars, and **radioisotopes**. Isotopes are different types of atoms belonging to the same element, i.e. having the same number of protons, but having different numbers of neutrons. Radioisotopes are radioactive because their constellation of subatomic particles is unstable due to its high energy. To transition to a more stable isotope, radioisotopes ‘decay’ – they eject a subatomic particle – and energy is released in the form of radiation. All **isotopes** of uranium, which can be found in certain rocks such as granite and marble, are **radioactive**. For example, the US Capitol Building emits far more radiation than would be allowed for a nuclear power reactor due to the high uranium content within its granite. When uranium decays it releases radon, which is a radioactive gas.

## A child-centric microbiology education framework



### Radiation: What is it? Where does it come from and how much is “too much”?

a. **Types of radiation.** Types of ionizing radiation fit into 2 broad categories that are defined by whether a source is particular (subatomic particles) or electromagnetic. Subatomic particles consist of alpha particles, protons, and beta particles. Electromagnetic radiation consists of gamma rays, X-rays and UV rays.

b. **Sources of radiation.** Radiation comes from a broad range of sources that vary widely in dosage. Doses are compared to the adsorbed dosage from eating a single banana.

c. **Effects of radiation.** Symptoms of radiation exposure range from skin irritation to increasing the chance of developing cancer. Indirect effects of radiation exposure due to disruption of the microbiome include nausea and fatigue. Created with BioRender.com.

Potassium-40 and radium-226 can be found in food in trace amounts, such as in bananas. Bananas contain potassium, which is an essential element that in trace amounts contributes to a healthy diet. Most potassium is nonradioactive, but around 0.012% of all potassium on Earth is potassium-40, which is a **radioisotope** that can emit **alpha** and **beta particles** during its decay. Luckily, you would have to eat a lot of bananas (70,000,000 to 100,000,000) to absorb a harmful dose of radiation. One banana emits approximately 0.01 **millirem**. As bananas are comparable to **millirem**, they provide a more familiar comparison of dosage.

Some elements, such as tritium (hydrogen-3), carbon-14, and phosphorus-32 are invaluable to research and industry.

### Radioisotopes in Industry and Research

Smoke detectors and carbon dating are two common uses of **radioisotopes**. Smoke detectors contain a small amount of americium-241, a synthetic element that does not naturally exist on Earth\*, which emits **alpha particles** that create an electrical current between two plates. Smoke can absorb **alpha particles**, thereby cutting off the current and triggering the alarm. Scientists can also infer the age of carbon-containing materials like rocks or trees because carbon-14\*\* naturally occurs at a specific proportion (1 per trillion carbon atoms). Carbon-14 moves freely in gases and liquids, maintaining the proportion of carbon-14 constant. However, in a solid material, no new carbon-14 can enter and replace decayed carbon-14, the proportion of which therefore slowly decreases over time. By measuring the percentage of carbon-14, which takes tens of thousands of years to decay, geologists can infer the age of a rock. Other applications of radioisotopes include industrial inspection, medical diagnosis, and radiopharmaceuticals.

\*All isotopes of Americium are radioactive, which is true of all synthetic elements

\*\* Carbon-14 contains 6 protons and 8 neutrons. The most common stable isotope of carbon is carbon-12, which contains 6 protons and 6 neutrons. The two additional neutrons in carbon-14 make the atom unstable.

Some places on Earth naturally have higher levels of radiation due to greater exposure to the sun's rays, such as high mountaintops and open fields. Air travel, and to a greater extent, space travel, leads to heightened radiation exposure due to lowered or a lack of atmospheric protection. A typical astronaut experiences the dose equivalent of 50-2000 millirem.

### 3. *Radiation is used in many medical procedures, which have dose-dependent side effects.*

The average American receives a dose of 620 **millirem** per year, half from natural sources and half from human-made sources such as medical procedures. The medical procedures that involve the use of radiation include **x-rays** and CT scans for diagnosis, and radiation therapy for **cancer**. For these procedures, the health benefits typically far outweigh the risks, but there are side effects involved. Radiation therapy delivers an approximately 5,000,000 **millirem** dose to a tumor site. This high dose would be lethal if it was delivered to the entire body, but when it is concentrated at the cancerous site, it kills mostly cancer cells. However, non-cancerous cells at the site of exposure are also killed. This can lead to skin irritation, hair loss, and an altered **microbiome**.

The **microbiome**, that is the diverse set of microorganisms like bacteria that live in and on our bodies, accounts for around half of all cells in the human body and has important roles such as helping us digest food and fortifying our immune systems. Radiation therapy can negatively affect cancer patients by altering the microbes present in their gut, leading to changes in how effective the treatment is, as well as the toxicity of the treatment itself. As such, there is much current research focused on how to target cancer cells without damaging healthy cells.

On the other hand, radiation exposure from an **x-ray** is much lower (10 **millirem** for a standard chest **x-ray**), and patients do not experience the same side effects as in radiation therapy. However, each exposure increases the chance of our cells becoming cancerous. This is because the **radicals** generated by exposure can damage our **genome** by breaking the bonds within DNA, like cutting the links on a chain, and create mutations. Since the mutations are permanent, they accumulate over time and increase the risk of **cancer**.

## A child-centric microbiology education framework

4. *Radioresistance in many microbes likely evolved from exposure to harsh environments such as arid deserts.* Only a few places on Earth, such as **Chernobyl**, have become radioactive hotspots due to **nuclear energy** accidents or nuclear warfare/defense. Humans cannot survive in **Chernobyl**, but some organisms can. Many of these organisms are **radioresistant** microbes.

The bacterium *Deinococcus radiodurans* is a model organism for learning about radioresistance due to its extreme resistance to radiation. However, while *D. radiodurans* is the most radiation resistant microbe, it is not the only microbe known to be resistant to radiation. Other microbes that exhibit high radioresistance include the bacteria *Kineococcus radiotolerans*, *Halobacterium sp. NRC-1*, *Rubrobacter radiotolerans*, and fungi such as *Cryptococcus laurentii*. Interestingly, several fungi, including *Cryptococcus neoformans*, *Cladosporium sphaerospermum*, and *Wangiella dermatitidis* have been discovered within the Chernobyl nuclear power plant, and appear to grow towards radiation (termed radiotropism), and might even use radiation as an energy source (like plants use the sun to grow).

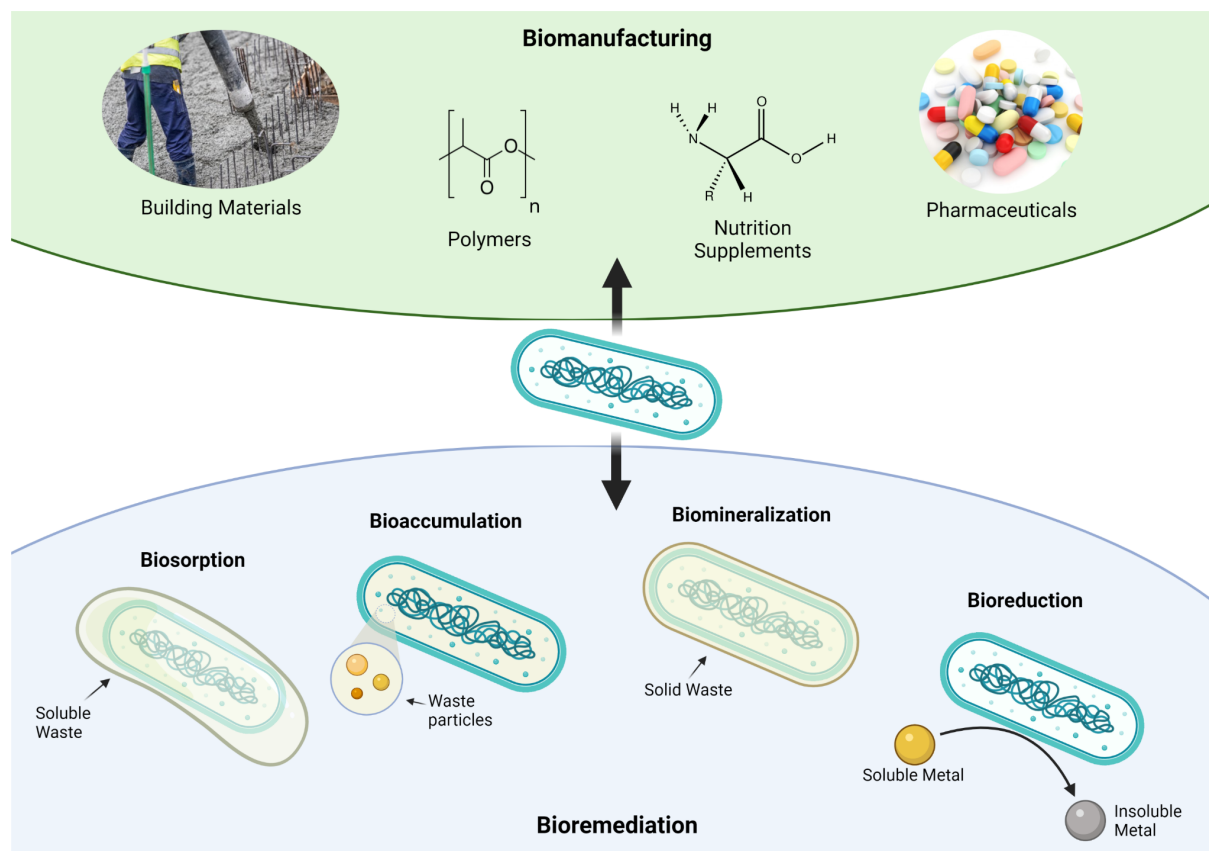
But how did these microbes evolve resistance to radiation when there are few highly **radioactive** locations on Earth, none of which occur naturally? One prevailing theory is that **radioresistance** is a byproduct of evolution under extremely dry conditions, such as in an arid desert. Dry regions are common on Earth and can cause cellular damage similar to radiation exposure, such as **DNA** breakage, protein damage, disruption of cellular membranes, etc. It is thought that, when regions on Earth changed climate long ago, turning forests into deserts, the microbes present in these environments evolved new mechanisms over time to deal with or avoid damage from the dry environment. Importantly, studying how these **radioresistant microbes** are able to withstand harsh environments can help create new biotechnology tools that improve our lives.

5. *Radioresistant microbes are exploited in multiple sectors of biotechnology, such as biomanufacturing, bioremediation, and bioenergy.* Radioresistant microbes are extremophiles or extremotolerant, because they tolerate or even prefer conditions too harsh for most forms of life. **Extremophilic** microbes have many applications in biotechnology. They can teach us how to survive in harsh environments and produce unique chemicals that are used in a variety of industries.

As previously mentioned, space exploration results in heightened radiation exposure. The average exposure on the **International Space Station** is 8,000 **millirems** per year. Under Mars' thin atmosphere, the levels of radiation are 2.5 times greater, or about 20,000 **millirems** per year. This is about 30 times greater than on Earth. As such, sending humans to Mars (or elsewhere in space), requires having ways to protect them.

While the Earth's atmosphere shields us from the **x-rays** and **gamma rays** of outer space, it does not protect us from all forms of radiation. **UV** radiation can leak through and is a common cause of skin cancers. Luckily, we can use sunscreen to protect ourselves from the sun's rays. Many of the compounds used in sunscreen are **biomanufactured** in **radioresistant** organisms such as red algae, corals, and cyanobacteria after **UV** irradiation. These same compounds can also be used as **antioxidants**, and some may be used to make medicines in the future. As an example, manganese-containing **antioxidants** made by *Deinococcus radiodurans* are currently being tested as an additive to vaccines.

## A child-centric microbiology education framework

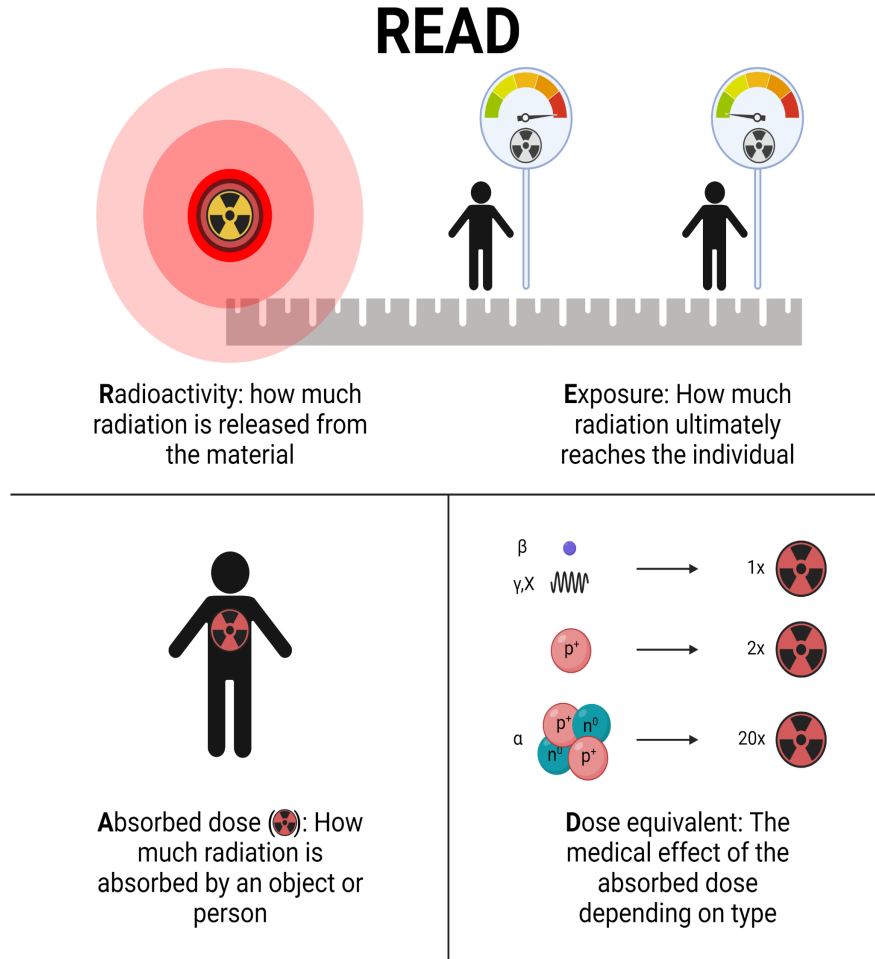


### Applications of Microorganisms in Biomanufacturing and Bioremediation

So far, radioresistant microbes have been used to manufacture compounds that are not commonly found naturally, as well as treat or “clean up” radioactive waste. The four types of bioremediation are biosorption (accumulation of waste around the surface of the cell), bioaccumulation (uptake into the microbial cell) biom mineralization (accumulation of waste as an insoluble shell located on the cell surface), and bioreduction (the conversion of a water-soluble toxic compound into an insoluble compound that can be more easily removed from the waste stream). Created with BioRender.com

Outside of the **biomanufacturing** sector, **radioresistant** microbes participate in **bioremediation**. We provide an overview of **bioremediation** in section 8. These processes can be improved with **genetic engineering** of the microbes to produce useful compounds faster or to remediate different types of waste more efficiently. There are still many open questions concerning the methods these microbes use to achieve such feats, but advances in scientific research are allowing us a closer look at these organisms. The resulting knowledge is expected to widen the range of possible uses and make improvements on the current uses in biotechnology.

6. *Radiation safety is relevant to people’s daily lives.* Everyone will encounter different types of radiation throughout their lives, whether it involves going to the beach, getting an **x-ray** for a broken arm, or working in one of the many industries that use **radioactive** materials. Different types of radiation affect the body in different ways. Whether or not a dose of radiation is dangerous depends on **R-E-A-D**: **R**adioactivity, **E**xposure, **A**bsorbed Dose, **D**ose Equivalent.



**READ: a radiation acronym for safety.** READ is a simple acronym that can be helpful for deciding whether a dose of radiation is dangerous. The actual effect of a radiation incident depends on the source, exposure, absorbed dose, and dose equivalent. Created with BioRender.com

Because we encounter radiation in our daily lives, it is important to learn how to protect ourselves from it. A simple example is using sunscreen to protect the skin from sunburns and skin cancer. Another is to regularly check your home for **radon**, a product of uranium decay, which is the second biggest cause of lung cancers after cigarettes. Exposure to indoor **radon** results in a dose equivalent of about 200 **millirem** per year. For higher doses of radiation, such as those encountered during medical procedures, more protection is needed. For example, lead aprons are used during dental **x-rays**.

People who work with radiation follow the ALARA principle, which stands for “As Low as Reasonably Achievable.” The amount of radiation used should be the lowest necessary and exposure should be minimized by decreasing the time spent around and distance from the source. Work areas must be labeled with the radiation caution symbol and the words “Caution Radiation Area.” The degree of radiation exposure should be constantly monitored using radiation survey instruments. Devices such as **dosimeters** should be worn to ensure that an individual does not receive too much radiation within a certain amount of time.

Lastly, it is imperative to use personal protective equipment (PPE) when handling **radioactive** materials. Lead aprons are an example of this, which can block **x-rays**, a highly

## A child-centric microbiology education framework

penetrative form of radiation. For **alpha particles**, which cannot penetrate the skin, PPE would include a lab coat, safety goggles, gloves, and maybe a respirator to prevent inhalation if needed. **Beta particles** can penetrate the skin and require stronger shielding with aluminum or plastic.

Even with all the safety precautions in place, accidents can occur. If a person is accidentally exposed, they must remove their clothes into a plastic bag and wash thoroughly with soap and water. If a radioactive substance is spilled, then the area must be blocked off and decontaminated with a lab-grade detergent. While most people will not encounter these situations in their everyday lives, these enhanced protective measures are incredibly important for those in the research, industrial, and medical fields that utilize high levels of radiation within their work.

7. ***Nuclear energy is a source of renewable energy that can aid in combating climate change.*** Nuclear energy is the second most common source of renewable energy used in the world. This resource does not emit pollutants into the atmosphere, uses limited space, and produces little waste. Globally, we will need to rely more on renewable energy to reduce carbon emissions and limit the impact of climate change.

While there are a lot of pros to **nuclear energy**, there are downsides to its use. Catastrophes can occur due to inappropriate care of the facilities or when natural disasters strike, as in the cases of the **Chernobyl** and **Fukushima Daiichi** disasters. There is also public fear of groundwater contamination as **radioactive** waste is often buried underground. While **bioremediation** and other clean-up efforts are underway, these methods are not perfect, and some types of **radioactive** waste can take hundreds to thousands of years to naturally **decay**. It is important to weigh the costs and benefits of using **nuclear energy**. Furthermore, it is imperative that workers at these sites are properly trained on radiation safety and waste management.

8. ***Bioremediation of radioactive waste and pollution contribute to healthy environments.*** Most uses of radiation, including research and especially nuclear energy, create waste – radioactive waste which requires safe methods of disposal. Some highly **radioactive** waste must be stored in special sites that shield the materials from the outside environment; this process allows the materials to **decay** over time in a controlled space. For areas with less waste in the soil or water, microbes can be used to alter or remove the radioactive waste through a process called **bioremediation**. There are four main types of **bioremediation**:

a. Biotransformation/Bioreduction: **Radioactive heavy metals** are often **soluble** in water. Some microbes such as *Deinococcus radiodurans*, *Shewanella putrefaciens*, and *Geobacter sulfurreducens*, can metabolize these metals and alter them so that they become **insoluble**, reducing their dispersal in groundwater.

b. Biomineralization: Some bacterial microbes such as certain species of *Citrobacter* and *Serratia* can collect solid waste on their cell surfaces, concentrating the waste onto themselves instead of a wider area of the ground.

c. Biosorption: Some microbes such as the fungi *Rhizopus arrhizus* and the algae *Chlorella vulgaris* can hold **soluble** waste on their cell surfaces.

d. Bioaccumulation: Some microbes can accumulate radioactive waste inside the cell. Certain *Pseudomonas* species are capable of uranium accumulation.

## A child-centric microbiology education framework

### Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 3. Ensure healthy lives and promote well-being for all at all ages** We constantly encounter radioactive sources throughout our everyday lives. From radon present in our homes to the sun's UV rays, exposure to radiation is unavoidable. By educating ourselves about various sources of radiation, we can determine the best ways to limit our exposures to radiation. Regularly screening for radon in our homes can lower the yearly exposure to radiation indoors. Applying sunscreen before heading outside can protect our skin from UV rays and lower our risk of developing skin cancer. We can keep ourselves healthy by educating ourselves on radiation safety and by taking proper precautions when around radioactive sources, as well as by following the ALARA principle to limit exposure.

- **Goal 6. Ensure availability and sustainable management of water and sanitation for all.** Advances in bioremediation over the years have led to the development of a variety of tools for treating radioactive waste. Through processes like bioreduction, biosorption, biomineralization, and bioaccumulation, we can harness the power of microbes to help treat water contaminated with radioactive material in a sustainable manner.

- **Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all.** Nuclear energy is the second most common renewable energy source. Its low waste production and relatively low space requirement make nuclear power appealing as a major source of sustainable energy.

- **Goal 12. Ensure sustainable consumption and production patterns** Radioactive waste from both research and industrial facilities can represent dangerous sources of exposure if not properly handled. By regulating how radioactive waste is disposed or treated, we can prevent contamination of public water streams.

- **Goal 13. Take urgent action to combat climate change and its impacts** The impacts of fossil fuels on our environment, and especially global warming, underpin the need for climate neutral renewable sources of energy. Nuclear power fulfils these criteria. Through further research and development in the field of nuclear energy, we can advance this source of energy to slow the impact of our energy sector on the environment. Additionally, through study of microbes that are resistant to forms of radiation, we can find new ways to treat our radioactive waste streams.

### Potential Implications for Decisions

#### 1. *Individual*

- a. When do I need to be concerned about protection against radiation?
- b. What are the benefits and drawbacks of common medical procedures such as x-rays?
- c. How to protect other parts of the body from unnecessary radiation during a dental x-ray?
- d. How to protect against radon at home?

#### 2. *Community policies*

- a. How can nuclear energy benefit or hurt a community?

## A child-centric microbiology education framework

- b. What happens if a nuclear energy reactor leaks radioactive waste into the groundwater or has a failure?
- c. How can microbes help clean up waste?

### 3. *National policies*

- a. What governmental policies limit radiation exposure?
  - i. Environmental Protection Agency (EPA)
  - ii. Centers for Disease Control and Prevention (CDC)
  - iii. National Aeronautics and Space Administration (NASA)
- b. Why do astronauts experience more radiation than the average person? How are they protected from greater doses of radiation?

### Pupil Participation

#### NGSS Connections

Standard	Possible Connections
Kindergarten - K-PS3-1 and 2 (Sunlight warms earth)	Sunlight also emits UV radiation. With kindergarten, it can be linked with the need to wear sunscreen while outside.
1st - 1-PS4-3 (Objects block light)	It could be possible to link this standard with the ability of certain objects to block radioactivity as well.
3rd - 3-LS4-3 (Adaptations)	It could be possible to link this standard with radioresistant organisms.
4th - 4-PS3-4 (converting energy into useable forms) 4-ESS3-1	It could be possible to link this standard with various energy resources like solar, petroleum, and nuclear.
4th - 4-ESS1-1 (evidence of geological history)	It could be possible to link this standard with radioactive dating.
5th - 5-LS2-1 (energy flow in an ecosystem)	It could be possible to link this standard to radiosynthetic organisms.
5th - 5-ESS3-1 (Humans' activities have impacted the environment)	It could be possible to link this standard to radioactive waste.

1. *Class discussion on the issues associated with radiation*

2. *Pupil stakeholder awareness*

## A child-centric microbiology education framework

a. Scientists today are warning about the dangers of society continuing to rely on non-renewable resources for our energy needs. However, there is still resistance, disbelief, or distrust surrounding the switch to renewable resources such as solar, wind, and nuclear. Why do you think there is such resistance, and what might we do as scientists to help overcome it?

b. Repeated, or prolonged exposure to radiation can increase the chance that someone develops cancer later in life. However, one of the main treatments for cancer is also radiation. Why do you think doctors use radiation to treat a condition that can be caused by radiation?

### 3. Exercises

a. Compare and contrast various types of energy resources (renewable and non-renewable). Include nuclear specifically, but others can include petroleum, natural gas, water, solar, wind, coal, biomass, etc.

b. Presence of radiation (UV specifically). Obtain Nature Paper ([click for example](#)) and tape to transparency paper. The paper reacts to UV light and turns white. Use sunscreen on the transparency to test the strength or effectiveness of various sunscreens.

c. Focus on bioremediation. Have students research different forms of current bioremediation, then design their preferred type of remediation, explaining why they chose the strategy they did.

d. Genetic Engineering focus (7th grade or higher because this is where DNA is introduced). Introduce students to various species of bacteria that are resistant to radiation or involved in bioremediation. Explain how specific genes enable the different species to do what they do. Then, have the students brainstorm on ways to convert a regular bacteria or cell into one that can better resist or remediate radiation.

e. Molecular biology focus (7th grade or higher because this is where DNA/RNA is introduced). Ask students to imagine that they discover a new bacterium that is the most radiation resistant to date. Ask them to suggest different studies that they might carry on understanding mechanistic features that the organism uses for radioresistance.

## The Evidence Base, Further Reading and Teaching Aids

### Teaching Aids

*Radiation and Your Health*, Centers for Disease Control and Prevention, 6 August 2021, <https://www.cdc.gov/nceh/radiation/default.htm>.

*Radiation Protection*, United States Nuclear Regulatory Commission, 20 March 2020, <https://www.nrc.gov/about-nrc/radiation/health-effects/measuring-radiation.html>.

“Calculate Your Radiation Dose.” *Radiation Protection*, United States Environmental Protection Agency, 17 August 2020, <https://www.epa.gov/radiation/calculate-your-radiation-dose>.

Connor, Nick. “What is Banana Equivalent Dose - BED - Definition.” *Radiation Dosimetry*, 14 December 2019, <https://www.radiation-dosimetry.org/what-is-banana-equivalent-dose-bed-definition/>.

“Consumption & Production.” *U.S. energy facts explained*, U.S. Energy Information Administration, 14 May 2021, <https://www.eia.gov/energyexplained/us-energy-facts/>.

## A child-centric microbiology education framework

- “Health Effects of Ionizing Radiation on People.” *Understanding Radiation*, National Environmental Agency, 13 February 2020, <https://www.nea.gov.sg/our-services/radiation-safety/understanding-radiation/health-effects-of-ionising-radiation-on-people>.
- Office of ES&H Reporting and Analysis. *Radiation in Perspective*. Brochure. U. S. Department of Energy, 2016, [https://www.energy.gov/sites/prod/files/2016/09/f33/Radiation\\_in\\_Perspective.pdf](https://www.energy.gov/sites/prod/files/2016/09/f33/Radiation_in_Perspective.pdf).
- Perez, Jason. “Why Space Radiation Matters.” *Analog Missions*, NASA, 8 October 2019, <https://www.nasa.gov/analogs/nsrl/why-space-radiation-matters>.
- “Radiation in Everyday Life.” International Atomic Energy Agency, <https://www.iaea.org/Publications/Factsheets/English/radlife>
- “Radiation Sources and Doses.” *Radiation Protection*, Environmental Protection Agency, 2021, <https://www.epa.gov/radiation/radiation-sources-and-doses>.
- Rutledge, Kim, et al. “Nuclear Energy.” Edited by Jeannie Evers and Kara West. *National Geographic*, vol. Resource Library, no. Encyclopedic Entry, 2011, <https://www.nationalgeographic.org/encyclopedia/nuclear-energy/>.
- “Teaching radioactivity.” Institute of Physics, 2021, <https://spark.iop.org/collections/teaching-radioactivity#gref>
- “3 Reasons Why Nuclear is Clean and Sustainable.” *Office of Nuclear Energy*, Energy.gov, 31 March 2021, <https://www.energy.gov/ne/articles/3-reasons-why-nuclear-clean-and-sustainable>.

### ***Further Reading***

- Information Library*, World Nuclear Association, 2021, <https://world-nuclear.org/information-library.aspx>.
- American Cancer Society medical and editorial content team. “Radiation Therapy Side Effects.” *American Cancer Society*, 10 December 2020, <https://www.cancer.org/treatment/treatments-and-side-effects/treatment-types/radiation/effects-on-different-parts-of-body.html>.
- Conca, James. “How Extremophile Bacteria Living In Nuclear Reactors Might Help Us Make Vaccines.” *Forbes*, 2020, <https://www.forbes.com/sites/jamesconca/2020/07/21/if-extremophile-bacteria-can-live-in-nuclear-reactors-maybe-they-can-help-us-make-vaccines/?sh=12b2edc77619>.
- “Everyday Exposures to Radiation.” *Frontline*, PBS, 2014, <https://www.pbs.org/wgbh/pages/frontline/shows/reaction/interact/facts.html>.
- “Ionizing Radiation.” *Occupational Safety and Health Administration*, United States Department of Labor, <https://www.osha.gov/ionizing-radiation>.
- “Microbial Biopolymers.” *ScienceDirect*, Elsevier B.V., 2021, <https://www.sciencedirect.com/topics/engineering/microbial-biopolymers>.
- “Radiation and Health.” *Department of Health*, New York State, October 2016, <https://www.health.ny.gov/publications/4402/>.
- “Radiation Exposure.” *MedlinePlus*, U. S. National Library of Medicine, 15 September 2021, <https://medlineplus.gov/radiationexposure.html>.
- “Radiation Health Effects.” *Radiation Protection*, United States Environmental Protection Agency, 14 April 2021, <https://www.epa.gov/radiation/radiation-health-effects>.
- “Radiation Safety.” *Environmental Health & Safety*, The University of Texas at Austin, 2021,

## A child-centric microbiology education framework

- <https://ehs.utexas.edu/working-safely/radiation-safety>.
- “Spills & Incidents.” *Environmental Health Safety*, Princeton University, 2021, <https://ehs.princeton.edu/laboratory-research/radiation-safety/radioactive-materials/spills-incidents#LabCoat>.
- “Various Factors.” *Booklet to Provide Basic Information Regarding Health Effects of Radiation*, Ministry of the Environment, 31 March 2015, <https://www.env.go.jp/en/chemi/rhm/basic-info/1st/02-03-05.html>.
- White, Jason, and Beth Ripley. “Calculating Patient Dose: Page 3 of 5.” *Medical Imaging & Radiation Safety*, 2015, <http://www.whiteripleyradsafety.com/3-3>.
- Williams, Matt, and Universe Today. “How bad is the radiation on Mars?” *Space Exploration*, Phys.org, 21 November 2016, <https://phys.org/news/2016-11-bad-mars.html>.

### *Scientific Articles*

- Abatenh E., Gizaw B., Tsegaye Z., Wassie M. The Role of Microorganisms in Bioremediation- A Review. *Open J Environ Biol* 2.1: 038-046. (2017) doi: 10.17352/ojeb.000007
- B S, and Beebi K Sk. Bioremediation of Ammonia from Polluted Waste Waters- A Review. *American Journal of Microbiological Research* 2.6: 201-210. (2014)
- Bardhan P, Gupta K, Mandal M, Chapter 15 - Microbes as Bio-Resource for Sustainable Production of Biofuels and Other Bioenergy Products, *New and Future Developments in Microbial Biotechnology and Bioengineering*, 205-222 (2019) doi: 10.1016/B978-0-444-64191-5.00015-8.
- Frane N., Bitterman A. Radiation Safety and Protection. *StatPearls [Internet]*. (2021)
- Gabani, P., Singh, O.V. Radiation-resistant extremophiles and their potential in biotechnology and therapeutics. *Appl Microbiol Biotechnol* 97, 993–1004 (2013). doi: 10.1007/s00253-012-4642-7
- González Henao S. and Ghneim-Herrera T. Heavy Metals in Soils and the Remediation Potential of Bacteria Associated With the Plant Microbiome. *Front. Environ. Sci.* 9:604216. (2021). doi: 10.3389/fenvs.2021.604216
- Greffe, V.R.G., Michiels, J. Desiccation-induced cell damage in bacteria and the relevance for inoculant production. *Appl Microbiol Biotechnol* 104, 3757–3770 (2020). doi: 10.1007/s00253-020-10501-6
- Hollingsworth B.A., Cassatt D.R., DiCarlo A.L., Rios C.I., Satyamitra M.M., Winters T.A. and Taliaferro L.P.. Acute Radiation Syndrome and the Microbiome: Impact and Review. *Front. Pharmacol.* 12:643283. (2021) doi: 10.3389/fphar.2021.643283
- Newsome L., Morris K., Lloyd J.R. The biogeochemistry and bioremediation of uranium and other priority radionuclides. *Chemical Geology* 363, 164-184 (2014). doi: 10.1016/j.chemgeo.2013.10.034.
- Vandana U.K., Gulzar A.B.M., Laskar I.H., Meitei L.R., Mazumder P.B. Role of Microbes in Bioremediation of Radioactive Waste. *Microbial Rejuvenation of Polluted Environment. Microorganisms for Sustainability* 25 (2021) doi: 10.1007/978-981-15-7447-4\_13

### Glossary

**Alpha particles** are the largest radioactive subatomic particles composed of two protons and two neutrons. Due to the size and positive charge, this radiation can be blocked by paper (and human skin) but can cause damage to sensitive lung tissue if ingested or inhaled.

**Antioxidants** are compounds that can combat oxidation, a process that can produce radicals and lead to cellular damage.

**Atoms** are the units that make up all matter: solid, liquid, and gas. They are composed of neutrons, protons, which make up the central nucleus, and electrons that orbit the nucleus. Stable atoms require specific ratios of all 3 subatomic particles (where electrons balance the protons for a net neutral charge). When atoms have a different number of electrons, they can become highly reactive radicals. When atoms have a different number of neutrons or protons, they become radioisotopes. We can calculate the number of neutrons in an atom by knowing its atomic mass unit (which includes neutrons and protons) and its atomic number (which refers to the number of protons); electrons are very light and are negligible in the mass.

**Beta particles** are smaller than alpha particles. They are composed of a single negatively charged electron. This type of radiation is used for Carbon-14 dating and can be blocked by slightly thicker materials like aluminum or plastic.

**Biomanufacturing** uses materials from biological sources to synthesize/manufacture products. Often this can involve genetic engineering of an organism to produce the desired product.

**Bioremediation** uses an organism's natural ability to break down or contain dangerous compounds to lessen pollution from ground or water sources.

**Cancer** is a disease that is caused by uncontrolled cell growth, which can be triggered by DNA damage to parts of the genome that control growth.

**Chernobyl** is the site of a nuclear power plant disaster that occurred in 1986 caused by design flaws in the reactor and a breach of safety protocols. The site remains uninhabitable by people.

**Decay** (or radioactive decay) refers to the process by which high-energy unstable radioactive atoms release subatomic particles (neutrons, protons and/or electrons) and gamma rays over time, emitting radiation. Over time, enough subatomic particles are released that the atom stabilizes and is no longer radioactive.

**DNA** is the biological macromolecule that encodes genetic information using a 4-letter alphabet (A, C, G, and T). In cells, DNA exists as two strands wrapped around each other, forming a double helix. Both strands are needed so that organisms can replicate their cells and decode genetic information. When radicals break the bonds in DNA, that can create cuts in one or both strands of DNA or cut off a letter. These mutations make it difficult for DNA to be replicated properly as some of the information is lost. If the mutations are not repaired before replication occurs in the cell, the wrong information is copied into the newly replicated cell and all subsequent cells replicated from that cell.

**Dosimeters** are devices that detect ionizing radiation. When worn (for example, on clothes), they measure and track external radiation exposure.

**Electromagnetic spectrum:** The electromagnetic spectrum defines the range of all types of electromagnetic radiation, including ionizing and nonionizing. Electromagnetic radiation exists in the form of waves that are composed of tiny photon particles. High-energy waves are forms of

## A child-centric microbiology education framework

ionizing radiation and include UV, X-, and gamma rays. These waves can penetrate materials and require materials like lead to block this source.

**Extremophiles** are organisms that can survive under extreme conditions, such as high temperatures, frozen environments, high acidity, and/or high radiation. Often these organisms have unique characteristics and abilities that permit them to survive and thrive under these conditions.

**Fukushima Daiichi:** A nuclear power plant failure that occurred in 2011 and was caused by a tsunami.

**Gamma rays** are the highest-energy form of electromagnetic radiation. They are released during radioactive decay and emitted by stars.

**Genetic engineering** is a method in changing the characteristics of an organism to achieve a desired product or behavior. This is done by altering the DNA of the organism, either by inserting or deleting specific parts to change what the organism looks like or what it does. For example, we can insert a piece of DNA into the genome of a bacterium that will then make the bacteria create a protein that turns the bacterial cell blue. This method is very useful for a variety of biotechnological applications.

**Genomes** are the collection of DNA that encodes the recipe for various factors an organism needs to survive.

**Heavy metals** are highly dense, toxic metals that are environmental pollutants. Some are radioactive, such as uranium, while others are not, such as mercury and lead.

**International Space Station (ISS):** the satellite in low Earth orbit occupied by astronauts and cosmonauts (the Russian equivalent of astronauts) from around the world. The ISS serves as a research laboratory for space experiments.

**Ionizing Radiation:** Forms of ionizing radiation include alpha particles, beta particles, protons, UV rays, X-rays, and gamma rays. All forms of ionizing radiation are so energetic that they can change atoms into radicals.

**Microbiome:** The microbiome of an organism includes all the microbes that live in or on an organism's body; for instance, a high number of diverse organisms live in the skin and gut. These microbes provide several useful services for the body, including protection from other germs (or pathogens).

**Millirem (also known as Milli-Sievert)** is a unit of absorbed radiation used for commonly encountered doses. 1000 millirem is equal to 1 rem, the standard unit for measuring equivalent dose, or health effect on the human body.

**Non-ionizing radiation:** Forms of non-ionizing radiation such as visible light does not have the ability to create radicals and are typically safe or less harmful to the body than ionizing radiation.

**Nuclear energy** is a type of clean energy that uses the power of nuclear reactions to generate electricity. Currently, around 9% of all the energy consumption in the U.S stems from nuclear energy.

**Protons**, along with neutrons and electrons, form the particles that make up an atom. Protons and neutrons make up the nucleus of an atom, which is tightly packed. When protons are split from an atom, radiation is produced.

**Radicals** are formed when an electron is gained or lost by a stable atom or molecule. This change makes the radical highly energetic and unstable, such that it is very reactive. Radicals can be made

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from water molecules when they are hit with radiation, which in the cell can react with biological molecules such as DNA, RNA, and proteins.

**Radioactive:** Materials, objects, or environments that emit radiation.

**Radioisotopes** are forms of an atom with extra neutrons and/or protons that make them unstable. In order to release some of their energy, they undergo radioactive decay.

**Radon** is a non-odorous gaseous decay product of uranium that is still radioactive. It is emitted from rocks like granite that have high uranium content, making it common in human-built structures. However, it can be detected and mitigated by radon reduction systems.

**Subatomic particles:** neutrons, protons, and electrons. See “Atom”

**UV rays** are the lowest-energy form of electromagnetic radiation. Some types of UV rays are non-ionizing but can still cause skin damage. The sun is the most well-known source of UV rays.

**X-rays** are higher energy than UV rays, but lower energy than gamma rays. X-rays are commonly used in medicine to look at skeletal structures.

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