A learner-centric microbiology education framework

Recycling to Reincarnation

"The nature guy on TV said some of my atoms might have once been part of a dinosaur! But if I'm not a dino now ... does that mean we turn into something new when we die?"

Lord of Death and Desire, clutches a Wheel of Reincarnation, Dazu Rock Carvings, Chongqing, China Mara. https://commons.wikimedia.org/wiki/File:Buddhist_Wheel_of_Life.jpg#/media/File:Buddhist_Wheel_of_Life.jpg

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Recycling to Reincarnation

Storyline

Why Recycle? The Real Reason (Beyond Just Saving the Planet). We all know recycling helps keep the planet clean. Without it, trash would pile up until we'd be wading through garbage just to find our shoes. Gross, right?

But here's the cool part: recycling is how nature keeps life going. Living things—plants, animals, even people—wear out. Cells break down, bodies age, and eventually, life ends. But the tiny building blocks that make us—*atoms*—don't wear out. They're super tough and can be reused again and again.

So, the carbon in your hand might have once been part of a dinosaur, a tree, or even a volcano! Nature takes these atoms and rearranges them to build new life—like using Lego pieces to make endless creations. Recycling is not just about trash—it is nature's way of rebuilding life, over and over again.

So now, let's think about YOU in relation to all this recycling. If nature reuses atoms to build new life, then the atoms in your body have been on an incredible journey. They've traveled through oceans, forests, animals, and even the air. You're part of a much bigger story—one that connects you to everything that's ever lived. Across cultures and centuries, people have wondered about this deep connection. From Hinduism's cycle of rebirth to ancient Greek ideas of transformation, many traditions believe that life continues in new forms, carrying pieces of the past into the future.

What is Reincarnation? The term *reincarnation* is derived from Latin roots, combining *re-* meaning "again" with *incarnare*, meaning "to make flesh." It refers to the belief that an aspect of a living being—often interpreted as the soul or consciousness—is reborn into a new physical form after death. In ancient Greek thought, the concept was known as *metempsychosis* (μετεμψύχωσις), while in Indian religions such as Hinduism and Buddhism, it is closely tied to the cycle of *samsara*, or continuous rebirth. The word *reincarnation* entered the English lexicon in the 19th century and has since been used to describe various interpretations of life's cyclical nature. Depending on the cultural or religious context, reincarnation carries different nuances, but it generally reflects a belief in continuity beyond a single lifetime.

In this story, we do not seek to challenge any cultural or religious beliefs—or lack thereof—about reincarnation. Instead, we offer a scientific lens to explore a different kind of reincarnation: one grounded in matter—atoms, molecules, microbes and communities—rather than souls and identities. This version does not require spirits or magic, but it's just as amazing. Let's journey into the science of how life recycles itself—and how, in a very material way, we—the community of life, including people—are constantly being reborn.

The Microbiology and Societal Context

Microbiology: The human microbiome plays a vital role in health during life, but after death, these microbes shift into the **necrobiome**, initiating decomposition. The **thanatobiome**—a specialized microbial community—breaks down tissues, recycling nutrients back into the soil. Soil microbes, including bacteria and fungi, incorporate these nutrients, supporting plant growth and sustaining ecosystems. This microbial cycling means atoms from a human body may eventually become part of other organisms, from plants to animals, in a continuous loop.

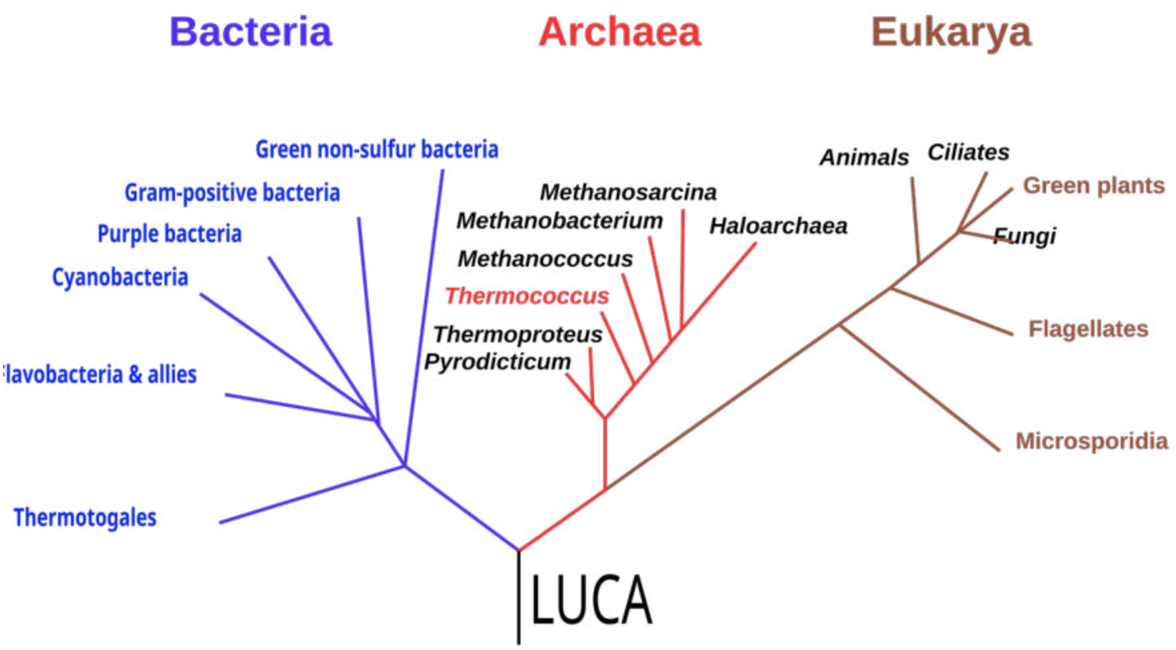
Industrial burial practices (e.g., embalming fluids) can disrupt microbial decomposition and contribute to soil and groundwater pollution. Decomposing organic matter releases greenhouse gases (methane, CO_2), linking death practices to climate change.
Societal Context: Many cultures and religions, such as Hinduism and Buddhism, embrace the concept of reincarnation, viewing death as a transformation rather than an endpoint. Indigenous traditions often emphasize returning to the Earth, with burial practices that support ecological balance. Economic factors influence funeral choices, with eco-friendly options often being more affordable but less culturally entrenched. Ethical debates arise over whether humans have a responsibility to minimize their ecological footprint even in death.
Sustainability Issues: Modern funeral industries face sustainability challenges, as conventional burials and cremation have significant environmental costs. Emerging alternatives, such as *green burials* (e.g., biodegradable shrouds, mushroom suits, or tree pod burials), aim to reduce harm and promote nutrient cycling (EarthFuneral, 2025). Health & Environment: Toxic embalming chemicals contaminate soil, while natural decomposition supports healthy ecosystems. *Food & Energy:* Decomposed organic matter enriches soil, reducing the need for synthetic fertilizers in agriculture. *Economy & Employment:* The funeral industry must adapt to demand for sustainable practices, creating new green jobs. *Pollution & Climate Change:* Burial practices affect greenhouse gas emissions, making eco-friendly death care a climate mitigation strategy.

Recycling to Reincarnation: the Microbiology

1. ***Reincarnation begins with microbes, not mysticism.*** If we trace the line of continuity between lives—the scientific story of how living things change and pass on their traits—we arrive at evolution. And if we follow that line all the way back to the beginning of life on Earth, the story of who and what we are becomes far more fascinating than we might expect. We may be familiar with the idea of the "tree of life"—a branching diagram that starts at the origin of life and spreads out into all the different species that now exist in the biosphere.

But modern evolutionary science suggests that this image is too simple. Instead of a single tree, it's more like a forest of trees whose branches connect and intertwine, forming a vast web of life. This interconnectedness becomes especially fascinating when we trace it all the way back to the microbial world, where life began and where the roots of our own biology still run deep.

As Carl Woese and George Fox revealed in their groundbreaking 1977 paper, life is not simply divided into prokaryotes and eukaryotes, but into three domains: Bacteria, Archaea, and Eukarya (Woese and Fox, 1977). Molecular phylogenetics has since shown that eukaryotes—organisms like us—are deeply intertwined with these ancient microbial lineages. Our cells are mosaics, containing both archaeal and bacterial features, and our mitochondria—the powerhouses of our cells—descend from once free-living alphaproteobacteria. In a very real sense, we are the evolutionary descendants of microbes. They are our ancient parents, and they continue to accompany us on our evolutionary journey.



A phylogenetic tree based on rRNA data, emphasizing the separation of bacteria, archaea, and eukarya as proposed by Carl Woese et al. in 1990 with LUCA, the hypothetical last universal common ancestor. Image courtsey Wikimedia Commons.

2. ***The Material Principles of Recycling Life.*** Life is built from a handful of essential elements: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P) and sulphur (S)—along with a few others in smaller quantities. These elements combine in sophisticated ways to form the complex organic compounds that make up every living organism. For instance, water, which makes up more than half of our bodies, is essential for nearly every biological process. Proteins carry out most of the metabolic functions in our cells and serve as structural, regulatory, and organizational molecules. Lipids and fats, together with proteins, form the membranes that enclose our cells, controlling what enters and exits, and compartments within them to house specialised functions or to separate incompatible activities, while also acting as energy reserves. Nucleotides, the building blocks of DNA and RNA, store and transmit our genetic information, while sugars (or carbohydrates) serve as the primary fuel, speedily providing energy to power cellular activities.

When living things die, their bodies do not simply disappear. Instead, they undergo a remarkable transformation: they are broken down into their basic components and reused by other life forms. This is biological recycling, and it begins at the cellular level. When cells die, they are dismantled, and their parts are repurposed to build new cells. This process happens constantly—even within our own bodies.

In fact, every time we eat, we participate in this recycling. When we consume a carrot, for example, our digestive system breaks it down into proteins, fats, and sugars, which are then absorbed and used to build and fuel our own cells. This is the recycling of biological compounds—the reuse of complex molecules from one organism to another.

But recycling goes even deeper. Much of the biological material that dies isn't just reused—it's disassembled into its fundamental atomic components (C, H, O, P, S, N). Consider carrot peelings decomposing in compost or human waste processed in treatment plants: microbes dismantle complex organic matter into molecular fragments—hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), formate ($HCOO^-$), and volatile fatty acids. These liberated molecules re-enter the environment, becoming raw ingredients for new life through the metabolic machinery of other organisms. This atomic-molecular alchemy—the relentless deconstruction and reassembly of matter—is orchestrated by nature's ultimate chemists.

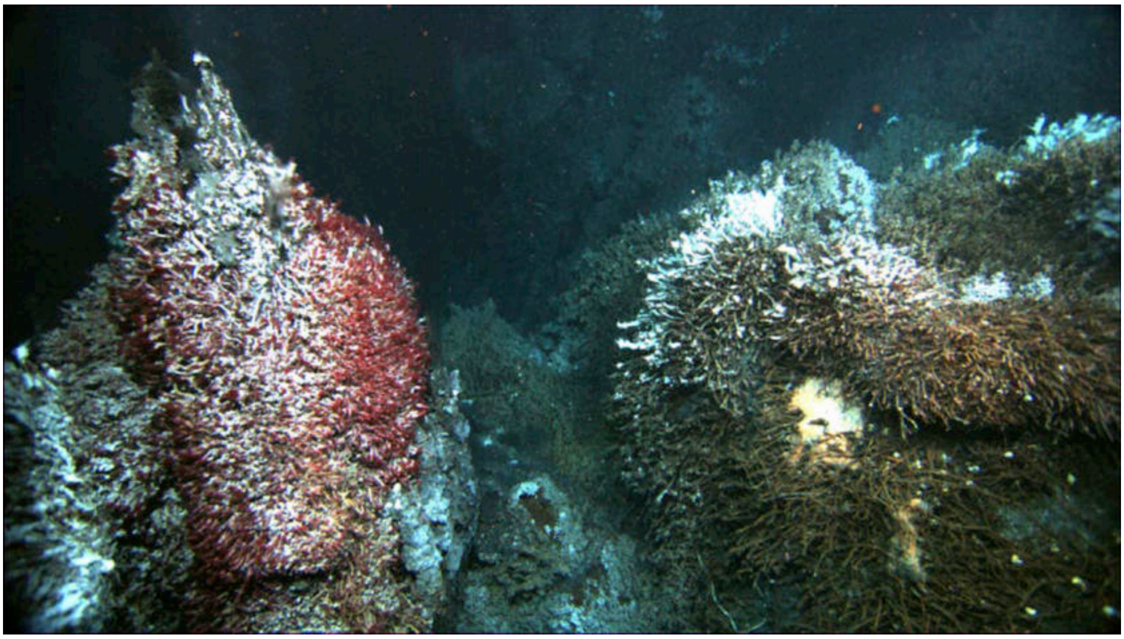
3. ***Microbes: The Hidden Heroes.*** Imagine a force so ancient, so pervasive, and so fundamentally creative that it underpins possibility of life persisting on our planet. These are the microbes—the invisible custodians of Earth's biogeochemical cycles, the tireless reclaimers of the spent and discarded, transforming death and decay back into the building blocks of life with a persistence and diversity unmatched anywhere else in the known cosmos.

This work of reincarnation rests on a profound truth: all life burns. As writer William Bryant Logan observes in *Dirt: The Ecstatic Skin of the Earth*, "Metabolism is a slow fire" (Logan, 2007). Unlike the devouring flames that reduce wood to ash, life's metabolic fire is a *controlled combustion*—one that liberates energy while preserving the integrity of the living structure. In Logan's poetic vision, the biblical burning bush, alight but unconsumed by the flame, becomes a metaphor for life itself: a sustained configuration of molecules releasing energy without self-destruction. This is no mere spiritual allegory. It is the scientific reality governing every cell, from the humblest soil bacterium to the human body. Microbial metabolism—whether oxygen's fiery efficiency in aerobic respiration or the smouldering patience of fermentation in anoxic mud—holds life in a state of perpetual flux. Atoms flow through microbial metabolisms like water through a millwheel: harnessed, transformed, yet never annihilated. A microbe metabolises, feeds, and excretes, yet remains *embodied*; it burns without being consumed. In this perpetual molecular exchange, death becomes disassembly, decay becomes redistribution, and waste becomes the beginnings of rebirth—the very essence of *material reincarnation*.

a. *The Microbial Architects: Earth's Ancient Recyclers.* So, what exactly are these extraordinary entities capable of sustaining the cycles of life? They are microscopic life forms—bacteria, archaea, fungi and protists—that inhabit virtually every conceivable niche on Earth, from the deepest ocean trenches and the most barren deserts to the soil beneath our feet, the air we breathe, and even the intricate ecosystems within our own bodies. Though unseen by the naked eye, these tiny powerhouses are the indispensable workhorses of the biosphere, their ceaseless labour driving the perpetual cycling of matter and energy that has shaped our world for billions of years. Their metabolic genius, and astonishing array of chemical strategies for generating energy, quietly drives the essential processes sustaining all life, enabling nature's recycling on a planetary scale.

Viruses do not recycle in the traditional sense—they do not metabolise or break down matter. But they play a vital role in life's recycling system by triggering the death of organisms, especially those that are old or vulnerable. In doing so, they release biological materials back into the environment, feeding the cycle of renewal.

b. *The beginning of life.* Microbes first emerged over 3.8 billion years ago on a primordial Earth shrouded in an atmosphere utterly devoid of life-giving oxygen. In those harsh, anaerobic beginnings, the earliest microbes pioneered ingenious ways to survive, harnessing energy from the very minerals and chemical compounds surrounding them through different types of anaerobic metabolism. They were the original recyclers in an oxygen-free world, extracting food from an inorganic and organic soup that included: hydrogen gas (H_2), often produced in hydrothermal vent systems; ferrous iron (Fe^{2+}), which could be oxidized in iron respiration; hydrogen sulphide (H_2S) and other sulphur compounds, used in sulphate reduction; methane (CH_4), both as a byproduct and a substrate in methanogenesis; carbon dioxide (CO_2), which could be reduced to methane or other organic molecules; and organic acids and alcohols, fermented in the absence of oxygen.



Vent communities near the top of Hulk chimney, Main Endeavour Field. The particles are predominantly very fine-grained sulphide minerals formed when the hot hydrothermal fluids mix with near-freezing seawater. These minerals solidify as they cool, forming chimney-like structures. "Black smokers" are chimneys formed from deposits of iron sulphide, which is black. "White smokers" are chimneys formed from deposits of barium, calcium, and silicon, which are white. Courtesy of NOAA - NeMO 2007 Cruise Report, 2007, Wikimedia Commons.

c. *A window into our beginnings.* To glimpse the metabolic landscapes of Earth's earliest biosphere—before oxygen transformed the planet—we can look to the deep sea, where hydrothermal vents and black smokers still host microbial communities reminiscent of those ancient worlds. These environments, rich in hydrogen gas, ferrous iron, and hydrogen sulphide, mirror the chemical conditions that once dominated the Archean oceans. Here, life persists without sunlight, relying instead on chemosynthesis and anaerobic metabolisms that predate oxygenic photosynthesis. In these vent systems, we see a living archive of metabolic innovation: microbes oxidize iron, reduce sulphate, and ferment organic compounds in ways strikingly like their primordial ancestors. These ecosystems offer a rare window into the transitional world between anaerobic and aerobic life—a time when microbial metabolisms were not only surviving but actively shaping the planet's geochemistry. Studying these environments allows us to reconstruct the evolutionary steps that led from a world without oxygen to one transformed by it, and to appreciate the resilience and adaptability of life in its most elemental forms.

d. *Oxygen Apocalypse and Aerobic Rebirth.* Then, in a revolutionary leap of biochemical innovation approximately 2.4 to 2.1 billion years ago, a group of these microbial pioneers, the cyanobacteria, achieved something extraordinary: they evolved oxygenic photosynthesis. Using sunlight to split water molecules, they unlocked a vast new energy source while releasing oxygen—a mere waste product to them—into the environment. This act of microbial metabolism triggered the cataclysmic *Great Oxidation Event* (GOE), a planetary transformation that forever altered Earth's destiny by filling the atmosphere with oxygen for the first time. While this monumental shift created the possibility of complex, oxygen-dependent life like us, it was an unmitigated catastrophe for the legions of established anaerobic microbes. Oxygen, highly reactive and corrosive, proved toxic to their ancient cellular machinery, causing a mass extinction that affected 80–95% of microbial life.

e. *But oxygen, ever present where humans now roam, is not everywhere.* Despite the plentiful production of oxygen by plants, cyanobacteria and other photosynthetic organisms, and its high concentration in the atmosphere, it penetrates the Earth's water bodies and sediments only slowly. The deeper the water depth and sediment, the slower the penetration. And since oxygen is such an energy giver, and hence in high demand by the microbial world, any that does penetrate deeply into the water column or sediment is instantly captured and used, so that at a certain level – the oxic:anoxic boundary – its concentration becomes effectively zero, i.e. anaerobic conditions prevail. Between this boundary and the surface of the water or sediment, there is an oxygen concentration gradient.

f. *Metabolic Mastery: Nature's Toolkit for Energy Extraction.* However, microbial resilience and adaptability is extraordinarily creative. Faced with this oxygen apocalypse, microbes did not simply vanish. Some retreated into sanctuaries shielded from the poisonous gas – the depths of sediments, the anoxic waters of oceans and lakes, hidden pockets within rocks. Others developed new enzymes to neutralize the destructive reactive oxygen species and, ultimately, learned how to metabolise using oxygen itself. In this way, the microbial survivors transformed a deadly element into a powerful ally, using oxygen as an incredibly efficient terminal electron acceptor in a new process: aerobic respiration.

g. *Microbial exploration of all potential sources of food and energy: the creation of habitats.* Over immense stretches of time, microbes mastered the art of navigating between the aerobic and anaerobic realms, evolving metabolisms of astonishing flexibility that could change in response to the ever-changing conditions around them. But oxygen was not the only issue. Because of their extremely small size, microbes are distributed all over the planet by wind, water and their own mechanisms of movement, and wherever they go they seek and discover food and energy sources that can allow them to grow and flourish, creating new habitats for them, and ultimately for other types of organism. Many of the places they end up in are very hostile to life, characterised by extremes of temperature, acidity, alkalinity, salt content, low water levels, and others (see Topic Frameworks in Section *Adventures and Discovery*).

Amazingly, whereas other forms of life just die when exposed to such conditions, microbes often develop new metabolisms that allow them to survive and flourish. The reasons are two-fold: (a) microbes have an amazingly diverse and adaptable metabolic toolkit, and (b) some can reproduce rapidly (in minutes, rather than in years) and hence evolve much more rapidly than higher organisms. Because of this unique adaptability to harsh conditions, microbial habitats define the biosphere: microbes are the biological transition between the biosphere and geosphere!

h. *The microbial recycling engine.* This deep evolutionary heritage is precisely why microbes today possess such an unparalleled metabolic toolkit – capable of aerobic respiration, diverse forms of anaerobic respiration, fermentation, and a myriad of other energy-yielding processes. This vast repertoire is the engine driving Earth's natural cycles and sustaining its ecosystems, a direct inheritance from their ancient struggle and triumph over planetary upheaval.

The vast metabolic diversity of microbes enables them to act as nature's ultimate recyclers, extracting energy and sustenance from an almost unimaginable variety of discarded materials. While many microbes today now readily use oxygen for respiration when it's available, vast communities can also thrive where oxygen is limiting or absent, using a range of alternative strategies that are fundamental to decomposition and nutrient recovery. In the hidden, oxygen-deprived corners of our world – within waterlogged soils, deep sediments, animal guts, and engineered digesters – they perform fermentation, breaking down complex organic molecules like sugars into simpler acids and alcohols. Others specialize in methanogenesis, converting these fermentation products or carbon dioxide itself into methane gas. Some are sulphate reducers, breathing sulphate instead of oxygen and generating hydrogen sulphide, while others are iron reducers, using rust as their electron acceptor.

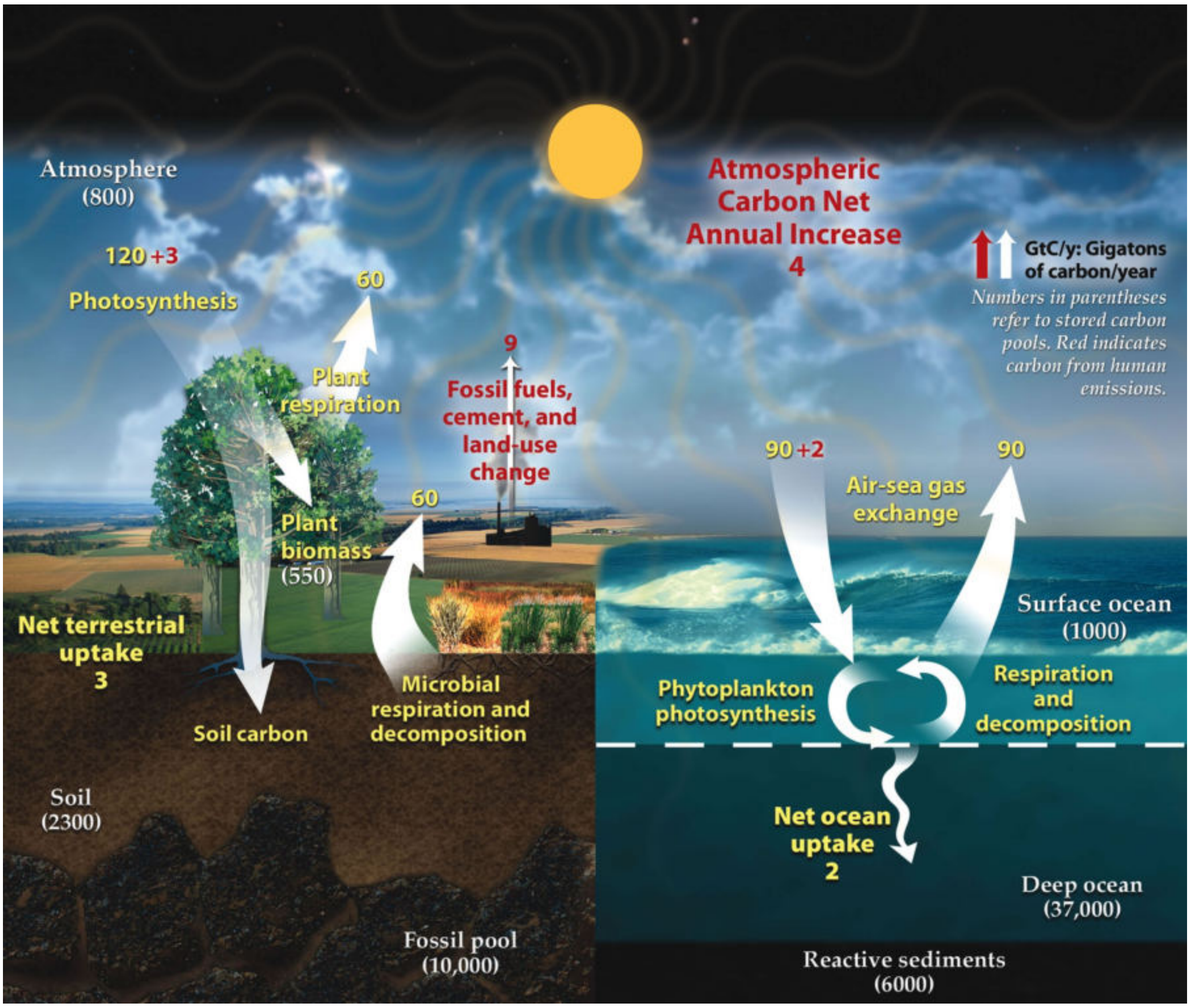
Remarkably, certain microbes even perform electrogenic respiration, transferring electrons directly onto solid surfaces like minerals or even electrodes; this incredible ability is now used in microbial fuel cells (a living microbial battery), generating electricity directly from the decomposition of organic waste – a technological demonstration of their natural recycling abilities.

i. *Biogeochemical Creativity: Disassembling and Redistributing Life.* Acting as nature's microscopic disassemblers, microbes undertake the relentless task of breaking down all forms of complex biological matter, whether it's a fallen tree, a pile of manure, a discarded apple core, a sardine in the digestive tract of a shark, a migratory bird that does not quite make it to a warmer clime and falls out of the sky, or perhaps an animal crossing the road that unwittingly enters into a conflict with another road user, into their fundamental elemental and atomic constituents. Whether operating unseen within a steaming compost heap, carpeting a damp forest floor, or thriving in the concrete basins of a treatment plant, microbes tirelessly deconstruct spent or dead organic matter. They dismantle the intricate molecules of life—cellulose, proteins, lipids, DNA—liberating locked-up carbon, nitrogen, phosphorus, and sulfur. But their recycling power does not stop there! Sometimes, carbon gets trapped for much longer—like in peat bogs or deep ocean sediments—where it is buried for millions of years. When geology (or humans) disturbs these stores, microbes finally get their chance to feast, releasing that ancient carbon back into the cycle. This isn't just nature's cleanup job; it's a planetary balancing act with huge consequences, like shaping Earth's climate over time.

These minuscule chemists also vigorously interact with abiotic (non-living) substances – rocks, minerals, atmospheric gases. They *weather* stone, slowly breaking it down into soil, dissolve metals, precipitate minerals forming solid deposits from liquids, and fix gases trapping them into useable compounds, like turning air into fertiliser, making them the indispensable central players in the vast, interconnected biogeochemical cycles. These planetary-scale loops move essential elements like carbon, nitrogen, oxygen, phosphorus, and sulphur through the Earth's atmosphere, hydrosphere, lithosphere, and biosphere, across continents and millennia, constantly redistributing the raw materials of life.

j. *The Leaf's Journey along the Microbial Disassembly Line – a Microcosm of Planetary Recycling.* Consider the journey begun by a single leaf detaching from a tree and falling to the forest floor. It doesn't rot away passively; it becomes a vibrant microbial metropolis. Bacteria and fungi swiftly colonize its surface and penetrate its tissues, secreting powerful enzymes that degrade complex carbohydrates, proteins, and lignin. This microbial disassembly line breaks down the leaf's intricate molecules, releasing carbon dioxide and nitrogen compounds back into the soil and atmosphere through the carbon and nitrogen cycles.

These liberated gases are then caught by global wind currents, embarking on journeys that span the globe. Later, perhaps continents away, photosynthetic plants and cyanobacteria capture the carbon dioxide molecules. Using the energy of sunlight and water, they perform the alchemy of photosynthesis, weaving that reclaimed carbon into new sugars – the fundamental building blocks from which all new life is constructed. Simultaneously, they release life-sustaining oxygen back into the air as a byproduct. This oxygen, generated through microbial ingenuity billions of years ago and replenished daily by photosynthetic microbes and plants, eventually finds its way into our lungs. There, it fuels the controlled combustion within our own cells, oxidizing sugars derived from plants (or plant-eating animals) to release the energy that powers each of our thoughts and movements – a direct metabolic inheritance from microbial recyclers.



The Carbon Cycle: A Leaf's Legacy in Motion — From forest floor to global winds, from microbial decomposition to photosynthetic rebirth, this cycle traces the elemental journey of carbon. What begins as decay beneath a tree becomes the potency of life in distant ecosystems, showing how every fallen leaf fuels the planet's metabolic rhythm. Courtesy U.S. DOE. 2008. Carbon Cycling and Biosequestration: Report from the March 2008 Workshop, DOE/SC-108, U.S. Department of Energy Office of Science. Prepared by the Biological and Environmental Research Information System, Oak Ridge National Laboratory, genomicscience.energy.gov/ and genomics.energy.gov/ Wikimedia Commons.

k. *Nitrogen's Gatekeepers: Capturing and Channelling the Inert into Biosphere Metabolism.* While oxygen readily participates in life's reactions, the abundant nitrogen gas (N_2)

filling our atmosphere presents a different challenge. Its strong triple bond renders it rather chemically inert – it cannot readily participate in biosphere metabolisms – and unusable for most organisms. But nitrogen is essential for life, a vital component of proteins – the cellular agents of cellular chemistry and structural elements used to build cells and traffic molecules in and outside of them.

This is where another type of specialized microbial recyclers, the nitrogen-fixing bacteria and archaea, perform their essential magic. Possessing the unique enzyme nitrogenase, these remarkable microbes accomplish what industrial chemistry, and nature in the form of lightening, requires immense heat and pressure to achieve: they capture atmospheric nitrogen gas and convert it into reactive, biologically accessible forms like ammonium (NH_4^+) and nitrate (NO_3^-). Plants and other microbes can then assimilate these forms, using them to construct vital molecules like proteins and nucleic acids. Without these microbial nitrogen-fixers, actively reclaiming atmospheric nitrogen and incorporating it into the biosphere's nutrient stream, the nitrogen cycle as we know it – and consequently, all complex life – would cease to function. They are the essential gatekeepers, transforming an inert atmospheric reservoir into the currency of life.

l. *Atoms Without Borders: The Eternal Redistribution.* Microbes, therefore, are not merely local janitors cleaning up a forest floor or a sewage pipe; they are agents of global redistribution. The carbon atom released by a decomposing fungus on a fallen log in the Amazon rainforest might be swept high into the atmosphere as CO_2, carried by jet streams across oceans, absorbed by plankton in the North Atlantic, consumed by a fish, and ultimately become part of a polar bear on the Arctic ice. Through the ceaseless work of microbial metabolism and decomposition, atoms and molecules are perpetually liberated from spent forms and redistributed across the planet via the elemental media – soil, air, water. They journey for days, years, or eons, traversing continents and oceans, cycling through countless forms. Every new organism that comes into being – a sprouting seed, a newborn animal, a blooming algal cell – is composed of atoms and molecules that have a deep history, potentially having resided within a thousand, a million, or even a trillion other organisms before being reclaimed by the microbial multitudes. Nothing is truly created anew; everything in the biosphere is repurposed, recycled, metabolised, reborn.

m. *Architects of Continuity: Earth's Uniqueness.* In this grand, billion-year-old narrative, microbes are far more than invisible heroes; they are the fundamental architects of continuity. Their relentless metabolic activity ensures that no atom, no molecule, no particle of energy bound in organic matter is ever truly lost or wasted in the biosphere. Death, decay and decomposition are not the end to an organic body, but a doorway opened by microbes, leading to transformation and renewal. They reclaim the unwanted, the fallen, the excreted, weaving the discarded threads of existence back into the vibrant, ever-changing tapestry of life. This persistent, creative, and infinitely diverse system of microbial recycling, actively maintaining the cycles that sustain our living planet, stands as a phenomenon unique to Earth in the vast expanse of the known universe.

4. *You Are a Microbial Superorganism*

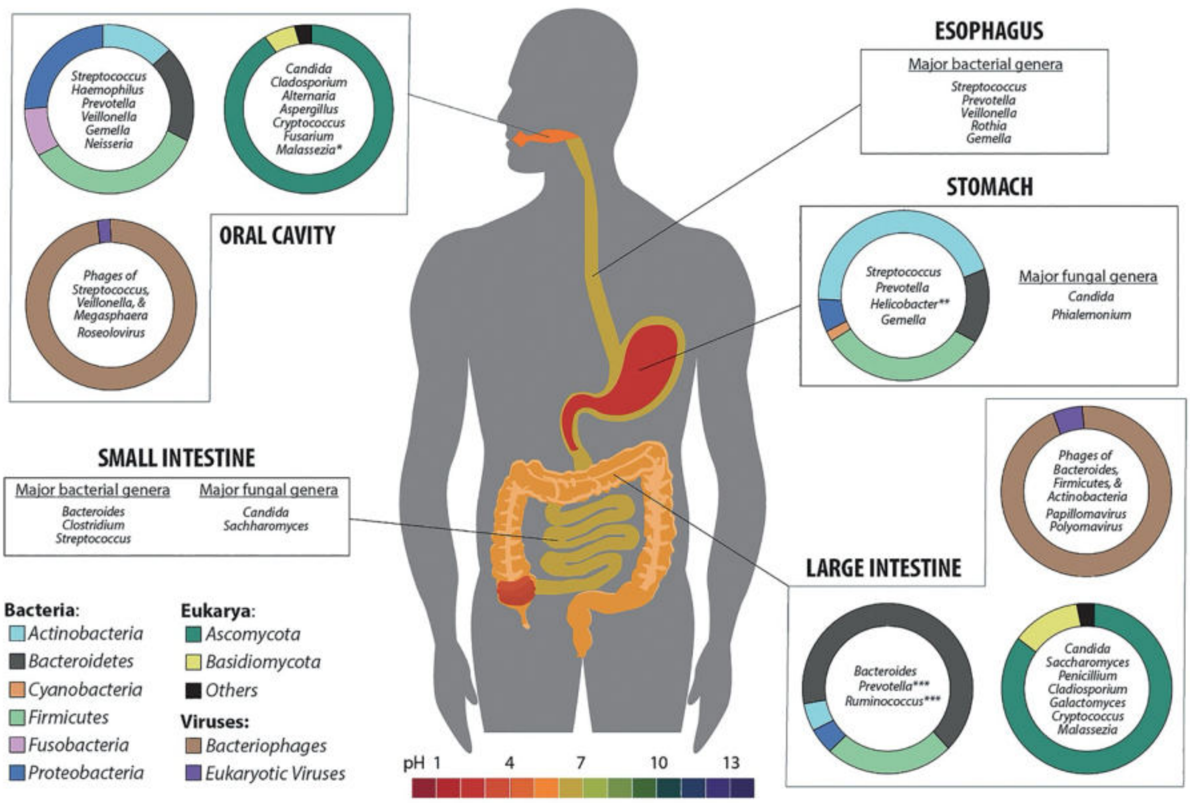
a. *The Inner Universe: Your Body as a Microbial World.* While microbes orchestrate Earth's grand recycling networks beyond your skin, *your own body is also a unique, living world* for trillions of microbial inhabitants. Though microbial interactions are ubiquitous across life—from the simple microbial films coating a Hydra to the gut communities of a gorilla—the dependence on these partners exists on a spectrum. Some creatures, like aphids relying on bacteria for essential amino acids, or corals housing and being fed by photosynthetic algae, are profoundly symbiotic. Others, like certain deep-sea worms or specialized insects, appear to function with minimal microbial intervention.

Human beings, however, are among the most deeply intertwined with their microbiomes. While microbes orchestrate Earth's grand recycling networks beyond your skin, your own body is a unique, living planet for trillions of microbial inhabitants. Your human microbiome represents roughly half the cells in your body: approximately 30 trillion human cells share your existence with 39 trillion microbial cells (Sender, Fuchs and Milo, 2016).

The genetic contribution of your microbiome dwarfs your own human blueprint. While your genome holds roughly 20,000 genes, your microbial partners contribute an astonishing 2 to 20 *million* genes—a genetic reservoir 100 to 10,000 times larger than your native DNA. This immense library is the code of a biochemical prowess far beyond the human capacity alone enabling us to: detoxify poisons, synthesise neuroactive compounds, and calibrate immune responses with detailed precision (Fung et al., 2022).

Some of the compounds made by microbes in our guts have hormonal activities with profound influence on our wellbeing, including our mental wellbeing. Consequently, scientists regard the gut microbiome as our unique second "endocrine organ."

The influence of microbial metabolites on us is so foundational that our microbiome must be regarded as a distributed chemical command centre enabled by trillions of microbial lives. They dwell in bustling ecosystems—your skin's salty plains, your mouth's moist caverns, and especially your gut's winding, nutrient-rich rivers. Together, you and your microbial citizens form a holobiont, a metaorganism: a unified superorganism forged from millennia of coevolution.



Human microbiome. Hillman, E. *et al.*, 2017. *Diagram of human gut microbiome depicted in various regions.* [image] Uploaded 7 April 2025. Available at: Wikimedia Commons [Accessed 19 July 2025].

b. *Our microbial friends not only accompanied us on our evolutionary path: they hugely influenced it.* This is no mere colonisation of the human body by microbial contaminants we randomly pick up from the environment; it is a deep, ancient symbiosis. As early modern humans migrated out of Africa starting around 60,000–70,000 years ago, they carried their microbes with them. These microbial communities co-diversified with their human hosts as they adapted to new environments and lifestyles. This means that the bacteria, fungi, and other microorganisms, especially those in their guts, evolved alongside the humans, influenced by factors like diet, climate, and social interactions. The gut microbiome plays a central role in digestion, immunity, and even brain function. Genomic studies of ancient human remains, including preserved faecal matter (paleofaeces), reveal that many of the microbial species found in modern human guts—such as *Faecalibacterium*, *Bifidobacterium*, and *Roseburia*—were also present in our ancestors tens of thousands of years ago. This continuity suggests that these microbes have long been essential partners in human development and health.

Recent research confirms that certain microbial species have co-evolved with humans, showing genetic patterns that mirror human evolution. These microbes are often highly specialised to the human gut environment and are passed down vertically from parent to child, much like genes. Importantly, the human microbiome is not limited to the gut. Microbial communities also inhabit the skin, mouth, lungs, and other body surfaces, each shaped by their local environment. For instance, the skin microbiome is directly exposed to external conditions and may be among the first to respond to climate change. However, it is the gut microbiome that has received the most attention due to its profound influence on metabolism, immunity, and overall health.

Yet, this ancient partnership is under threat. Industrialization, antibiotics, and dietary changes have significantly altered the composition of the human microbiome in recent centuries. Some ancient microbial lineages—sometimes called our "old friends"—are disappearing in Western populations, potentially contributing to the rise in autoimmune and inflammatory diseases.

c. *The Vital Work of Your Inner Ecosystem.* Your microbiome is a collaborating community, performing metabolic feats far beyond the capabilities of your human cells. Masters of digestive transformation, these microbes break down complex fibres like cellulose—indigestible by your own enzymes—releasing short-chain fatty acids that energise your gut lining and regulate metabolism. They serve as vitamin factories, synthesizing indispensable nutrients such as Vitamin K, B12, riboflavin, and thiamine that are often scarce in your diet.

As immune trainers and peacekeepers, they constantly educate your defence systems, helping distinguish benign companions from true threats while physically crowding out pathogens and secreting antimicrobial shields. Beyond digestion and immunity, they work as metabolic regulators: microbial metabolites mimic hormones, fine-tuning appetite, fat storage, insulin sensitivity, and bone density. Perhaps most remarkably, they influence your mind as neurochemical architects, producing serotonin and dopamine precursors while signalling via the vagus nerve—directly shaping mood, stress resilience, and cognition.

When this delicate community falters—a state called dysbiosis—the consequences ripple through body and brain, linked to anxiety, depression, and neurodegenerative decline.

d. *The Delicate Truce: Immunity as Gatekeeper.* This intimate partnership thrives on a knife-edge equilibrium. Though most resident microbes are commensal (thriving without harming) or mutualistic (exchanging benefits), their activities are transactional and are context dependent. Polly Matzinger's "Danger Theory" explains this dynamic: your immune system responds not to foreignness alone, but to signals of cellular distress—tissue damage, uncontrolled invasion, or molecular chaos indicating genuine harm.

Imagine your immune defences not as xenophobic soldiers, but as vigilant molecular diplomats. They perpetually monitor dialogues between your tissues and microbial denizens. Commensals typically broadcast "safety" signals or actively quell inflammation. But when microbes breach barriers, secrete toxins, or when injury exposes internal alarm molecules, the immune system unleashes targeted containment. This elegant framework allows peaceful coexistence with trillions of "outsiders" while remaining poised to neutralize true danger. Disrupt this dialogue—through antibiotics, chemotherapy, immunosuppressants, chronic stress, poor nutrition, or even the alien environment of space—and the balance shatters into dysbiosis and disease. Even subtle immune changes—like those caused by chronic illness or aging—can reshape the microbial landscape, creating feedback loops that influence health and resilience.

e. *How Diet Shapes the Microbial "Self".* Among the many forces that shape this microbial-immune equilibrium, one of the most immediate and powerful is diet. What we eat not only fuels our bodies but also feeds our microbial partners—guiding their composition, activity and influence on our health. Food is not only nourishment for the human body—it is also sustenance for the gut microbiome, which relies on dietary components as substrates for fermentation and metabolism. In turn, they produce a wide array of bioactive compounds that influence gut physiology, immune function, and overall health.

Different food components—fibres, fats, proteins, and polyphenols—selectively nourish distinct microbial populations. Diets rich in plant-based fibres, for example, promote the growth of beneficial bacteria such as *Faecalibacterium* and *Bifidobacterium*, which produce short-chain fatty acids that support intestinal barrier integrity and modulate inflammation. Conversely, high-fat or low-fibre diets can reduce microbial diversity and promote dysbiosis, a microbial imbalance linked to conditions like obesity, diabetes, and inflammatory bowel disease (IBD).

Importantly, dietary restriction—whether due to fasting, illness, or therapeutic intervention—can also reshape the microbiome. Studies show that caloric restriction and intermittent fasting can increase microbial diversity and enhance the abundance of bacteria associated with metabolic health. However, prolonged or severe dietary restriction may reduce microbial richness and impair gut barrier function, especially in vulnerable populations.

As research advances, nutritional strategies are increasingly being explored not just to feed the body, but to cultivate a resilient and health-promoting microbiome. This includes using diet as a therapeutic tool in managing irritable bowel disease (IBD) and other chronic diseases, where restoring microbial balance may be as important as treating symptoms.

f. *A Developing Conversation: Age, Immunity, and Microbial Change.* This immunological dialogue is not static—it evolves over a lifetime. From birth, when microbes first colonise the body, to old age, when immune function wanes, the composition and behaviour of the microbiome change alongside the immune system. In infancy, the gut microbiota is shaped by how the baby is delivered, breastfeeding, and early exposures to the environment. During adulthood, it stabilizes but remains sensitive to diet, stress, and medications. In older age, microbial diversity often declines, and beneficial species may be lost—potentially contributing to increased inflammation and vulnerability to disease. Understanding this dynamic interplay is crucial, especially as human lifespans increase and medical interventions become more common. The microbiome is not just a passive passenger—it is a responsive, evolving partner in the story of our health.

g. *The Fragility of Balance: Lessons from the Final Frontier.* Spaceflight lays bare the microbiome's vulnerability and its lifeline to health. Astronauts endure significant microbial changes: in the gut, beneficial anti-inflammatory bacteria like *Fusicatenibacter* diminish while inflammation-linked genera like *Parasutterella* flourish; vital metabolic pathways for bile acids and butyrate—crucial for energy and immunity—are disrupted; and latent pathogens like *Salmonella* previously held in check are freed up to do their unpleasant work. Upon the skin, microbial diversity collapses as protective tribes like *Gammaproteobacteria* retreat, inviting rashes, hypersensitivity, and sluggish wound healing under cosmic stressors—radiation, desiccated air, space travel diet and sterile confinement. Even saliva microbes change, with *Prevotella* increasing as *Neisseria* and allies decline. These disruptions correlate strongly with spaceflight's toll: brittle bones, fading muscles, inflamed tissues, and clouded cognition. Though Earth's embrace often restores balance post-mission, this extraterrestrial stress test proves how deeply our holobiont's health hangs on its microbial tapestry—and how violently danger signals erupt when the planet-bound pact between host, microbe, and immune gatekeeper fractures.

So, when we think about what a human being is, remember: we're not just one being—we're a vibrant, ancient community. Your microbes are deeply connected to your health and emotions; they are chemically and electrically wired into your very physiology. In a profound and literal sense, you carry a living ecosystem within you—a dynamic inner world that is constantly negotiating the limits of our bodies and community members through vigilant gatekeeping. This ecosystem is your direct, intimate link to the vast microbial networks that sustain the planet. It is the bridge between *your* life and the atoms that will one day be reclaimed by the Earth's eternal recyclers.

5. ***The Great Unbinding: Necrobiome, Thanatobiome and the Science of Return.*** While we are alive, the immune system acts as a vigilant mediator, maintaining a delicate balance with the microbiome. Upon death, this protection vanishes. The heart stops, oxygen levels plummet, and immune regulation ceases. This collapse initiates a significant biological shift: the very microbes that once sustained life now begin to dismantle it. What follows is a description of the recycling of human remains if left to nature. This recycling process is like that experienced by other animals and to some extent by plants. However, in some cultures, the recycling process is not permitted to proceed naturally because of traditions of dealing with the dead, such as cremation or burial in coffins that restrict access of insects and scavengers.

a. *Phase 1: Internal Unravelling (0-48 Hours)*

<u>Gut Revolt and the Birth of the Necrobiome.</u> Decomposition begins in the gut, where microbial density is highest. As soon as breathing and circulation stop, oxygen delivery to tissues ceases. Cells and tissues, deprived of fresh oxygen, rapidly consume the remaining intracellular stores in a desperate attempt to maintain basic functions. Professional recyclers—such as aerobic bacteria and immune cells—initially continue their work using the last traces of oxygen. However, as oxygen is depleted and not replenished, the environment becomes increasingly anoxic. Neutrophils—the body's first responders—can no longer patrol tissues or

summon reinforcements. Without immune barriers, gut microbes begin digesting the intestinal lining and spread outward, releasing gases such as methane, hydrogen sulphide, and volatile organic compounds (VOCs). These gases cause bloating and act as chemical signals, attracting external decomposers. This transformation marks the emergence of the necrobiome—a rapidly evolving microbial community adapted to thrive in the oxygen-deprived conditions of the dead body (*see TF on whale fall*).

Microbial Succession: Nature's Forensic Clock. Anaerobic species like *Clostridium* and *Bacteroides* dominate early stages, penetrating tissues and releasing pungent compounds like cadaverine (from cadaver)[1] and putrescine (from putrefaction)[2]. As decomposition progresses over the first 48 hours, tissue acidification favours acid-tolerant microbes such as *Enterococcus* and *Lactobacillus*. Forensic scientists use these predictable microbial succession patterns—shaped by temperature, humidity, and environment—as a biological clock to estimate the postmortem interval (PMI) (Javan et al., 2017; Pittner et al., 2020; Dash and Das, 2020; Moraleda et al., 2022) and predict the time of death, which is crucial information for investigations of deaths under suspicious circumstances.

b. Phase 2: Breach and Convergence (48+ Hours)

The Body Opens: Inviting the Thanatobiome. Eventually, internal pressure from accumulating gases causes the body to rupture—through splitting skin or leaking orifices—releasing volatile organic compounds (VOCs) like putrescine, cadaverine, hydrogen sulphide, methanethiol, dimethyl sulphide, butyric acid, propionic acid, acetone, butanone, formaldehyde, ethanol, methanol, isopropanol into the environment – all of which can be produced during the fermentation process. This breach invites the thanatobiome, a specialized subset of the necrobiome focused on deep tissue decomposition. Oxygen-tolerant species—including certain Proteobacteria (e.g., *Pseudomonas*) and Firmicutes (e.g., *Enterococcus*)—infiltrate organs once the body ruptures, accelerating breakdown in newly oxygenated tissues (Pechal et al., 2014).

Insects Arrive: The Recyclers Converge. These volatile compounds simultaneously attract a new wave of decomposers, expanding the process into a broader ecological network. Flies are among the first to arrive, often within minutes of death, laying eggs in moist crevices like the eyes, nostrils, and wounds. These hatch into maggots that consume soft tissue with remarkable efficiency. Over the following weeks, maggot populations peak, rapidly skeletonizing the body. Once their task is complete, they migrate *en masse* to pupate in the surrounding soil—a synchronized exodus known as *maggot migration* (Michaud and Moreau, 2009).

c. Phase 3: Return to the Earth (Weeks to Years)

Bones, Wax, and Mineral Liberation. With soft tissue reclaimed, the thanatobiome changes focus to remaining lipids and bones. Anaerobic bacteria convert fats into *adipocere*, a grave wax

[1] The name "cadaverine" comes from the Latin word cadaver, meaning "corpse." It reflects the compound's association with the decomposition of animal tissue. Cadaverine is a diamine produced by the bacterial decarboxylation of the amino acid lysine during putrefaction.

[2] The word "putrescine" is derived from the Latin putrescere, meaning "to rot" or "to decay," which is also the root of the English word putrefaction. Putrescine is a diamine (like cadaverine), formed by the decarboxylation of ornithine, and is one of the key contributors to the foul smell of decaying flesh.

that can persist for decades (Forbes et al., 2005). Simultaneously, soil microbes and fungi dissolve bone minerals, releasing calcium, phosphorus, and other elements.

Forensic Evidence: Reading the Body's Timeline. A decomposing body becomes a temporal blueprint. Forensic experts decode its transformation: VOC profiles reveal hours since death; maggot development stages pinpoint days; bone weathering and adipocere formation chronicle years. This biochemical timeline turns the body into an ecosystem-scale clock (Cláudia-Ferreira et al., 2023).

d. *Environmental Impact*. As the thanatobiome initiates internal decomposition and the necrobiome expands outward, the cadaver becomes more than a body in decay—it becomes a biochemical epicentre, seeding transformation into the surrounding soil. This process unleashes what scientists describe as an *ephemeral pulse of matter*: a sudden influx of carbon, nitrogen, phosphorus, and other bioelements that reshapes the microbial and chemical landscape of the soil. In ecological terms, death often triggers a burst of new life. Just as fallen leaves enrich forest floors and whale falls nourish deep-sea ecosystems for decades, the decomposing body becomes a nutrient-rich hub that fuels microbial blooms, feeds scavengers, and supports plant and fungal growth. Life, in this sense, does not end—it is redistributed.

As a body decomposes, it becomes a node of nutrient redistribution, feeding fungi, plants, and soil fauna. This transformation is not merely a return to the Earth—it is a rewiring of the soil's metabolic circuitry, embedding itself in the microbial memory of the landscape. The process is accompanied by a molecular cascade: anaerobic microbes break down tissues, releasing volatile organic compounds (VOCs) and nutrient-rich fluids into the surrounding earth. These emissions alter the soil's pH, redox potential, and microbial community structure.

The disturbance favours fast-growing, opportunistic taxa—such as *Proteobacteria* and *Firmicutes*—while suppressing others like *Acidobacteria*, leading to a temporary but significant shift in microbial diversity. This microbial bloom, fuelled by the body's nutrients, is not random but follows a succession shaped by environmental conditions, body size, and time. The cadaver's influence extends beyond microbial succession: it creates electrochemical hotspots, alters nutrient fluxes, and introduces novel microbial taxa—some of which are unique to the decomposition process and absent from surrounding bulk soil.

The soil remembers through chemistry: altered pH, recalibrated nutrient cycles, and communities rewired by decomposition's biochemical ingenuity—turning death into an act of ecological immigration. This microbial signature etches memory into the land long after flesh vanishes. Studies have shown that the cadaver imprint—the measurable effect of decomposition on soil chemistry and microbial composition—radiates far beyond the body and can persist for years, with microbial signatures detectable up to 1,051 days postmortem (Fiedler et al., 2023).

The full persistence and ecological consequences of this imprint remain poorly understood. Yet what is clear is that the cadaver does not simply disappear—it leaves behind a biochemical legacy, a microbial echo that reshapes the soil's living architecture.

This is reincarnation as material continuity. Atoms diffuse, transform, and re-enter life's web. Carbon becomes forest humus. Nitrogen fuels root networks. Phosphorus fortifies fungal highways. The necrobiome and thanatobiome are not mere agents of decay—they are landscape alchemists, transmuting death into ecological reciprocity. The body's final act is one of radical generosity: rewiring soil metabolism, seeding microbial legacies, and catalysing new life where it lies.

e. O*n Kusōzu*. This scientific understanding of decomposition finds a poignant parallel in Kusōzu (九相図), the Japanese Buddhist art form that depicts the nine stages of a decaying corpse. Traditionally portraying the gradual dissolution of a noblewoman's body, these paintings were not intended to horrify, but to cultivate awareness of impermanence and release attachment to the physical self. In many ways, modern microbial ecology echoes this ancient meditation—revealing that decay is not merely loss, but transformation. Where Kusōzu visualized the body's return to the Earth as a spiritual teaching, contemporary science reveals its ecological truth: the cadaver is not an endpoint, but a biochemical node that rewires the soil's metabolic circuitry. It becomes a site of nutrient redistribution, microbial innovation, and ecological renewal. The body's dissolution is not disappearance—it is diffusion, integration, and continuity. In this light, death is not a failure of biology, but its fulfilment. It is the moment when the body ceases to be an individual and becomes an ecosystem. And just as Kusōzu invited reflection on the transient nature of form, the science of decomposition invites awe at the enduring intelligence of life's design—where even in decay, there is generosity, memory, and the promise of renewal. The following eight pictures depict this process.

Kusozu (九相図), literally "pictures of the nine stages," refers to a Japanese Buddhist art genre depicting the sequential stages of a decaying corpse, often a noble lady. These paintings, popular from the 14th to the 19th centuries, were created to encourage meditation on the impermanence of life and the futility of attachment to the physical body. This is the first in a series of 9 watercolour paintings. In the first painting a court lady in a kimono is seated indoors at a low red table, with a scroll in her left hand, upon which she has written her farewell poem: she is pallid, and her expression is preoccupied. Iconographic Collections Keywords: Komachi Ono, uploaded 2014, courtesy Wellcome Collection gallery (2018-03-30) https://wellcomecollection.org/works/tc3d4p9a CC-BY-4.0

Kusozu: the death of a noble lady and the decay of her body. Second in a series of 9 watercolour paintings. Here, she has died, and is laid out on the floor covered to her shoulders with a blanket, with a lady and a gentleman in attendance. Iconographic Collections. Wellcome Collection gallery (2018-03-30):
https://wellcomecollection.org/works/jmgj8dpb CC-BY-4.0

Kusozu: the death of a noble lady and the decay of her body. Third in a series of 9 watercolour paintings In this painting, her body is out of doors, naked apart from a loincloth, on a mat, the lower part of which is folded up over her legs; her skin now has flesh tones. Iconographic Collections. Wellcome Collection gallery (2018-03-30):
https://wellcomecollection.org/works/c7eqpwth CC-BY-4.0

Kusozu: the death of a noble lady and the decay of her body. Fourth in a series of 9 watercolour paintings. Here, putrefaction has set in, her lower body is covered with a loincloth. Iconographic Collections. Wellcome Collection gallery (2018-03-30): https://wellcomecollection.org/works/hkk5834g CC-BY-4.0

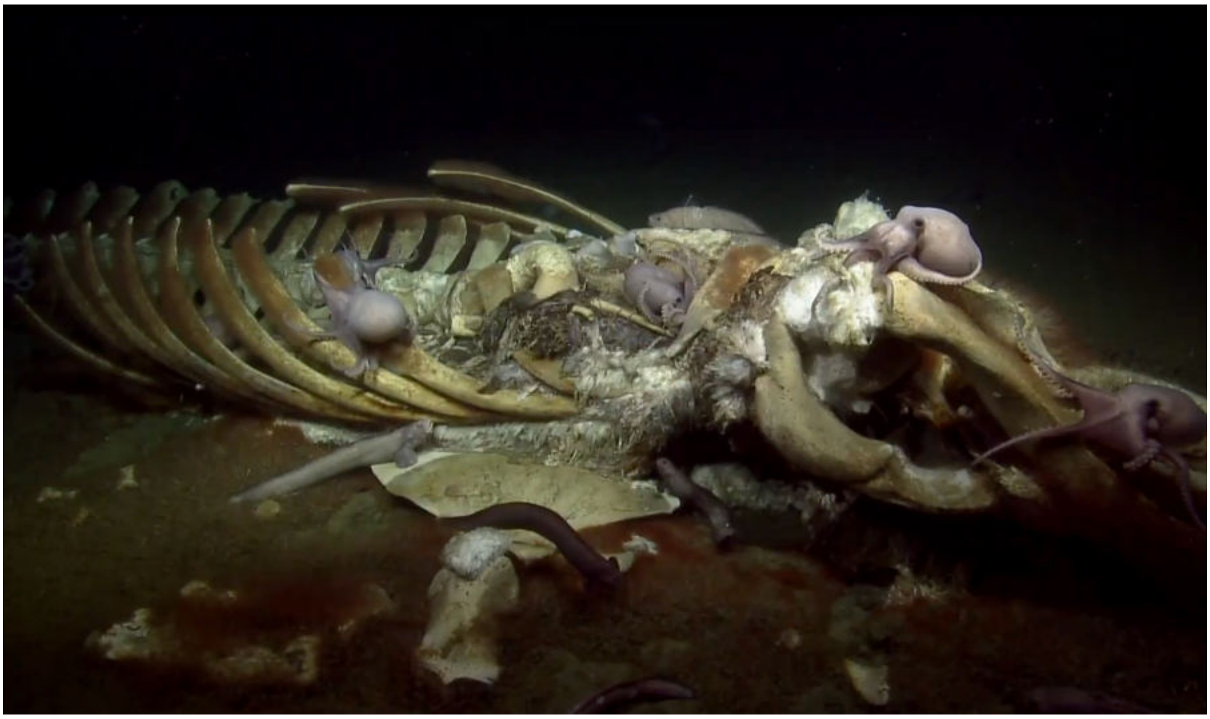
Kusozu: the death of a noble lady and the decay of her body. Fifth in a series of 9 paintings. Here her body is decaying in the advanced stages of putrefaction. Iconographic Collections. Wellcome Collection gallery (2018-03-30): https://wellcomecollection.org/works/jwpjdf4v CC-BY-4.0

Kusozu: the death of a noble lady and the decay of her body. Sixth in a series of 9 watercolour paintings. The putrefying body is now carrion for scavenging birds and small animals. Iconographic Collections. Wellcome Collection gallery (2018-03-30): https://wellcomecollection.org/works/nytdck6m CC-BY-4.0

Kusozu: the death of a noble lady and the decay of her body. Eighth in a series of 9 watercolours. Only a few fragments of bone, including the skull and fragments of rib. hand and vertebrae remain visible. Iconographic Collections. Wellcome Collection gallery (2018-03-30): https://wellcomecollection.org/works/aj4yxqkz CC-BY-4.0

Kusozu: the death of a noble lady and the decay of her body. Final painting in a series of 9 watercolour paintings. The final image is of a memorial structure upon which her Buddhist death-name is inscribed in Sanskrit. Iconographic Collections. Wellcome Collection gallery (2018-03-30): https://wellcomecollection.org/works/yhj4yhnb CC-BY-4.0

f. Atoms Reborn



Whale Fall: Whale skeleton submerged in Monterey Bay National Marine Sanctuary, covered in octopuses October 2019. (Photo: OET/NOAA)

If you've ever seen a time-lapse of a decomposing animal—like a whale fall on the ocean floor—you will witness the astonishing efficiency of these changes (Smith and Baco, 2003). In days or weeks, a body is reduced to bones; its nutrients dispersed into the environment. A single whale carcass sustains deep-sea ecosystems for decades. On land, the same principle applies: our bodies become part of the soil, the air, and the food web. This is reincarnation through matter—not spirit, but the endless transformation of atoms into life's building blocks.
often sinks to the seafloor.

The Microbial Stewards of Continuity

Though it may seem unsettling, this process is not only natural—it's essential. Methane once produced in the gut may, through biological and geophysical processes, become part of a leaf. Calcium may enter food chains to strengthen a bird's eggshell. Nitrogen may fuel a blooming flower. Decomposition returns our molecules to the Earth, where they nourish plants, feed animals, and re-enter the cycle of life. The microbes that once protected us in life now ensure nothing is wasted in death, weaving our atoms back into the web of existence. Microbes regenerate!

6. ***How old Am I really? – The recycling of YOU***. Let's pause for a moment and consider what all this constant movement and recycling of atoms means for you personally. Take for example, the idea of how old you are. You may assume your age is the same as the number of candles on your birthday cake. That's true in one way—your birthday marks the day you were born, when you became your own person, separate from your mother. But that's only part of the story.

Your body is made of lots of different parts, and not all of them are the same age. Some parts of you—like your skin cells, blood cells, and the tiny cells that fight germs—are super young. They're being made all the time, sometimes just seconds ago! Your body is always busy replacing old cells with new ones to keep you healthy and strong.

Then there's your microbiome—the trillions of tiny microbes (like bacteria) that live in your gut, on your skin, and pretty much everywhere in and on you. You started collecting these microbes when you were born, and you keep picking up new ones from food, people, pets, and the world around you. Some of these microbes are just minutes old, while others have been with you for years.

But let's go even deeper.

Each cell in your body is made of smaller parts, like proteins. Proteins are built from building blocks called amino acids. Your body gets amino acids from the food you eat—like lettuce, beans, or fish. When you eat, your body breaks down the proteins in food into amino acids and uses them to build new proteins for your own cells. Now here's the wild part: those amino acids might be really old. Some might have just been made by a plant yesterday. But others might have been recycled repeatedly by different creatures over millions or even billions of years. Imagine an amino acid that started in a tiny sea creature billions of years ago, got passed along through microbes, fish, and other animals, and finally ended up in your lunch!

If we go even further—to the tiniest level—we get to atoms and molecules.

If you recall, atoms are the building blocks of everything. One of the most common atoms in your body is hydrogen, which is part of water. Most of the hydrogen in your body was made just after the Big Bang, about 13.7 billion years ago. That means some parts of you are older than Earth itself!

So… How Old Are You?

You're as young as your newest cells, and as old as the atoms that have been around since the beginning of the universe. You're a mix of moments and millennia—a living, breathing story made of recycled parts from across time and space.

7. ***A Material View of Reincarnation.*** Science offers us a powerful and poetic way to think about reincarnation—not through the return of a soul, but through the recycling of matter. This is reincarnation through atoms—a continuous cycle of material transformation and flow of energy that does not reside in one identity but connects all living things across time—some of these are very old, and some are very new.

a. *Rituals of Return.* Faced with the imperceptible journeys of atoms and microbial timescales that stretch across millennia, humans have used ritual to make sense of death. Today, as we consider the environmental costs of cremation—its carbon emissions, mercury vaporization, and the synthetic toxins embedded in modern bodies from microplastics to PFAS—a new movement is emerging. Rather than denial or preservation, the idea of death is being reclaimed as a biological process and a reintegration into the living Earth (Fritts, 2021).

This approach contrasts sharply with historical efforts to resist decay, from Egyptian mummification to Iron Age bog burials, and even modern attempts to preserve the body's essence through technological means. While emotionally resonant, these practices often sequester atoms from life's cycles, freezing them in geological time. Today, companies like Algordanza and Eterneva continue this tradition by extracting 0.5–2.5% of cremated carbon and transforming it into synthetic diamonds—permanent, crystalline memorials that symbolically endure but materially withdraw from the ecological web.

Architecture, too, plays a role in shaping how we remember the dead. At the 2025 London Design Biennale, the Malta Pavilion presented URNA, a collective funerary object designed by Anthony Bonnici, Thomas Mifsud, and Tanif Raif. Crafted from stacked discs of poured Maltese limestone, URNA is intended to house the ashes of multiple individuals—often entire families—within a single, expandable structure. Inspired by the stratified geology of Malta, it grows over time like a living monument, challenging the individualism of traditional memorials and inviting reflection on the tension between preservation and transformation, between holding on and letting go.

This dilemma of preservation versus release, was also explored by Austrian artist and environmental visionary Friedensreich Hundertwasser, who imagined cemeteries as forests, not fields of stone. When he died in 2000, he was buried beneath a tulip tree in his "Garden of the Happy Dead," where his remains nourished the tree's growth. As he once wrote:

"*A person should be buried only half a meter, or two feet, below the surface. Then a tree should be planted there… When you visit the grave, you don't visit a dead man, you visit a living being who was just transformed into a tree.*"

This ecological vision is now being advanced through the science of microbes and the innovation of 21st-century design of readily biodegradable shrouds and eco-funery materials. Pioneers like Jae Rhim Lee through her work with Coeio via her Infinity Burial Suit (https://www.vogue.com/article/infinity-burial-suit-mushrooms-green-design-jae-rhim-lee-coeio); Bob Hendrikx, with the Living Cocoon (https://www.iflscience.com/you-could-one-day-be-buried-in-a-living-coffin-made-of-mycelium-64623); and Anders Zanichkowsky, with his woven burial blankets (https://design.newcity.com/2024/04/12/weaving-the-end-the-art-and-soul-of-burial-blankets-with-anders-zanichkowsky/), are reimagining the body not as waste to be contained, but as a resource to be returned.

These biodegradable materials harness the power of mycelium—fungi's root-like networks—to accelerate decomposition, metabolize toxins, and integrate the body into the underground web of life. These materials act as *biochemical collaborators*. As redox gradients ignite electrochemical hotspots around the cadaver, mycelium weaves through tissues—a silent conversation between decomposer, decomposed and the gift-receiving ecosystem, neutralizing pollutants while channelling nutrients. In this vision, death is not an end, but a transformation. The body dissolves into the soil, is taken up by roots, and reborn in the forest.

b. *Material Reincarnation: From Loss to Living Soil.* In this story, we have explored how death is not an end of a life, but metamorphosis. When breath stills and heartbeat fades, the human body ceases to be a bounded organism and becomes a biochemical offering with a new journey ahead of it within the webs of life. Stardust atoms—carbon, nitrogen, phosphorus—cycled through dinosaurs, forests, and oceans, loosen from their temporary constellation within us to enter Earth's ancient choreography of decay and renewal.

Microbes are the choreographers of this transformation. In life, our *human microbiome* thrives as a symbiotic partner: digesting food, training immunity, working with our microbial allies to carry out the *work of life*. But when the heart stops beating and our immune sentinels fall silent, these microbial partners seamlessly adopt new roles. The human microbiome *becomes* the *thanatobiome*.

Anaerobic maestros like *Clostridium* and *Bacteroides* dismantle our tissues from within, while oxygen-tolerant agents like *Proteobacteria* and *Firmicutes* radiate outward, carrying nutrients into the soil. Electrochemical gradients emerge in the postmortem microenvironment because of ion fluxes and redox reactions, facilitating biochemical interactions between decomposing organic matter and surrounding microbial communities. Fungal networks weave their way into the softening substrate of the cadaver, their mycelia not merely decomposing but *curating*: detoxifying pollutants, shuttling nitrogen to tree roots, binding carbon into stable humus.

Contemporary ecological burial practices—such as mycelium-based coffins, biodegradable linen shrouds, and natural forest interments—are designed to integrate the human body into biogeochemical cycles without introducing environmental toxins. These methods facilitate the decomposition process in a manner that supports soil health and ecosystem function. This microbial legacy promotes novel ecological interactions, effectively transforming burial sites into biologically active zones that enhance soil fertility and promote regeneration.

Death is not disappearance—it is redistribution.

The elements of the human body bloom in magnolias, thread through fungal networks, and drift in ocean currents as the scaffolding for new life. Biological reincarnation is not mystical but material, microbial and measurable, unfolding through the silent work of bacteria and fungi that deconstruct, recycle, and renew.

Soil becomes a living archive, recording our passage in microbial succession and nutrient flow. In this transformation, our personal losses become an investment in nature's future. Through their billion-year persistence, the ancient custodians of this transition offer an enduring message: we do not exit the world; we become it. And in that transformation lies a quiet, enduring hope—that life, through endless adaptation, cycling, and exchange, always finds a way forward.

8. ***Thinking About Life's Big Mysteries Through Riddles***. Riddles about life, death, and fate make us stop and think. The ones below show how death and destiny are part of life, even if we don't always understand them. The answers might seem obvious once you know them, but the questions make us wonder about life and think about it in new ways.

When we try to solve a riddle, we use our imagination and logic. They make us look at things differently and find hidden meanings. Thinking about these kinds of riddles can open our minds and help us see life's mysteries in a fresh way.

Even though riddles don't give us clear answers about life, death, and reincarnation, they make us reflect. Life is full of unknowns, but if we face them with curiosity, gratitude, and even a little humor, we can live more thoughtfully and fully.

a. *What question can you never answer yes to?*

Answer: "Are you dead?"

b. *What am I?* I am free for the taking through all of your life, though given but once at birth. I am less than nothing in weight, but will fell the strongest of you if held. What am I?

Answer: Breath

c. *What goes up and never comes down?*

Answer: Your age

d. *What am I?*
Two bodies have I,
though both joined in one.
The stiller I stand,
the quicker I run.

Answer: An hourglass

e. *What am I?* I'm tall when young and short when old.

Answer: A candle

f. *What is always in front of you but can't be seen?*

Answer: The future

g. *How is this possible?* A man dies of old age on his 25th birthday.

Answer: He was born on the 29th February.

h. *What is it?* The person who makes it has no need of it; the person who buys it has no use for it. The person who uses it can neither see nor feel it.

Answer: A coffin

i. *What do we …* Love more than life, hate more than death or mortal strife; that which contented men desire; the poor have, the rich require; the miser spends, the spendthrift saves, and everyone carries to their graves?

Answer: Nothing

Potential Implications for Decisions for Eco-funerary Burials

1. ***Individual***
    a. Ecology vs. tradition: Do the environmental benefits—like enriching soil and cutting carbon emissions—resonate with personal or spiritual views on burial?
    b. Scalability for different needs: Can the burial method accommodate varying body sizes without compromising its ecological integrity?
    c. Shared or single resting places: Are options like tree pod cemeteries or family plots available to reduce land use while honoring connections?
    d. Practical and emotional factors: Cost differences (biodegradable materials vs. conventional caskets), emotional comfort, and accessibility for loved ones.

2. ***Community policies***
    a. Protecting local ecosystems: How do burial practices affect groundwater purity and soil health—especially in densely used areas?
    b. Public health balance: Minimizing contamination risks while maximizing benefits like urban green spaces or wildlife habitats
    c. Supporting sustainable systems: Policies to grow green funeral businesses, adapt zoning for natural burials, and educate communities on eco-options

3. ***National policies***
    a. Health and economic trade-offs: Could reducing toxic embalming chemicals (e.g., formaldehyde) lower public health costs over time?
    b. Land use dilemmas: How to allocate space fairly among burials, agriculture, housing, and conservation needs.
    c. Safeguarding water resources: Preventing burial ground runoff from polluting rivers, lakes, or drinking water supplies.
    d. Nutrient management: Avoiding overload from traditional cemeteries vs. harnessing natural burials to nourish ecosystems.
    e. Climate impact: Measuring emissions from cremation/caskets against green burial's potential to store carbon.
    f. Land as a limited resource: When burial grounds compete with other critical needs, how should societies prioritize?
    g. Equity in green transitions: Ensuring affordability—could subsidies or sliding-scale pricing make eco-burials inclusive?

Pupil Participation

1. *Class discussion of the issues associated with eco-burials*

A sustainable goodbye?

Talk about these questions:

a. What happens to our bodies after we die? (Traditional burial? Cremation?)
b. How might burial choices affect the planet? (Think: land use, chemicals, carbon emissions.)
c. What would a "green" burial look like to you?

2. *Pupil stakeholder awareness*

a. SDGs & Eco-Burials
   Eco-burials can help or hinder the Sustainable Development Goals (SDGs). Which matter most to you?
   - **SDG 12 (Responsible Consumption)**: Biodegradable materials vs. metal caskets.
   - **SDG 13 (Climate Action)**: Less CO_2 than cremation.
   - **SDG 15 (Life on Land)**: Cemeteries vs. memorial forests.

b. Reducing Negative Impacts
   How could we:
   - Replace toxic embalming fluids (formaldehyde) with natural alternatives?
   - Use less land for graves (e.g., tree pods, mushroom suits)?

c. Personal Actions
   What could YOU do to promote green burials? (Example: Ask your family about eco-options!)

3. *Exercises*

a. Rethinking Burial Waste
   Most burials use non-biodegradable materials (varnished wood, metal). Design a zero-waste burial system for your town!

b. Sustainable "Burial Rituals and Recipes"
   Commercial caskets are mass-produced. Brainstorm:
   - Locally sourced materials (willow, bamboo, mycelium).
   - A "recipe" for a compostable shroud (what's in it?).

c. SDG City Challenge
   Task: Design a **sustainable cemetery** for 2050!
   - Where would it be? (Forest? Urban park?)
   - How would it help biodiversity/climate?
   - What rules would ensure fairness (cost, space)?

The Evidence Base, Further Reading and Teaching Aids

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Resources:

When a crime scene crawls away: Wired
https://www.wired.com/2013/10/when-crime-scene-evidence-crawls-away/

Solving crimes with the necrobiome, Ed Yong. I Contain Multitudes series. A series of interviews and great cartoons, 2018.
https://www.youtube.com/watch?v=B_lHQSxz9GI

Ed Yong has also written the book "I Contain Multitudes" available at Amazon:
https://www.amazon.com/Contain-Multitudes-Microbes-Within-Grander/dp/0062368591

.... and there is an accessible article in the Atlantic newspaper here in 2015:
https://www.theatlantic.com/science/archive/2015/12/meet-the-necrobiome-the-predictable-microbes-that-will-eat-your-dying-corpse/419676/

Jae Rhim Lee TED Talk. My Mushroom Burial Suit, 2011.
https://www.ted.com/talks/jae_rhim_lee_my_mushroom_burial_suit?language=en

The American Society for Microbiology also has a long great programme on the necrobiome through a talk by Jennifer DeBruyn, PhD Associate Professor Department of Biosystems Engineering & Soil Science, The University of Tennessee, which was prepared for Halloween, 2016. The opening introduction is worth watching for its lovely Halloween-themed animation: https://www.youtube.com/watch?v=iqVpL0y5ofM.