Microbial Sunscreens

Photo by Kindel Media
https://www.pexels.com/photo/a-boy-with-a-sun-on-his-back-8215118/

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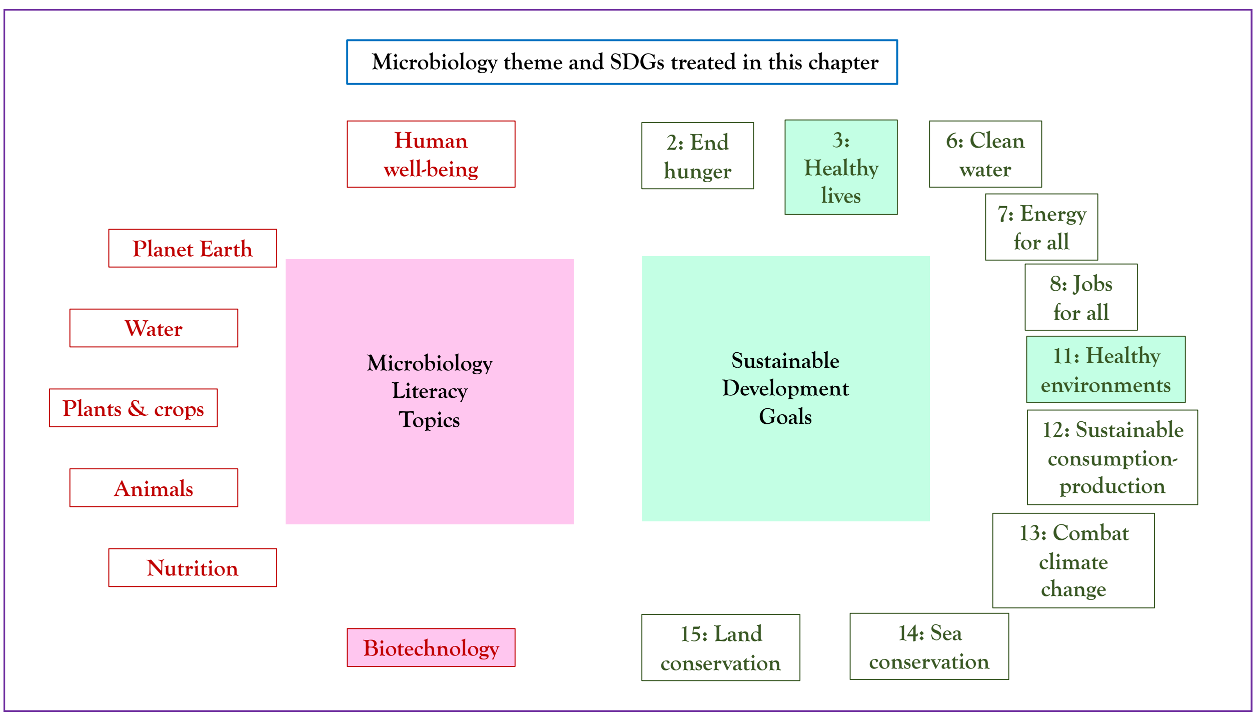
Microbial Sunscreens

Storyline

You may have heard that it is important to wear sunscreen lotion when you go outside; this is because sunscreens protect our skin from dangerous ultraviolet sun rays. Surely, not all organisms put on sunscreen as humans do. Instead, many forms of life use pigments. Pigments have multiple functions in biology, including visual communication, protection, and regulation of body temperature. In this case, pigments act as natural sunscreens, giving organisms their distinct colors along the way. These pigments function as sunscreens by absorbing radiation and dissipating it in form of heat. One pigment that helps protect organisms against too much UV sunlight is melanin. Melanin can be found on human skin, in plants, and also in microscopic fungi and bacteria! Microbial melanin not only protects against UV light but also against X-rays, gamma-rays, and a plethora of different environmental stresses, including heat stress. Scientists have slowly been learning how to use fungal melanin for our benefit. Fungal melanin's special properties can be used to clean up polluted wastewaters, for example. Scientists are currently working to see if fungal melanin can be used to protect astronauts from radiation while they are in space.

The Microbiology and Societal Context

The microbiology: microbial fungi; microbial adaptations to radiation stress; evolution; microbial stress response; fungal radioprotection. *Sustainability*: sustainable energy; biotechnology; space technology.



Microbial Sunscreens: the Microbiology

1. ***All life encounters and responds to radiation.*** Radiation is essential for life, but it can be harmful depending on the type and amount of exposure. On one hand, we need exposure to solar radiation to help us make vitamin D, which helps to build strong bones (see the Healthline article about some of the benefits of sunlight for more information). On the other hand, anyone who has gotten a sunburn knows that there can be a such thing as too much sunlight.

Biologists often use the term "stress" to describe any event that produces a response. Typically, when an organism is stressed, its response is crucial to its survival. Some examples of stress include extreme heat, extreme cold, or radiation. Radiation energy is a type of stress that all life has to respond to. Radiation is all around us and comes in the form of light or electromagnetic waves of different wavelengths (Figure 1). The electromagnetic spectrum includes wavelengths that we can see (like visible wavelengths), and wavelengths we cannot see but we feel as heat (like infrared wavelengths). The existence of such "invisible" wavelengths was discovered using special instruments (for a video journey about the history of these different electromagnetic waves see 'Limits of Light'). Although invisible, ultraviolet (UV) wavelengths emitted by our Sun can penetrate the Earth's atmosphere and cause the DNA of our skin cells to mutate. This can lead to skin cancer or melanoma. UV radiation can also trigger the accumulation of toxic, small molecules such as reactive oxygen species (ROS) which can also harm our bodies. Living organisms have evolved ways to respond and protect themselves against the stress induced by radiation energy (for more information, check out the electromagnetic spectrum video or radiation video).

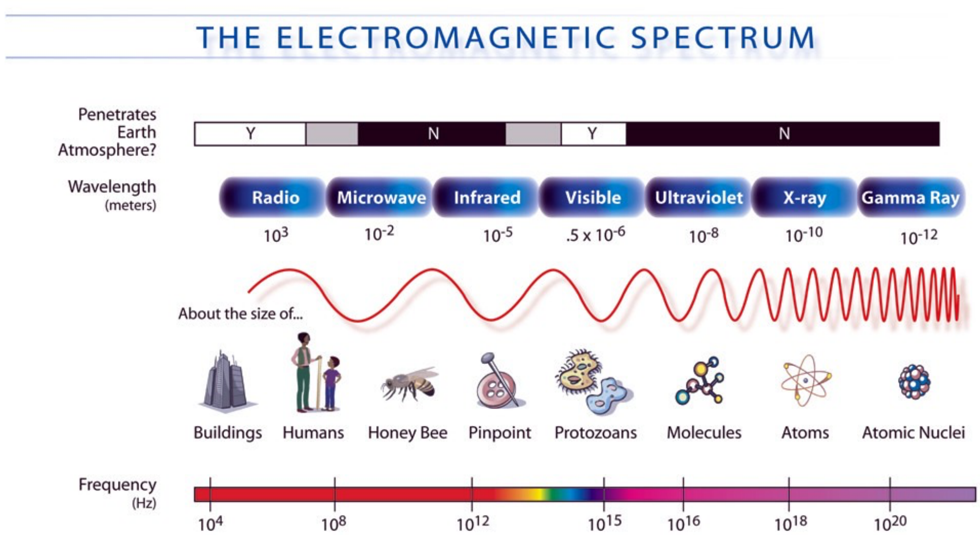


Figure 1. The electromagnetic spectrum. Electromagnetic waves are classified based on their wavelength: Radio waves, microwaves, infrared, visible, ultraviolet, X-rays, and Gamma rays. These rays have different properties in regards to their size, frequency, the temperature of bodies emitting the wavelength, and penetration of Earth's atmosphere. "Electromagnetic spectrum" by Allen Gathman is licensed under CC BY-NC-SA 2.0. Please note that the figure states that UV waves do not generally penetrate the Earth's atmosphere. However, longer UV waves can penetrate the Earth's atmosphere.

In addition to electromagnetic waves, radiation energy also exists in the form of atomic and subatomic particles traveling near the speed of light. This particulate radiation is known as cosmic radiation and can be extremely harmful to live organisms. Cosmic radiation comes from our Sun and other stars in space but cannot penetrate the Earth's magnetosphere. While humans on Earth need not to worry about cosmic radiation, it is a serious problem for astronauts traveling further into space. Particle radiation emitted by the Sun is also responsible for the Northern Lights (see the NASA Cosmic Radiation guide for more educational resources; further resources can be found at NOVA scienceNOW, Cosmic Perspective, Northern Lights).

2. Microbial pigments act as natural sunscreens protecting organisms from harmful radiation. You may have heard that it is important to wear sunscreen lotion when you go outside; this is because sunscreens protect our skin from damaging UV sun rays. Some sunscreens protect by absorbing the UV radiation and dissipating it in the form of heat. Other sunscreens work by reflecting the UV radiation; they contain small chemical compounds that make the radiation bounce back off of our skin the same way visible light bounces off of a white surface. That's why your nose or face might look a little white after putting on sunscreen (see the ThatPhysicsGirl and Veritasium videos for more information on sunscreens and UV).

Surely, not all organisms put on sunscreen as humans do! Instead, many forms of life use different pigments that act as natural sunscreens, giving organisms their distinct colors along the way. These pigments function by absorbing the radiation and dissipating it in form of heat. Most of these pigments, if not all, also act as antioxidants that neutralize dangerous reactive oxygen species (ROS).

Carotenoids are a family of orange-red pigments. Although they absorb UV light, they reflect the light that has longer wavelengths and looks red or orange to us (see Figure 1). You probably recognize carotenoids for the distinct color they give to carrots and tomatoes. A lot of people say that carrots are good for your vision because carotenoids can help protect your eyes from UV radiation by absorbing UV light and neutralizing ROS. This same molecule is found throughout the world of microbes, too! In microbes that use photosynthesis to make their food, carotenoids aid in the absorption of sunlight by protecting chlorophyll molecules.

Figure 2 is a picture of the Grand Prismatic Spring. It is located in Yellowstone National Park in the United States. The orange-red ring around the water comes from carotenoids found in algae and bacteria. During the summer months, when the sunlight levels are high, these microbes produce more carotenoids to protect themselves from UV rays.

Sometimes, the compounds that microbes use as sunscreen can be used as human sunscreen as well! Currently, scientists are working to produce sunscreens that use compounds called mycosporine-like amino acids (MAA) from Cyanobacteria and other marine microorganisms. Even though sunscreen protects humans from UV radiation, there are some environmental and health concerns that arise from certain synthetic compounds. Beginning in 2021, the state of Hawaii banned the sale of sunscreens using oxybenzone and octinoxate. These ingredients are good at absorbing UV rays but can also harm coral reefs and be absorbed into the body's bloodstream. In addition, the UV absorber para-aminobenzoic acid (PABA) is banned in Canada due to concerns that it may be slightly toxic in animal studies (read the Healthline article for more information). Using natural molecules like MAA may be a healthier and environmentally-friendly alternative to these compounds. MAA from the alga *Porphyra umbilicalis* is used in two commercial sunscreens to date: Helionori and Heliogard365 (see the LabRoots article for more information on these sunscreens).

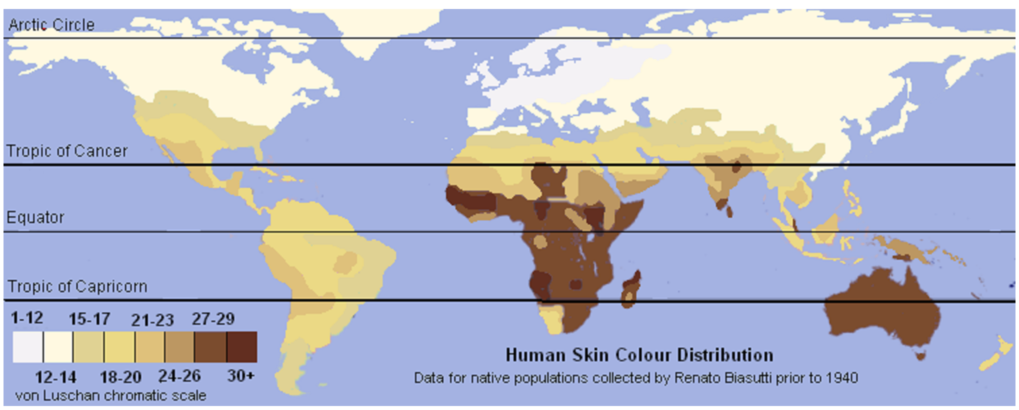
Figure 2. The Grand Prismatic Spring in Yellowstone National Park. The orange ring around the water, which becomes more apparent in sunny summer months, is attributed to pigmented microbes. "Grand Prismatic Spring - Yellowstone National Park, Wyoming" by Trodel is licensed under CC BY-SA 2.0.

3. Microbial melanins can protect microorganisms beyond UV radiation. You may have come home from a tan after a long day at the beach, especially if you forgot to put enough sunscreen on! This is due to a set of pigments in humans called melanins, which our bodies have been using to protect themselves from the sun's rays long before sunscreen was invented. Melanin can be found in our skin and hair, and it protects us by absorbing UV radiation and dissipating it as heat. Melanin also serves as an antioxidant, which means that it can neutralize ROS before they damage our bodies. There are two types of melanin in humans: eumelanin and pheomelanin. Pheomelanin produces yellow or reddish-brown pigments, such as those found in red hair or freckles. Eumelanin produces black or dark brown colors and is found in dark hair and dark skin shades. The amount of melanin humans produce can change over time. Think back to the last time you got a tan. This was because your body, recognizing that you were getting exposed to too much UV sunlight, began to create more melanin to protect you from absorbing too much UV radiation. For more information on melanin in general, check out the *Britannica* article.

Melanins are produced not just by humans, but by most animals and plants. One quick way to watch a plant melanize in order to protect itself is to submerge half a banana in warm water for about a minute (see the banana article and video for more information on this). Sure enough, its peel will start to melanize and turn brown! Like UV light, heat also produces reactive oxygen species. In the case of this experiment, the banana produced melanin where it needed to protect itself from the hot water. This melanin acted as an antioxidant that neutralized or absorbed the free radicals produced by the hot water. Fungi and other microorganisms also use melanin. Microbial fungi use melanin just like humans do. However, in these microbes melanin does more than just protect against UV radiation. Fungal melanin can protect fungi from the stress that comes from other kinds of radiation as well. Protection from radiation is known as photoprotection. Melanin can protect fungi from X-ray and gamma-ray radiation, making many fungi very adept at surviving harsh environments, such as the damaged nuclear reactor at Chernobyl. While most forms of life try to avoid radiation whenever possible, melanized fungi have been found to grow towards radiation. Such a phenomenon is known as radiotropism, or attraction to radiation. Melanin not only protects fungi against radiation but also appears to mediate harvesting of the radiation it absorbs for fungal growth. The details about how melanin can allow for this harvesting remain to be discovered.

Box 1: The Diversity of Human Skin Color

As certain human populations migrated out of Africa and into places with less direct sunlight, such as Europe or Asia, they encountered a different problem. Now there was too little sunlight to synthesize vitamin D! Their bodies had to learn to produce less melanin so that more light could pass through the skin to produce the vitamin D. Vitamin D is needed to build strong bones and absorb vital nutrients. This led to individuals with lighter skin and hair tones. Depending on where your ancestors lived, your skin and hair could be any one of a plethora of beautiful shades!



An approximate map of human skin colors based on latitude. "File:Unlabeled Renatto Luschan Skin color map.svg" by !Original: The OgreVector: Crisco 1492 is licensed under CC BY-SA 3.0

(For more resources, see the KidsHealth article on skin color, the TEDED video on skin color, or the Nina Jablonski TED Talk)

4. Scientists are working to use fungal melanin to protect humans from radiation. It took humans a very long time to adapt our melanization patterns to the Earth's climate. We don't want to wait that long to start exploring space! Nevertheless, cosmic radiation is dangerous to astronauts as it can damage cells. Space radiation can also interfere with electronics. How can we make more lightweight and efficient protection devices? Biology might be able to help.

Scientists were able to extract melanin from the yeast *Cryptococcus neoformans* and are currently testing it to see how well it can stand up to the radiation in space. One such experiment is ongoing at the International Space Station. It is possible that a black coating on a spacecraft and spacesuits derived from fungal cells may help realize the future of space travel (see the melanin in space article for more information). This radiation protection could also be adapted to help individuals on Earth. Cancer patients are often exposed to large amounts of radiation while they are receiving treatment, and doctors are exposed to radiation when they diagnose and treat patients. Fungal melanin may one day contribute to their protection as well.

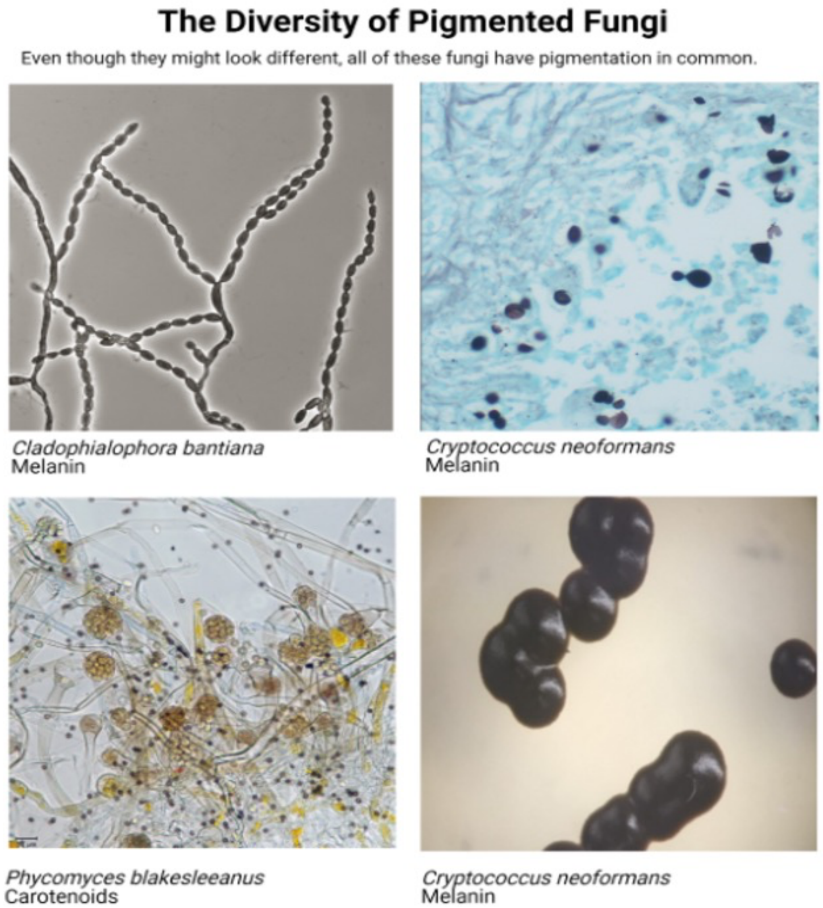


Figure 3. A panel of different melanized fungi. Figure created in Biorender.com. "Cryptococcosis - GMS stain" by Pulmonary Pathology is licensed under CC BY-SA 2.0. "File:Cladophialophora bantiana UAMH10767.jpg" by Medmyco is licensed under CC BY-SA 4.0. "Sporangia" by Cornell Fungi is licensed under CC BY-NC-SA 2.0.

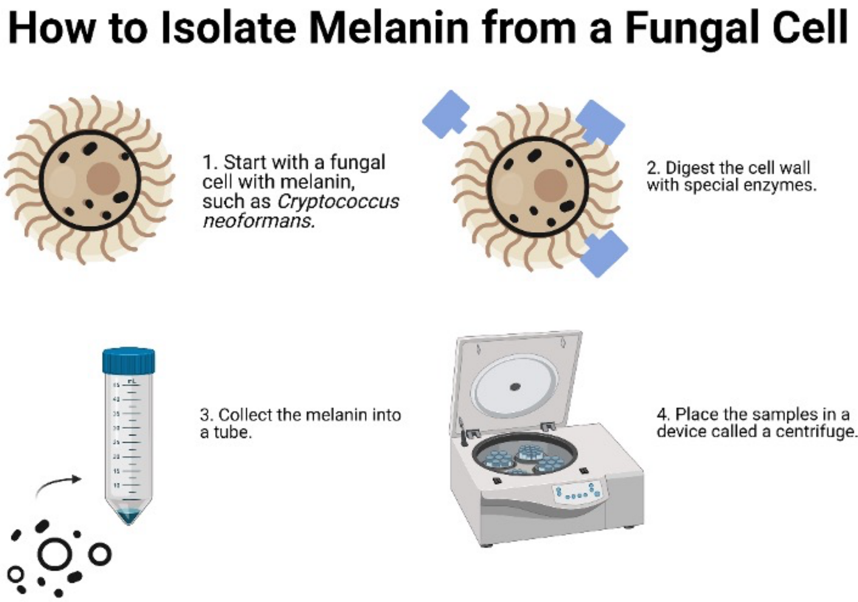


Figure 4. Schematic for isolation of melanin from a fungal biomass. Figure created in biorender.com. Digestive enzymes are represented as blue boxes.

5. Microbial pigments serve many biological functions. Microbial pigments don't just protect organisms from radiation. The color produced by pigmented microbes can visually attract other organisms like insects which then help the microbe spread and reproduce. Microbial pigments also serve in radiation energy capture, using the absorbed radiation for growth (photosynthesis) or warmth (thermoregulation). Pigments like melanin can also prevent fungi from drying out by increasing a cell's ability to absorb water. This helps fungi survive in dry environments. Melanized fungi placed in warm water have been shown to have better survival outcomes than non-melanized fungi. This speaks to melanin's ability to help microbial organisms survive hot environments. One such hot environment is the human body, where the internal temperature is a constant 37℃. To infect humans and cause disease, microorganisms have to survive at our high temperatures. Because melanin can protect fungi against temperature stress and other types of stresses, melanin plays an important role in the ability of melanized microorganisms to infect humans and withstand the human immune system (for the many functions of fungal melanin, see the article on the functions of fungal melanin beyond virulence).

6. Can we use microbial pigments for restoring ecosystems? Bioremediation refers to a process that helps to restore a polluted area by introducing a microbe that can remove or immobilize the pollutants in question. Heavy metals are one such pollutant that can seep into natural environments from landfills, animal waste, and runoff. When they accumulate in large quantities, these heavy metals can be dangerous to both animals in the habitat and the humans that eat those animals. Because metals cannot be degraded or destroyed, they tend to persist in an environment for a long time (see the heavy metal pollution article for more information).

Melanin's unique chemical properties give it the ability to bind various metals from the environment such as copper, calcium, magnesium, and zinc. In the environment, fungi need to absorb these crucial metals for their survival. While fungi want to collect metals with melanin, humans want to get rid of metals in waterways. Some scientists have been working to develop melanin-studded membranes to remove heavy metals from polluted water and have seen success.

Nearly 80% of the lead in a water sample was removed by these melanized membranes (see the scientific paper for more advanced reading).

Another pollutant of concern surrounds that of pharmaceuticals in waterways. Sometimes, bodies of water can become contaminated with diverse prescription or over-the-counter drugs that make their way into the waterway. This can happen if an individual flushes their unused drugs down the toilet, or if trace amounts of a drug remain in human urine. Although there is not yet conclusive evidence that this pollution is harming humans, the pollution has been shown to cause severe effects on aquatic life (see the pharmaceutical pollution article for more information). However, melanin may also be able to absorb these drugs and remove them from waterways. Melanized *E. coli* bacteria effectively absorbed 88% of the chloroquine in a water sample, for example (see the scientific paper for more advanced reading).

7. **Microbial pigments play a key role in the melting of polar ice.** The melting of polar ice in Antarctica and the Arctic is an urgent problem. When the ice melts, it pushes fresh cold water into the oceans. Tons of cold-water streams can change the normal flow of oceans around the globe, which is important for weather elsewhere in the globe. Melting of ice also changes the flow of air which can cause extreme weather changes, particularly in northern and southern countries. Many pigmented microorganisms (algae, fungi, and bacteria) are able to grow on ice surfaces. These microbes also produce pigments as sunscreens and for photosynthesis, but as the pigment absorbs sunlight, it also warms up the ice; increasing its melting. Scientists are actively working on this complex problem, looking to understand what drives the growth and pigmentation of these microorganisms, as well as, ways to predict their impact in the future of the world's climate. (See movie Ice Alive by Rolex Laureate Joseph Cook on how pigmented microbes are increasing the melting of polar ice and could be adding to climate change).

Relevance for Sustainable Development Goals and Grand Challenges
(https://sdgs.un.org/2030agenda)

The microbial dimension of melanin relates to several SDGs (*microbial aspects in italics*), including

- **Goal 3. Ensure healthy lives and promote well-being for all at all ages** (*microbial stress response, microbes adapting to their environment)* Fungal melanin has the potential to help humans withstand radiation both on Earth and in space.
- **Goal 14. Conserve and sustainably use the oceans, seas, and marine resources for sustainable development** (*remediate pollution)*. Fungal melanin's ability to bind heavy metals can help them play a role in the bioremediation of polluted ecosystems, including oceans. Microbial melanin may be able to be used in sunscreens as alternatives to ingredients that may harm humans and marine life.

Potential Implications for Decisions

1. ***Individual***

a. Should I cover up or use sunscreen to protect my skin from dangerous UV light when I go out in the sun? What are the advantages and disadvantages of using sunscreen? (*Advantages: UV* *protection, skin cancer prevention. Disadvantages: environmental/coral concern, health concern of various ingredients*)

2. ***National Policies***
   a. Education about the health dangers of UV irradiation and need to reduce exposure
   b. Support for biotechnology research on new sunscreens
   c. Anti-Pollution policies
   d. Environmental protection agencies to promote bioremediation

Pupil Participation

1. ***Class discussion of the issues associated with sunscreens***

a. Do you or does your family use sunscreen? What kind of sunscreen (lotion, stick, spray) or brand of sunscreen do they use? What kind do you prefer?

b. What is the right way to use sunscreen? Are you applying sunscreen the right way?

c. What kind of benefits are there for different SPF factors?

d. How is human melanization similar to melanization in other organisms? How is it different?

e. What different colors of organisms (plants, animals) can you see around you? Why do you think they are that color?

f. What kind of technology could benefit from fungal melanin?

g. If melanin does protect astronauts from space radiation, how can they use it to protect themselves?

2. ***Pupil stakeholder awareness***

a. Melanins are powerful molecules with powerful protective properties. If you could use melanin to make any invention, what would you choose? What about other microbial pigments?

3. ***Exercises***

a. Bring different sunscreen brands to class and compare the ingredients list. Look for ingredients such as MAA (mycosporine-like amino acid), which are often derived from bacteria!

b. Try the banana experiment mentioned in the main body! Submerge half a banana in hot water for one minute and watch it melanize!

c. If possible, take a nature walk and ask students to observe various plants and animals encountered along the way. Did it look like certain animals had more melanin than others?

The Evidence Base, Further Reading and Teaching Aids

Younger Grades (Ages 5-12)
The Science of Skin Color: TEDED
Kids-Health: Your Skin and You
Physics for Kids: Types of Electromagnetic Waves

Melanin and Bananas: Experiments
NASA Cosmic Radiation Guide

- Note Activity IIIc is an experiment on shielding yeast from UV Radiation
  Northern Lights

Older Grades (Ages 13+)
Radiation: SciShow
What Are the Benefits of Sunlight?
MAA Sunscreen: LabRoots
Melanin: Britannica Article
Nina Jablonski breaks the illusion of skin in every color
Functions of Fungal Melanin Beyond Virulence: Scientific Article
Why do Apples and Bananas Turn Brown? Fruit Melanization Video
Healthline: Sunscreen Ingredients to Look for and Avoid
Heavy Metal Pollution Article
Melanin and Heavy Metal Binding Paper
Harvard Pharmaceutical Pollution Article
Melanized *E. coli* and Bioremediation
Melanin in Space Article
That Physics Girl: Sunscreen Under UV Cameras
Veritasium: The World Under UV Cameras
Ice Alive by Rolex Laureate Joseph Cook

Glossary

Bioremediation: the restoration of a polluted natural environment via the introduction of a microorganism to degrade the environment
Carotenoids: yellow, orange, and red pigments produced to protect organisms from radiation
Chlorophyll: green pigments found in bacteria, algae, and plants that allow organisms to absorb sunlight for photosynthesis.
International Space Station: a modular, multinational space station in the Earth's orbit that is used for scientific research.
Melanin: a set of diverse polymeric pigments found through the biosphere with multiple biological functions.
Mycosporine-like Amino Acids (MAA): a widespread set of compounds in microbes and marine environments with well-known sun protection properties.
Photoprotection: protection from radiation
Photosynthesis: the biochemical process some organisms use to turn sunlight into food.
Radiation: energy in the form of electromagnetic ways or atomic/subatomic particles. Electromagnetic radiation can include radio waves, microwaves, ultraviolet waves, and everything in between.
Radiotropism: an organism's attraction to radiation, which can manifest in a tendency to grow towards radiation sources.

Reactive Oxygen Species (ROS): small molecules containing oxygen that are chemically unstable and can react with biomolecules inside the cells, altering their structure and function. ROS are largely formed when radiation causes the ionization of water molecules inside the cell.
SPF: short for sun protection factor, a number that corresponds to how much sun protection a particular sunscreen offers.
Stress: any event that elicits a reaction from an organism.