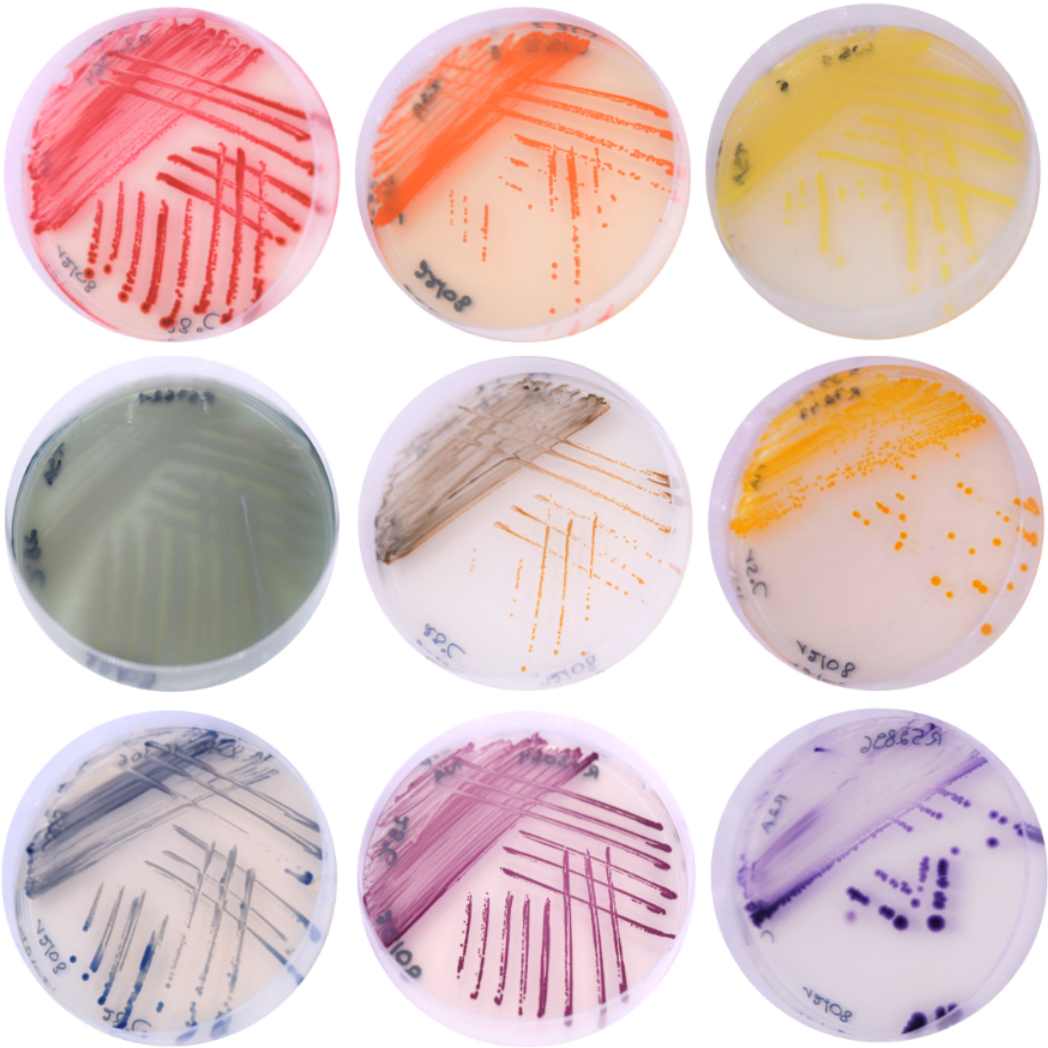
Microbes as Sources of Dyes and Pigments

Miss: I see colours in flowers and in butterflies. Where else does nature hide its colors?



Emmelie De Ridder, Fleur Willekens and Anne Willems

Laboratory of Microbiology, Department of Biochemistry and Microbiology,
Ghent University, Ghent, Belgium

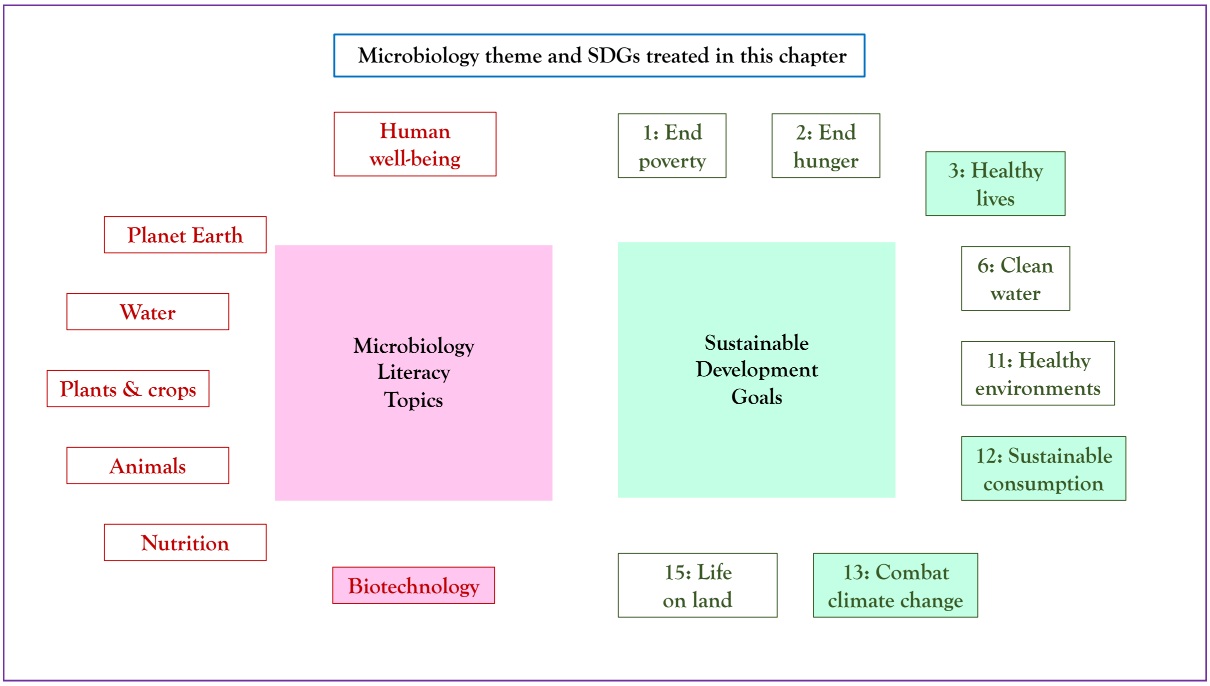
Microbes as Sources of Dyes and Pigments

Storyline

Long before synthetic dyes existed, people relied on pigments from nature to tell stories, shape their surroundings and express identity. Early humans used mineral pigments to paint cave walls, while later civilizations extracted colors from plants and animals to dye textiles, decorate objects and enhance their appearance. Today, color still defines much of what we see and use, from clothing and packaging to food and cosmetics. Yet the vibrant palette surrounding us largely comes from synthetic dyes developed during the industrial age. These chemicals made color cheaper, brighter and more consistent, transforming the color market. However, growing awareness of the environmental and health impacts of some synthetic dyes has renewed interest in natural pigments. One surprising source of natural color lies in the microscopic world. Many bacteria and fungi produce striking pigments in shades of red, pink, orange, yellow, green, blue, purple, brown and black. These colors are there for a reason: they help microorganisms survive harsh conditions, communicate with one another and compete with rival microbes. In recent years, scientists have begun exploring how these tiny pigment producers can serve human needs. By cultivating microbes in controlled environments, we can generate vibrant, functional colors with a limited environmental footprint, opening new opportunities for how modern society creates and uses color.

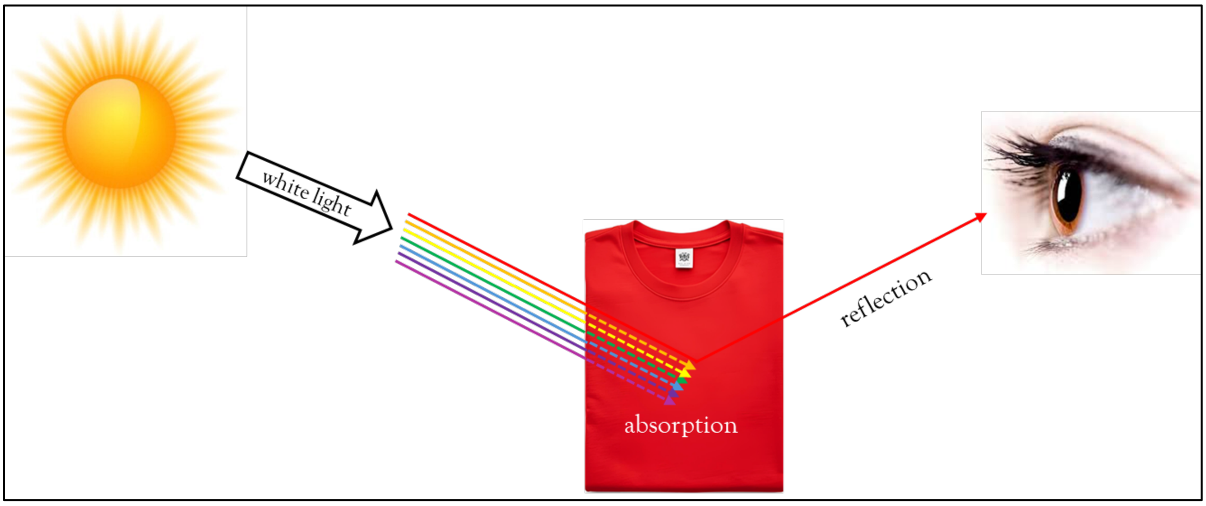
The Microbiology and Societal context

*The microbiology***:** microbial pigments and their biological functions; microbial stress responses; ecological roles of pigments (UV protection, communication, competition). *Sustainability:* environmental and health challenges of synthetic dyes; microbial pigments as renewable industrial resources; sustainable dye production; biotechnology for natural colorants *Other themes:* microbial pigments in food, textiles, and health applications.



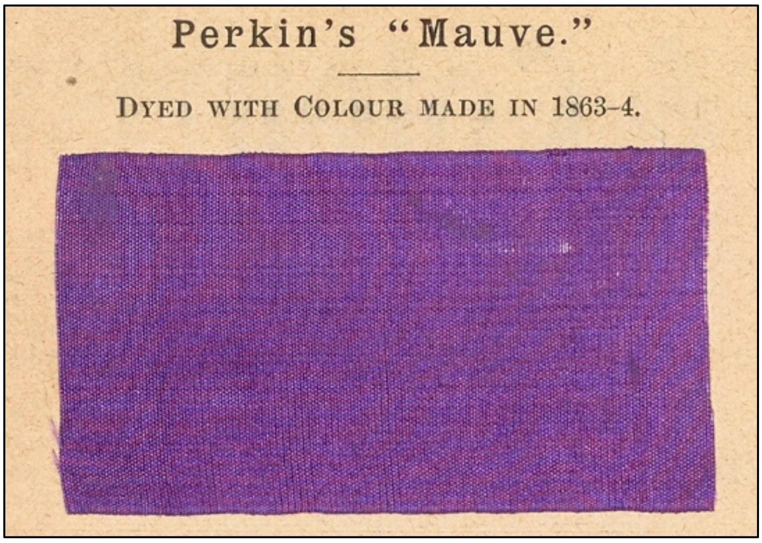
Microbes as Sources of Dyes and Pigments: the Microbiology

1. Understanding color and colorants. Color surrounds us in every aspect of life: from the clothes we wear to the food we eat and the objects we use. But what is color, really? At its core, color comes from molecules called chromophores, which absorb some wavelengths of visible light and reflect others. The reflected light reaches our eyes and our brain interprets it as color. Different chromophores absorb different parts of the visible spectrum, creating the rich variety of shades we see around us. For example, plant leaves appear green because the chromophore in chlorophyll absorbs mainly in the red and blue light and reflects green light back to our eyes. Substances that give materials their color are called colorants. There are two major types: dyes and pigments. Dyes are soluble molecules that soak into a material, often producing translucent or subtle coloring. Pigments, in contrast, are tiny solid particles that do not dissolve and that produce opaque, intense colors. Both dyes and pigments can be natural (made by plants, animals, fungi or bacteria) or synthetic (produced in laboratories). Natural pigments from living organisms and most synthetic dyes are carbon-based and called organic, while mineral-based pigments are usually inorganic, such as gold or silver. These different colorants form the foundation of the colors humans have used for centuries, and the same principles explain the colors created by microbes.



How light absorption and reflection create color. White light contains all visible wavelengths (= all colors). The chromophores in the red dye of the T-shirt absorb most wavelengths and reflects primarily red light, which is detected by the eye and perceived as color. Images licensed from iStock.

2. The synthetic dye revolution and its cost. From the Industrial Revolution onward, populations grew rapidly and the demand for abundant, affordable and durable colors grew with them. Traditional natural pigments from plant or animal sources, while used for centuries, were difficult to standardize and often faded quickly when exposed to light, heat or air. A turning point came in 1856 when William Henry Perkin accidentally discovered the first synthetic dye, the bright purple mauveine. This discovery triggered a true color revolution. Within decades, thousands of synthetic dyes were developed, offering bright, reproducible shades that were cheaper to produce and more stable than natural alternatives. However, this success came with substantial environmental and health costs. Synthetic dyes are generally made from non-renewable petrochemicals and are highly resistant to natural degradation, allowing them to persist in the environment. The manufacturing and use of synthetic dyes have also been linked to skin irritation, respiratory problems and long-term heath issues. Growing awareness of these impacts has intensified the search for safer and more sustainable sources of color.

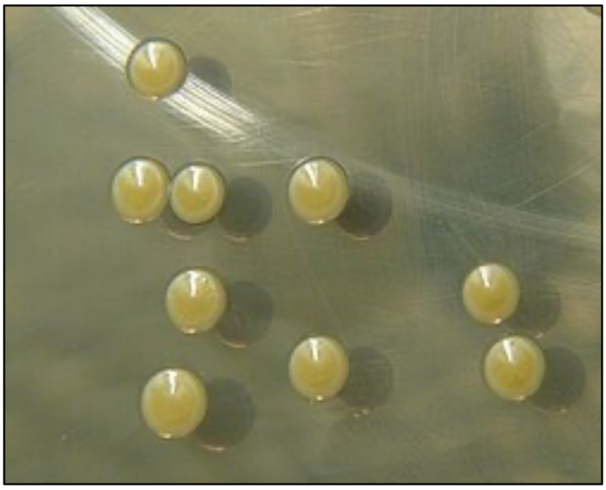


Sample of Perkin's Mauve (= mauveine), the first synthetic dye. Discovered by William Henry Perkin. Image courtesy of Science History Institute.

3. Natural pigment sources and microbial potential. In this search for alternatives, attention first returned to familiar biological sources such as plants and algae. For centuries, plants have supplied many pigments used in textiles and food, but these colors come with important limitations. Many plant pigments are chemically unstable and fade quickly. Their production depends on seasonal and climatic conditions and large-scale cultivation requires significant agricultural land and resources. Extracting pigments from plants is also often labor-intensive and costly. Algae can grow faster than terrestrial plants and offer higher productivity, but scaling up algal cultivation remains technically challenging and requires carefully controlled conditions. These limitations have led researchers to explore a smaller but very versatile source of natural color: microorganisms. Bacteria and fungi can be grown year-round in controlled fermentation systems that are already widely used in industrial biotechnology. Many microbial pigments are remarkably stable under extreme temperatures and pH conditions. In addition, microbes grow quickly and can be easily modified through genetic engineering to enhance pigment production. Together, these advantages make microbial pigments an increasingly attractive and sustainable source of natural color.

4. Why bacteria are colorful: key pigments and their roles. Bacteria produce a wide variety of pigments that can be broadly grouped into photosynthetic and non-photosynthetic types. Like plants, some bacteria use chlorophyll (or its close relative bacteriochlorophyll) to capture light energy and carry out photosynthesis. These pigments allow them to thrive in environments shaped by light availability, such as the sunlit surface layers of lakes and oceans.

All known photosynthetic bacteria also contain carotenoids, the yellow, orange, pink and red pigments familiar from carrots and tomatoes. In these bacteria, carotenoids play a dual role: they broaden the range of light that can be used for photosynthesis, while also protecting cells from damage caused by excess light and reactive oxygen species (ROS). These highly reactive, oxygen-containing molecules are generated by ultraviolet light radiation and can damage important cellular components such as DNA and proteins. Because carotenoids act as antioxidants that reduce oxidative stress, they are also common in non-photosynthetic bacteria. A well-known example is the human pathogen *Staphylococcus aureus*, which produces a yellow-golden carotenoid that helps it resist oxidative attacks from the host immune system.



Colonies of *Staphylococcus aureus.* Its characteristic golden-yellow color is due to the production of the carotenoid staphyloxanthin. Image credit: HansN., Wikimedia Commons.

Carotenoids can also help bacteria survive temperature extremes by stabilizing cell membranes. In Antarctic bacteria, for example, they help maintain membrane flexibility in freezing conditions. Other pigments support bacterial survival in different ways. Melanin, the brown-black pigment also found in human skin, acts as a shield against ultraviolet light and ionizing radiation and can bind toxic metals, reducing their harmful effects on the cell. Violacein, a striking dark purple pigment, gives bacteria an advantage over competitors because of its antimicrobial activity. It also helps bacteria coordinate group behaviors like biofilm formation.

5. From microbes to market. Beyond their ecological roles, microbial pigments are finding uses in a range of human industries. Violacein and melanin, for example, can dye cotton, silk, wool and even synthetic fabrics, offering a sustainable alternative to conventional synthetic dyes. In cosmetics, carotenoids are increasingly valued for their ability to protect the skin from damage by ultraviolet light and slow premature aging. The food industry can also benefit from microbial colors: carotenoids like β-carotene and astaxanthin add appealing red, orange and yellow colors to food and beverages, while providing nutritional and antioxidant benefits. Even packaging can benefit from microbial pigments: melanin can shield materials from light, helping preserve quality and extend shelf-life. Beyond coloring, many pigments, including violacein, show antibacterial, antifungal, antiviral, and even anticancer activity, highlighting their potential in medicine and therapeutics. In agriculture, microbial pigments could act as natural pesticides, offering an eco-friendly way to protect crops. Clearly, these tiny microbes can have a big, colorful impact on our daily lives.

Relevance to Sustainable Development Goals and Grand Challenges

Microbial pigments are highly relevant to several Sustainable Development Goals (SDGs), with their microbial origin playing a key role in each:

- **Goal 3. Ensure healthy lives and promote well-being for all at all ages:** Many microbial pigments exhibit antioxidant, antimicrobial, antiviral, and anticancer properties. Their natural protective functions, evolved in microbes to withstand environmental stress, can be used to improve human health through pharmaceuticals, nutraceuticals, and skin-protective products.
- **Goal 12. Ensure sustainable consumption and production patterns:** Microbial pigments offer sustainable alternatives to synthetic dyes and additives in textiles, food, and cosmetics. By reducing reliance on petrochemical-based colorants, they lower the ecological footprint of industrial production and minimize toxic chemical release.
- **Goal 13. Take urgent action to combat climate change and its impacts:** Many conventional synthetic dyes are derived from non-renewable petrochemicals and their production can contribute to pollution and greenhouse gas emissions. In contrast, pigments produced by microbes in controlled fermentation systems rely on renewable biological resources and are often less resource-intensive than plant cultivation, reducing land and water use while supporting more sustainable production practices in the face of climate challenges.

Potential Implications for Decisions

1. ***Individual***
   a. When choosing clothing, should I favor those dyed with natural colorants over those colored with synthetics?

2. ***Community policies***
   a. Should the local environmental authority encourage community procurement departments to favor products colored with natural dyes and pigments?
   b. Should local authorities introduce awareness campaigns about the pros and contras of natural versus synthetic colorants?

3. ***National policies***
   a. Should there be national policies that incentivise use of natural colorants and disincentivse the use of sysnthetics, e.g. by subsidies/taxes?
   b. Should funding agencies prioritise research and development programmes on microbial colorants?
   c. Should the issue of natural colorants versus synthetics become part of sustainability education?

Pupil Participation

1. Class discussions

a. Where do you see bright colors in nature around you (plants, animals, fungi)? Why do you think living organisms produce pigments?
b. Microorganisms are often invisible to us. Which colors do you think they can have and where could they live?
c. How might pigments help microbes survive in harsh environments such as strong sunlight or extreme cold?
d. Do you use products that contain natural colors (food, cosmetics, textiles)? Why might natural pigments be preferred over synthetic ones?

2. Pupil stakeholder awareness

a. Why is it important to develop more sustainable alternatives to synthetic dyes?
b. How could microbial pigments change the way we produce food, clothing, or cosmetics in the future?
c. How might using microbial pigments benefit both people and the environment?

3. Exercises

a. List everyday products that use synthetic colors. Which of these could potentially use natural microbial pigments instead? Explain your choices.
b. Compare natural colors in fruits and vegetables (e.g. carrots, tomatoes, berries). Research which pigments cause these colors and what their biological roles are.
c. Imagine you are designing a new eco-friendly product using microbial pigments. Describe the product and explain why pigments from microbes would be useful.

The Evidence Base, Further Reading and Teaching Aids

Barreto, J. V. de O., Casanova, L. M., Junior, A. N., Reis-Mansur, M. C. P. P., & Vermelho, A. B. (2023). Microbial Pigments: Major Groups and Industrial Applications. Microorganisms 2023, Vol. 11, Page 2920, 11(12), 2920. https://doi.org/10.3390/microorganisms11122920
Huang, X., Gan, L., He, Z., Jiang, G., & He, T. (2024). Bacterial Pigments as a Promising Alternative to Synthetic Colorants: From Fundamentals to Applications. Journal of Microbiology and Biotechnology, 34(11), 2153. https://doi.org/10.4014/jmb.2404.04018
Tang, Q., Li, Z., Chen, N., Luo, X., & Zhao, Q. (2025). Natural pigments derived from plants and microorganisms: classification, biosynthesis, and applications. Plant Biotechnology Journal, 23(2), 592–614. https://doi.org/10.1111/pbi.14522
BioChroma - Flanders' FOOD
Bacterial Pigments: Types, Functions, and Applications - Biology Insights

Glossary

Antioxidant: substance that prevents or slows damage caused by reactive molecules such as reactive oxygen species (ROS).
Biofilm: communal structure of microorganisms that adhere to living or inert surfaces and are encased in a protective coating that they produce.
Biotechnology: scientific use of living organisms, biological systems or their components to produce products and develop technologies that improve human life.
Carotenoids: class of mainly yellow, orange and red pigments produced by plants, algae and microbes, responsible for the color of many plant organs such as carrots, tomatoes and autumn leaves.
Chlorophyll: green pigment present in plants, algae and cyanobacteria that absorbs light energy for photosynthesis.
Chromophore: specific part of a molecule that absorbs certain wavelengths of visible light and gives a substance its color.
Fermentation: metabolic process in which microbes break down nutrients such as sugars into simpler substances such as acids, gases or alcohol.

Genetic engineering: the deliberate modification of the characteristics of an organism by modifying its genetic material.
Ionizing radiation: a type of high-energy radiation with sufficient energy to break molecular bonds and damage DNA within living tissues.
Oxidative stress: a state of imbalance between the production of ROS and the cell's ability to neutralize them.
Pathogen: a bacterium, virus, or other microorganism that can cause disease.
Petrochemical: chemical substance obtained from petroleum or natural gas.
Photosynthesis: biological process by which plants, algae and certain bacteria convert light energy into chemical energy, transforming carbon dioxide and water into sugars and releasing oxygen as a byproduct.
Reactive oxygen species (ROS): unstable oxygen-containing molecules that easily react with other molecules and can damage DNA, RNA and proteins when they accumulate in cells.
Sustainable: able to be maintained long-term without harming the environment or exhausting natural resources.
Synthetic dye: human-made coloring agent produced through chemical synthesis, typically derived from coal tar or petroleum.