

Living buildings
Systems Architecture

Can I grow my own home?



Future microbial home interior, Mid Journey drawing by Rolf Hughes, 2022

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Living buildings

Storyline

A growing, living house, a building made of materials that are sown and cultivated, initially seems to be a contradiction in terms. However, growing and cultivating our habitats by strategically developing our relationship with the landscape is an ancient practice that takes time and energy to establish. The convenience of instant, unlimited energy provided by the fossil fuels which powered industrialization, shaped our expectations of buildings, creating new kinds of structures (railway stations, skyscrapers, shopping malls) and practices (motorway lighting, constant interior room temperature) that are fundamentally resource-hungry and energetically unsustainable. Today the construction sector is responsible for over a third of the EU's total waste generation and 40% of our energy consumption is by buildings. Furthermore, greenhouse gas emissions resulting from material extraction, manufacturing of construction products, construction, and renovation of buildings amount to around 5-12% of total national greenhouse gas production. According to the World Green Building Council, our buildings are responsible for 39% of total global carbon emissions, which is more than industry or transport.

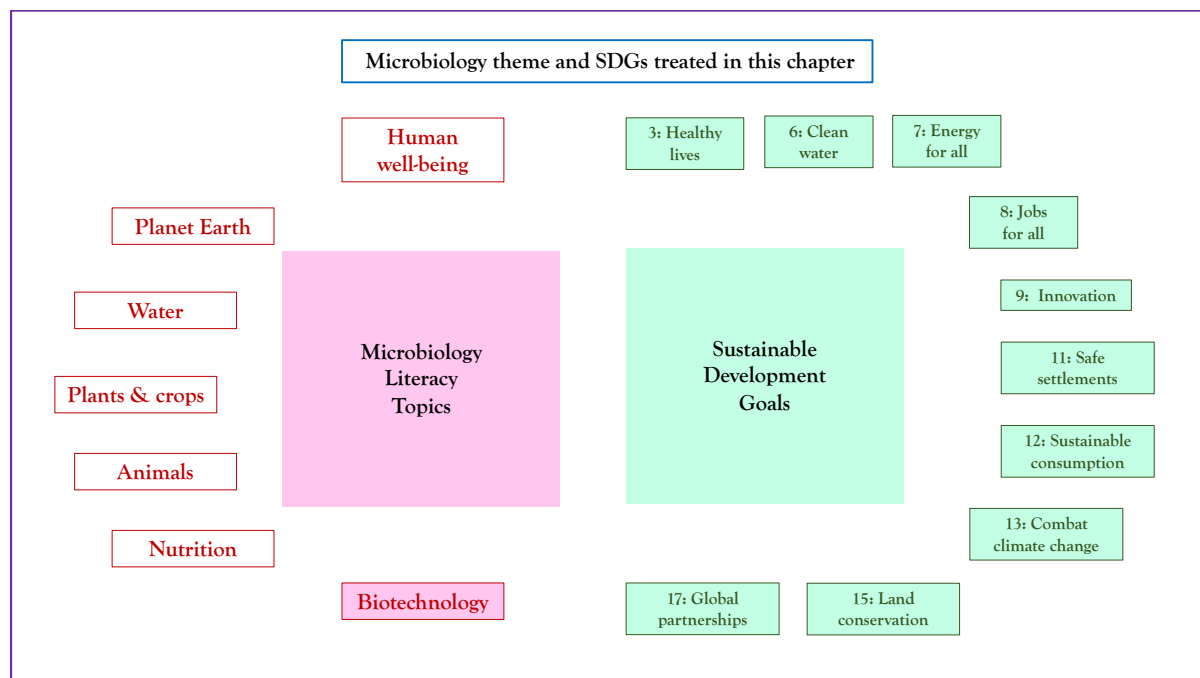
Can changing our construction platform from the extractive, resource-consuming “machines” that characterise modern infrastructure, to “microbial technologies” – which refers to the use of microorganisms, such as bacteria and fungi, to produce goods or services, and can convert waste into valuable products – radically alter the carbon footprint for sustainable human development? Advances in biotechnology and insights from molecular biology provide a new look at how we might live and work by acknowledging and incorporating the collective actions of the tiniest creatures on the planet into our homes and cities to produce new materials and provide building services that significantly reduce our environmental and energetic **footprints**, resulting principally from squandering the ‘infinite’ energy made possible by fossil fuels. These excesses occur through embodied energy (which deal with extraction and production) and building operations (which is concerned with how we run buildings). These vast carbon footprints can, however, be mitigated by incorporating the regenerative processes of microbes within a range of waste streams with the prospect of establishing domestic circular economies with multiple downstream consequences for **Sustainable Development Goals**.

The Microbiology and Societal Context

The microbiology: microbes have versatile metabolisms that have catalysed the natural biogeochemical cycles of the world providing various “goods,” comprising a range of biomolecules, that enrich ecosystems. Forming a basic currency that enables organisms to grow and change with time, this biochemical exchange system called the **microbial commons** also promotes biodiversity. Small, versatile, metabolically robust, extremely diverse, superabundant, biologically alien (in comparison with multicellular organisms) and existing within an ethical grey zone (with respect to their relationship with humans), microbes provide a system for catalysing radically new forms of environmental relationships through architectural and design practices. Importantly, microbes are fundamentally environmental actors, transforming their surroundings into high value biological compounds by using their unique metabolisms to work within the carrying capacity of their different sites. Drawing on these circular characteristics, **a new generation of sustainable design** engages a spectrum of microorganisms (bacteria, yeast, fungi, algae) to produce new categories of low impact products such as building materials, and services which incorporate microbially co-produced materials into experimental installations, packaging,

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furnishings, and indoor spaces. *And, peripherally for completeness of the storyline:* understanding that ecological management also involves microbes, making spaces for ‘good’ microbes in soils and urban spaces (microbiomes); interspecies communication. *Sustainability issues:* health; next generation sustainable design, food and energy, waste management, resource recycling, circular economy and employment; environmental bioremediation; global warming.



Living buildings

1. **What are our homes made of?** Growing our homes has been something that we’ve done since ancient times, but how we make our buildings today means that growing our own homes seems unlikely—and perhaps a bit strange. However, growing our buildings (or at least large parts of them) is something we have done for a very long time.

The first shelters were ‘found,’ like natural caves, such as those that are still occupied by approximately 117 families in the town Kandovan, in Iran’s East Azerbaijan Province. As people settled the land as farmers, specialist craftspeople could fashion local materials such as wood and stone harvested from quarries (which are open pits), to make buildings stronger and better buildings. The formation of villages meant that people could claim their own land on which they built their homes, to produce dwellings like Kirkjubøargarður (King’s Farm), the oldest inhabited wooden house which was built on the Faroe Islands during the 11th century.

Owning your own land meant there was somewhere to grow and harvest materials for your home, whether you were making a new building, or repairing an old one. Many kinds of homes were possible using a range of grown resources from – from wooden beams to straw rooves. Each material was shaped by local craftspeople (artisans) in ways that made sense of their habitats using those available resources that could be sustainably sourced from the land, or in limited amounts from a quarry.

With the enclosure acts in England, between 1604 and 1914, the landed gentry took land from ordinary people, turning them into tenant farmers (rather than freeholders) who had to work on rented land. Enclosures caused poverty, homelessness, and rural depopulation as workers lost their farms, their jobs and migrated to cities to find work. With no shared natural

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resources from which to grow materials to build their houses, workers were tenants once again having to resort to the marketplace to rent their homes from landlords.

With rapid urbanisation in the 19th century, the demand for housing rose and construction needs were met by the building techniques of modern times, which can be seen today in the two-up, two-down terraces, built from Accrington brick in Manchester's Trafford Park, the first industrial estate. Characterised by industrialisation, these building methods extracted resources from under the ground (mining), or the land (agriculture, forestry) beyond the city, rather than using local materials, creating scarcity, carbon emissions and waste. These materials used a lot of energy in their processing (kilning, smelting etc.) to turn them into the shapes needed to make our buildings, and then they needed to be transported to a distant building site.

As modern cities grew, the places and ways of making our modern buildings required far more materials and energy than in agrarian times, which were carried out by contractors aiming to making a profit, for landowners, who were also doing the same. To keep up with the demand, a new kind of fuel was used—fossil fuels (first, coal and then oil, which is even more energy dense than coal)—were burned to generate energy, which released a seemingly 'clean' gas (colourless, odourless) called carbon dioxide (chemical formula CO₂). Over decades, the amount of carbon dioxide has built up in the Earth's atmosphere, which stops heat leaving from the planet's surface, causing an overall average rise in temperature, leading to increasingly unpredictable weather patterns—a process called climate change, or more recently, the climate emergency.

As, we have lost touch with our land management practices, and home maintenance using locally available materials, increasingly, the idea of growing a home seems unlikely.

2. *How does modern architecture affect our planet?* The idea of 'sustainable' architecture was inspired during the 1970s energy crisis, when architects noticed that buildings which were enclosed in glass-and-steel boxes, required huge amounts of energy to power their heating and cooling systems.

The idea of sustainable development was more specifically defined in a landmark report called "Our Common Future," also known as the Brundtland Report in 1987, which proposed:

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Sustainable buildings are those that are designed to help reduce the overall impact on the environment and human health during and after construction. Exactly how this is achieved depends on the architect, and the kinds of materials and systems available to them in preserving and protecting the natural resources that surround the project site.

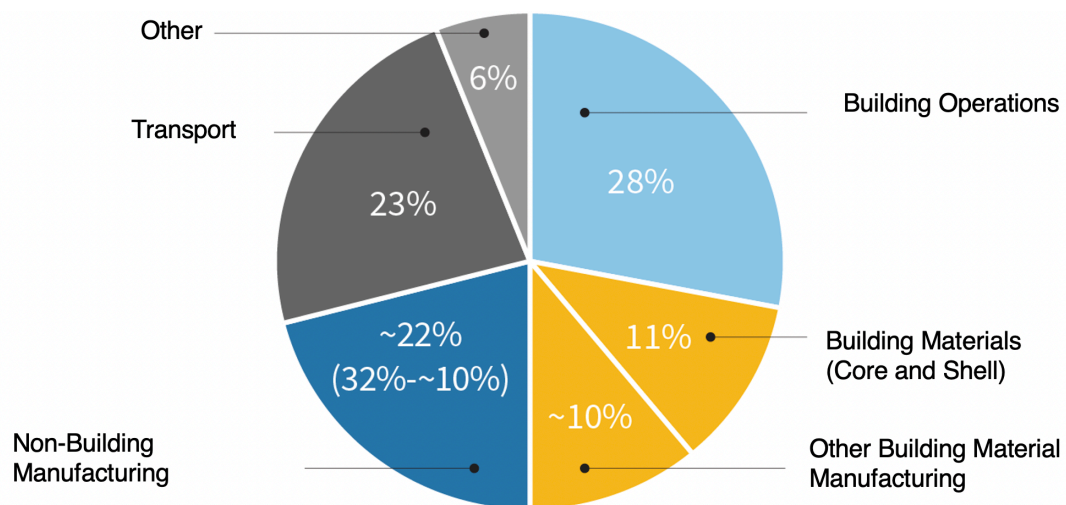
Present trends in sustainable design are "bio-inspired," which means that the geometry of the plant or animal is copied to make an "organic"—or nature-based design statement that also implies the building or object shares some qualities of the original organism. For example, the 300 St Mary Axe building in London, designed by Foster + Partners is better known as "The Gherkin." Its mesh-like exoskeleton mimics the structure of the Venus' flower basket sea sponge, whereby the skyscraper's ventilation system is said to mimic how nutrients flow through the sea sponge, by directing airflow from the street level and open windows along the spiral frame to the offices.

However, an "organic-looking" building is not necessarily a sustainable building as making these shapes requires huge amounts of concrete and steel. For example, Beijing's Olympic Stadium at the 2008 Olympic Games was designed by Herzog & De Meuron

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Architekten, Arup Sport and the China Architecture Design and Research Group, which was configured in a form popularly known as the “Bird’s Nest.” At the time, it was the largest steel structure, totalling 45,000 tons of the purest ever steel produced in China, used 10,000 tons of concrete, and generated at least 130,000 tons of CO₂ emissions in the process. According to the Climate Neutral Group, the capture of 1 tonne of CO₂ emissions requires 50 trees growing for one year.

Architects, therefore, have a very important role to play in achieving sustainable development, as the built environment is the industrial sector that consumes the most energy and natural resources. According to the Carbon Leadership Forum, our buildings are responsible for about 40% of total global carbon emissions, which contribute to global warming (the climate emergency). This is shocking, as this impact is more damaging than industry (20-30%) or transport (23%).



This figure shows the percentage of total global carbon emissions contributed by each industrial sector, and is adapted from 2019 Global Status Report, Global Alliance for Building and Construction (GABC) and Architecture 2030.

For buildings to be truly sustainable, all the different types of energy needed to make and run our homes must be considered. The first kind of energy is used for **building operations** (which are all the active functions performed by buildings) is called operating energy, which is mostly used to run, maintain, and manage our buildings. Most of this energy comes from fossil fuels to, for example, heat and cool our homes. This precious energy is often used inefficiently, as poorly insulated buildings squander heat, so more fossil fuel is needed.

The second kind of energy is called **embodied energy**, which refers to the energy needed to extract resources, shape, and compile them into a building. Manufacturing materials like bricks, glass, steel, and concrete is very energy expensive, contributing 11% of total global carbon emissions. Modernity’s favourite building material, concrete, is perhaps, the most energy-expensive material. Together with cement, it produces about 8% of global carbon emissions, which is more than double that from flying or shipping.

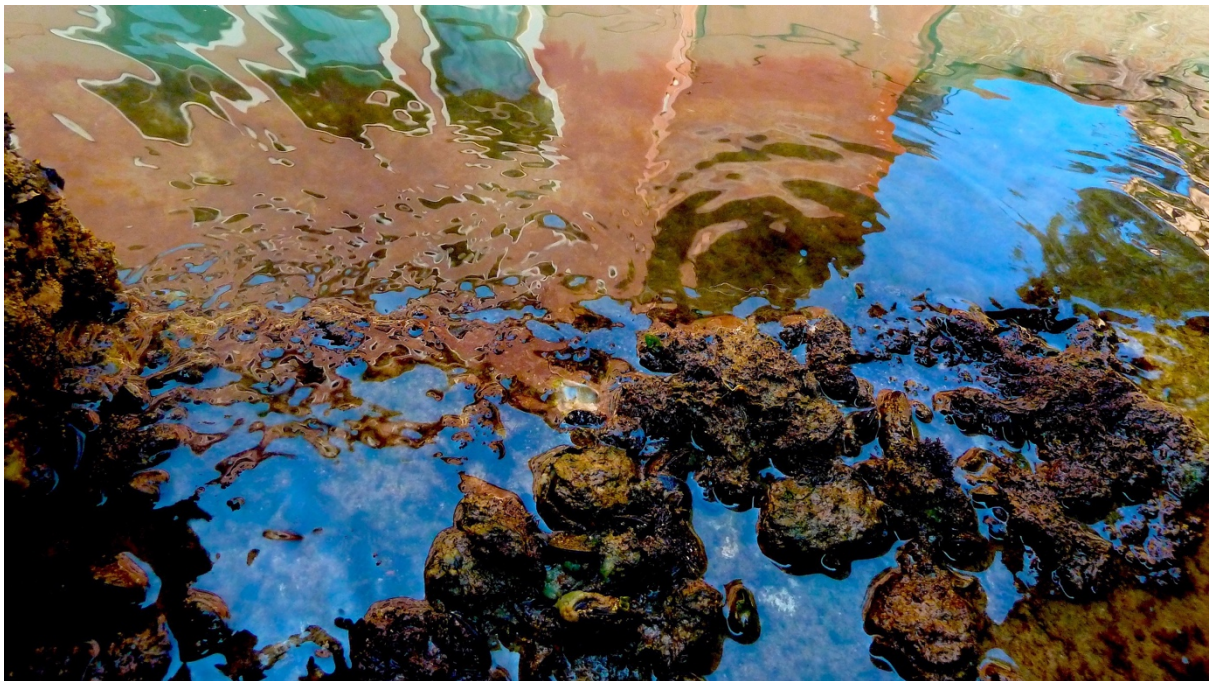
3. Changing Unsustainable Architectural Practices. The good news is that small changes can make relatively big impacts, and, in architecture, we’ve started to do something quite drastic about our huge carbon footprint and unsustainable management of natural resources.

Using the technology of “life” and the new know-how from the field of biotechnology, architects are setting out to make a new generation of sustainable buildings. These buildings are

much more ambitious than net zero and aim to benefit the natural world by not only using natural energy to run their operations, but also by growing their materials and re-using them at the end of their lifespan.

4. *A New Generation of Sustainable Architecture.* Microorganisms (bacteria, archaea, fungi, protists, viruses) are key to this new kind of sustainable architecture. Although microbes are so small that we cannot see them individually, without a microscope, they are everywhere—outside in our urban spaces, inside our buildings, on our skin and even inside our guts. For more than 3 billion years microbes were the only lifeform on the planet. During this time, they learned how to draw energy from their surroundings in many ways that have brought a net benefit to and overall enlivening of the environment (particularly through the soil).

Since the earliest times, they have even formed rocks by helping many minerals released through weathering processes to crystallize and sediment to become stone structures. Forming the world's first circular system (one with no waste), the waste products from one species is often the food source for another. When they work together (symbiosis) they form complex structures called biofilms, which we can think of as microbial cities. By working with the extraordinary, versatile metabolisms of microbes, which refers to all the biochemical reactions that occur in a cell or organism, it is possible to grow building materials and run building operations for a new generation of sustainable buildings.



Thrombolites (microbial colonies with an irregular internal organisation) forming around the waterways of Venice. Photograph by Rachel Armstrong, 2014.

5. *What kinds of microbes can help us make a New Generation of Sustainable Buildings?* The three types of microbes most frequently used in the new generation of sustainable architecture are: algae, fungi, and bacteria.

a. **Microalgae.** Algae are a large class of plants that mostly live in water. While they use the sun's energy in photosynthesis, they lack the true roots, stems, leaves, and specialized multicellular reproductive structures of terrestrial plants. Microalgae are microscopic algae that

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are invisible to the naked eye, which exist as individual cells, or form chains or groups, which we often encounter as ‘pond scum.’



Microalgae on polystyrene, Photograph by Rachel Armstrong, 2015.

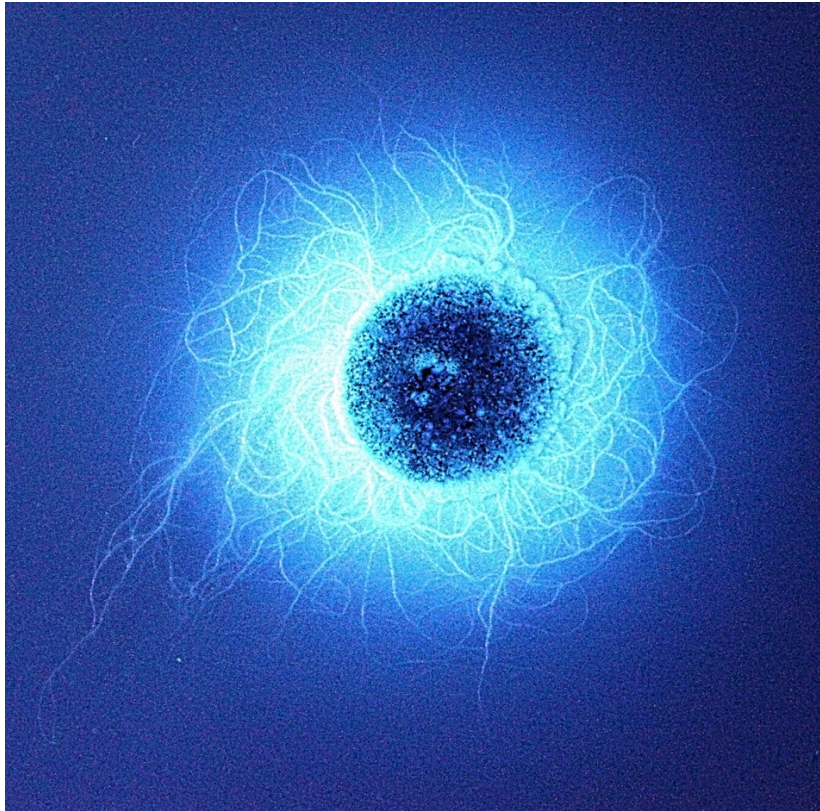
b. **Fungi.** At first sight, fungi resemble plants but, biologically speaking, they are much more like animals and have an insect-like shell, which stiffens their cells. They are most recognizable as “mushrooms,” or “toadstools” - which are the reproductive organs of fungi. Mostly, however, fungi exist as a fine filamentous system (the vegetative body), which is a root-like structure called “mycelium,” which push through their food, binding the organic particles together.



Mycelium growing through printed and fired, but not glazed clay. Collaboration with Studio UNSEEN, Tallinn Biennale. Photograph by Rachel Armstrong, 2017.

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c. **Bacteria.** Millions of bacteria, which are microscopic, single-celled organisms, exist in every environment and are found both inside and outside other organisms. While their cellular forms are usually considered simple, they have powerful metabolisms. The bacterial cell is a highly specialized transformer of materials and energy, so different kinds of bacteria collectively produce a huge range of substances from their surroundings and, in doing so, contribute to soil fertility, biogeochemical cycles, and ecosystem exchanges that enable life on Earth. Effectively, bacteria make up the foundations of the biosphere—our living world.



A microbial colony, photograph courtesy Simon Park, 2018.

6. *How do microbes become architecture?* Although microbes are very small and cannot be seen individually with the naked eye, they can form much larger complex colonies (biofilms), which are highly visible but not particularly attractive structures as they are “formless,” like slime. Unlike modern architectural technology, when microbes are grown under the right conditions, they grow at an exponential rate and can be scaled up significantly to make sustainable (circular) materials, and provide services whose impacts align with, or even benefit, nature.

7. *Microbial materials.* The following examples show how microbes can **act as organic factories** and be cultivated to produce new kinds of building materials that are sustainably grown from available resources, rather than being extracted from the ground.

a. **Turning waste agricultural materials into building blocks.** The fine root-like structures of fungi (mycelium) can bind agricultural waste particles together (e.g., sugarcane bagasse, rice husks, cotton stalks, straw) acting like a living glue to make a single, solid material called a “mycelium biocomposite.” Part organic block, part fungal matrix, these versatile materials can be moulded, or 3-D printed, into a wide range of forms to become insulating bricks and even patchwork ‘tapestries’ of recycled materials—which keep our homes warm and insulate them against unwanted noise.

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The properties of material can be altered by selecting different types of fungi, changing the growing conditions, and using a final processing method to confer the material with a specific property (e.g., structural support, acoustic and thermal insulation). Several companies such as MOGU and Grown.bio are now selling these materials commercially for packaging, home insulation, soundproofing and as attractive interior panels for sustainable home design.



Mycelium bio composite flooring detail using recycled materials, Armstrong and Ningsih, Retrofuture Exhibition, Evluon, Eindhoven, 2022.



Mycelium biocomposite flooring using recycled materials, Armstrong and Ningsih, Retrofuture Exhibition, Evluon, Eindhoven, 2022.



Different methods of moulding mycelium DSC07506 biocomposite using cardboard and Tupperware mould (above); PVC pipe (left) and Tupperware container (right) Samuel Hoornaerts, Wicked Home, Masters Studio, Ghent, 2022.

b. **Mineralisation.** Microorganisms can also create stone-like new building materials, just like their ancient ancestors, through an active mineralization process called Microbial Induced Calcium Precipitation (MICP). By adding specific strains of bacteria, or fungi, to a calcium-rich solution, their metabolic by-products cause the calcium to solidify which mineralizes the organic substrate in which they are embedded, producing a material that is like natural limestone like 'biobricks' and 'bioconcrete', which are described below.

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i. *Biobricks* are not fired from clay using a kiln, which produces air pollution and carbon emissions, but grown from biomass, aggregate, nutrients, and minerals like sand, by culturing them with friendly microbes, which absorb carbon dioxide from the air. The final material has the consistency of sandstone and is sold by the company BioMason. Since brick manufacturing makes 800,000 tonnes of CO₂ emissions per year, biobricks are set to make a significant reduction in embodied carbon emissions (see *Biobricks* by BioMASON).

ii. **Bioconcrete.** Invented by Henk Jonkers at TU Delft, bioconcrete lasts longer than ordinary concrete, as it is seeded with hardy microbial spores that are activated by the entry of water when the concrete block develops a tiny fracture. On hydration, the spores spring to life and plug the hole with mineral carbonate, extending the life of the material through this self-healing characteristic.



Future Venice, a speculative project conceived by Rachel Armstrong, whereby 'living' technology catalyses mineralisation around the foundations of the city forming bioconcrete. Rendering by Christian Kerrigan, 2010.

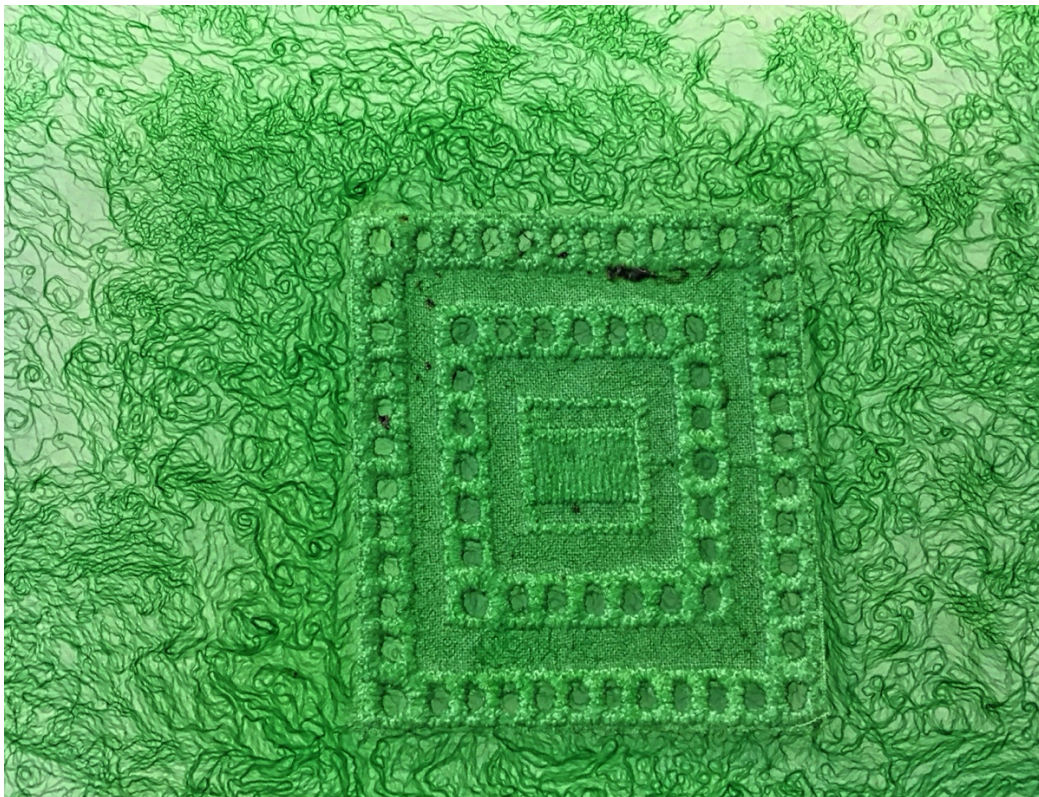
c. **Bacterial cellulose.** The ancient Chinese noted that when they made kombucha tea, a fermented beverage using a symbiotic colony of bacteria and yeast, the organisms became embedded within a thick cellulose mat made of fine fibres. As they formed at the surface of the drink, these fibres could be harvested, dried, and processed to be used in different ways. This microbial cellulose has several unique properties that make it useful in next generation sustainable architecture as it is lightweight, has stronger properties than plant cellulose and is suitable for architectural applications such as facades, furniture and even for use in green walls, as a sustainable and environmental-friendly alternative to traditional materials like plastic and synthetic fibres.

d. **Microalgae.** By absorbing carbon dioxide, sunlight and nutrients, microalgae can produce biomass and other biomolecules such as oils and fertilizers. At the micro-level, free-living microalgae make excellent substrates for generating bioinks, which are embedded in a gel, so they can be used in 3-D printing to create the final shapes of different applications, like artificial leaves, photosynthetic skins, or photosynthetic bio-garments.

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Designs for various photobioreactors at the IDEA Laboratory, Azerbaijan Pavilion, 56th Venice Biennale, Venice, with Artwise Curators, featuring, Rachel Armstrong, Studio Swine, Julian Melchiorri, BioLogic Studio, 2015.



A lace/Cyanophyte hybrid biomaterial. The cyanobacterium first infiltrates the fibres of the textile and then spreads from it as curling green tendrils. Where does the manmade material end and the biology begin? Victoria Geaney and Dr. Simon Park, 2020. First published in *Experimental Architecture*, p71, with permission.

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When there are excess nutrients in the water – primarily nitrogen and phosphorus – which mostly arise from agricultural run-off when farmers use too much fertilizer on their soils, a process called eutrophication begins. Algae quickly grow and turn the water green, in some cases, even releasing toxins. During the IDEA laboratory in Venice (2015), which was an experimental space for art and design at the Azerbaijan Pavilion, the possibility of turning the eutrophication in the lagoon into good use was explored through a hypothetical lagoon island built of plastic waste whose agglutinating plastics invite algae colonies, such as diatoms with heavily silicon skeletons, to make them their home. As rafts of biofilms weave their membranes around the plastics, they produce long yards of thread-like materials, which are knitted into mats by the tides and eddies.



Future Venice II, a speculative concept for making a new island for the Venice archipelago from a combination of plastics and algal eutrophication, drawing courtesy IDEA Laboratory, 2015.

e. **Water-absorbing microbial spores [actuators].** *Bacillus subtilis* microbial spores are hygroscopic and can be turned into a solution for printing on fabrics to form a heterogeneous multilayered structure that responds to moisture by changing its shape. With the right kind of microbes, geometry and material, the water absorption e.g., from human sweat can be used to make biohybrid films that can reversibly change shape within a few seconds owing to the entry of water. Presently, these spore-based shape-change materials are being developed for sports clothes but are also being considered as architectural textiles for outdoor structures that are actuated by water. (see Media Lab's BioLogic material).

f. **Heat-absorbing fungal pigment [melanin].** Melanin is a dark, protective pigment in your hair, skin, and eyes. It absorbs harmful ultraviolet (UV) rays from the sun (which accounts for its darkness), and scavenges toxic *free radicals*, which are unstable atoms that can cause tissue damage when their levels become too high, and so, protects cells from damage. Melanin is found in all kingdoms of life, including fungi, which helps them survive in harsh environments such as high temperatures, chemical stresses, and biochemical threats. Some fungi even use melanin to use energy for cell growth, which makes melanin of interest to next-generation sustainability

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researchers in architecture and design. The integration of melanin-producing fungi into biocomposites, or bio-degradable substrates like bioplastics will perform energy harvesting functions, provide a barrier for building skins, or in living fungi will mediate between the internal and external environments of a building—just like a ‘living’ skin does.

g. **Mixed biomaterials.** Nature’s materials are never homogeneous, so different microbial processes can be combined to create hybrid materials, whose performance is more than the sum of their ingredients. For example, BioMason (which makes biobricks) is working with Evocative (which is known for its mycelium biocomposites) to make a stunning new kind of stone that is grown from agricultural waste, mushrooms, bacteria, and sand. (see Ecovative and BioMASON collaborate)

8. **Building Services.** While inventing new materials that can reduce embodied energy is exciting, our bigger challenge is in reducing emissions from building operations. However, the incredible metabolic processing power of microbes helps us with this too.

a. **Microalgae building facades.** Microalgae cultivation can be scaled up to the macro level in photobioreactors, (which, are specialised ‘homes’ for photosynthetic microbes and take the form of building facades, tubing, and various cladding systems) to promote their growth so their products can be harvested and used as sustainable resources e.g., biofuels and biomass, resulting in energy saving, reduced carbon dioxide emissions, oxygen generation, biofuel production, wastewater treatment, and solar heat absorption. These bioreactors can be incorporated into urban space – not just to produce novel, functional building materials but also to power building operations by extracting biofuel from the microalgae.

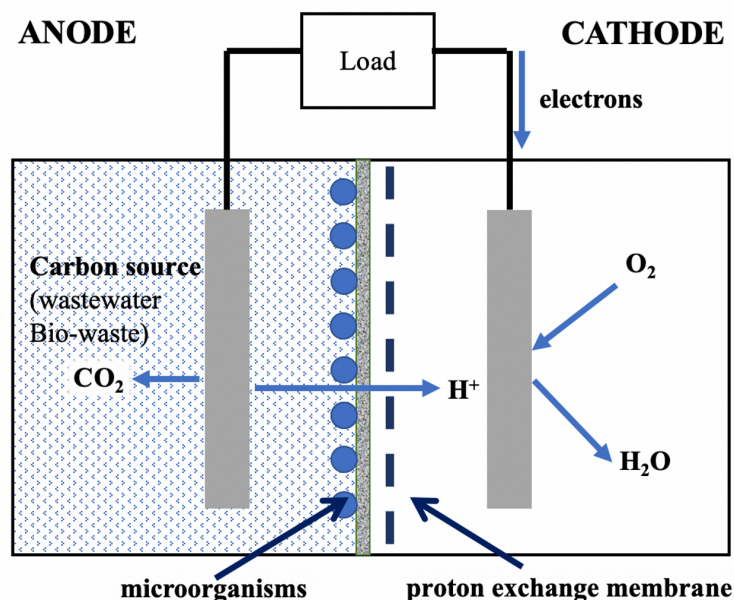


BIQ House, the world’s first building powered by algae, Hamburg, Germany, courtesy of Colt International, Arup, SSC GmbH, 2011.

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b. **Microbial Fuel Cells.** The power of microbes to perform useful services was noted by Michael Cresse Potter in 1911, who designed a kind of ‘living battery’ called the Microbial Fuel Cell (MFC), which produced several hundred millivolts of energy from the *Saccharomyces* yeast that converted the chemical energy of sugar into electrons that flowed into an external circuit to provide electrical power for as long as they continued to be fed. Potter also noted that *Escherichia coli* bacteria produced electricity under these circumstances but, as microbial culturing was in its earliest days as a science, he had very little success with these organisms or other bacterial species.

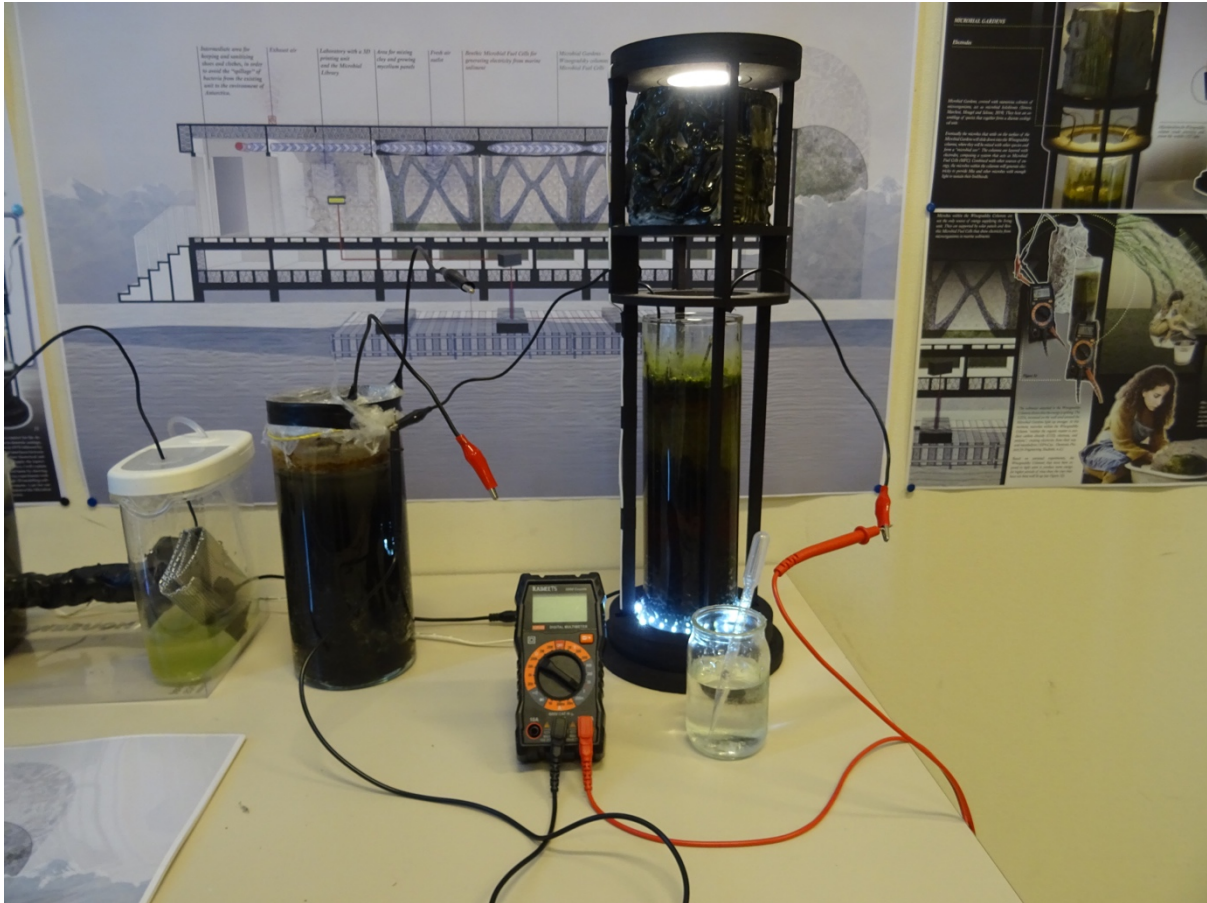
The organization of these battery cells was like a chemical battery with an anode and cathode but, instead of using inert solutions, the MFC cultivates an anaerobic biofilm in the anode, which is separated from the cathode by a proton-exchange membrane. To produce energy the biofilm metabolizes an organic ‘feedstock’, which can be urine, grey water, black water, or any kind of liquid organic waste. While it digests the feedstock, the biofilm excretes electrons, which are captured by electrodes, to generate an electrical current sufficient for powering electronic devices. Simultaneously, protons pass through the membrane where they combine with oxygen to produce water.



Technical diagram showing electrons produced from an anaerobic biofilm that are captured by electrodes to produce electricity while performing ecosystems services (bioremediation of wastewater).

While they are making bioelectricity, the biofilms in the MFCs are also recovering nutrients, making biofertiliser (in the stabilised sludge they produce, which is a rich source of nitrogen and phosphate), treating wastewater, and killing pathogens – just like natural soil biofilms – and are, therefore different than modern utilities, which are designed to process one type of resource at a time. MFCs provide a foundational bioremediating platform that can change the impacts of human settlement by providing environmental services and generating an overall net-positive impact on ecosystem health.

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Benthic Microbial Fuel Cell as an exemplar of how microbes can produce electricity in a design context, project by Anna Vershinina, photograph by Rachel Armstrong, 2021.

Breakthroughs in MFC technology in the last couple of decades, have led to field trials for the treatment of wastewater streams. For over a decade, a range of PeePower® urinals have been developed by Ioannis Ieropoulos, funded by The Bill & Melinda Gates Foundation, and Oxfam, as part of the reinvention of the toilet challenge for use in refugee camps and schools. These toilets provide basic lighting that keeps people safe at night, as well as providing water and sanitation.

The technology has also been installed in a Western context in the last 5 years at the pop-up Glastonbury festival where revellers can exchange their urine for charging their mobile phones, playing computer games, and powering some of the festival screens.

Living Architecture Project. By sequencing different bioreactors, the range of products that could be treated, produced, and reclaimed by the system could be increased. The EU-funded Living Architecture project successfully proved that a range of bioreactors (photobioreactors, Microbial Fuel Cells and synthetic bioreactors with engineered microbes) were arranged to exchange different types of nutrients within household liquid wastes and turn them into electrical energy 4-5 mW/unit and biomass. While the power output for this system is low, it invites the development of low-powered Direct Current (DC) electronic systems instead of modernity's high power (230V) Alternating Current (AC) supplies.

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The Living Architecture bioreactor 'wall' courtesy of the Living Architecture project, 2019.



The Living Architecture bioreactor 'wall' courtesy of the Living Architecture project, 2019.

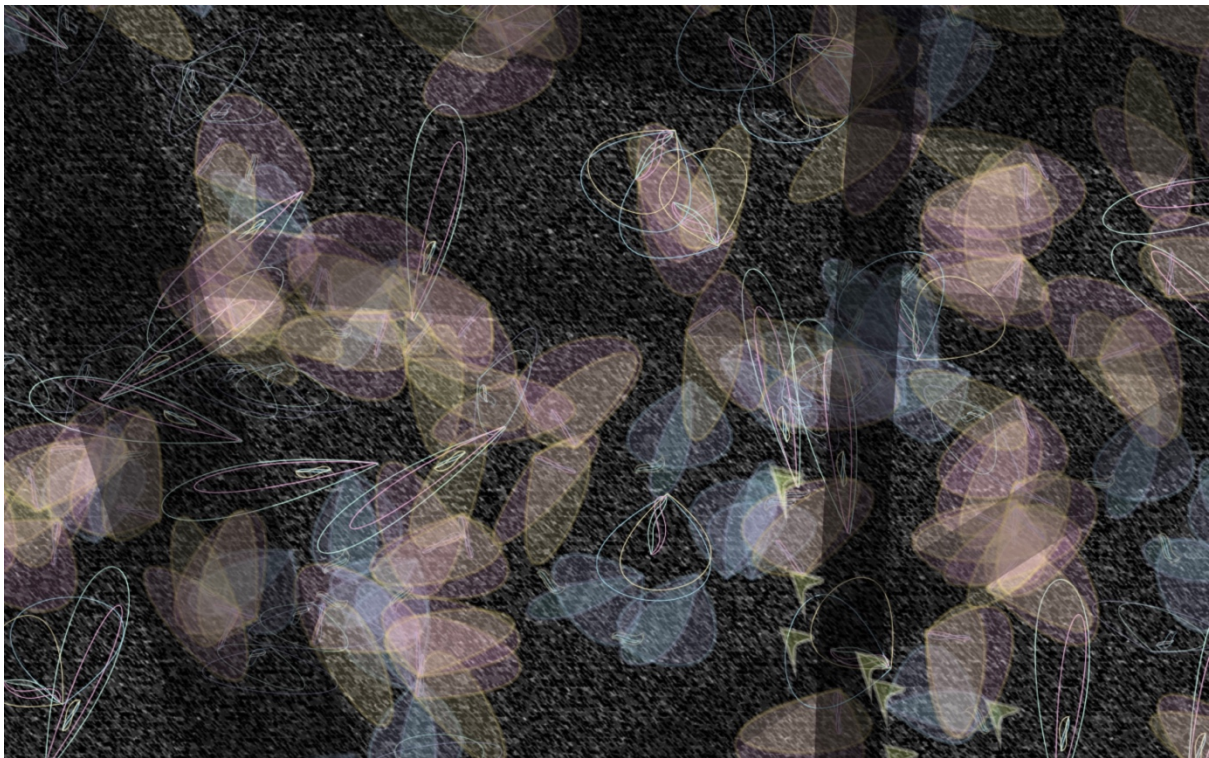
Active Living Infrastructure: Controlled Environment (ALICE) prototype. To enable non-specialists to understand how much energy the resident microbes produce as they process our waste, the “Active Living Infrastructure: Controlled Environment,” or ALICE project, was developed to provide an accessible digital interface that made the outputs of the system readable and relatable. Artist Julie Freeman developed characterful animations called “Mobes” that provided a way of interpreting the many different processes within the biofilm and respond to

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them by activating options to feed or warm them remotely in the laboratory. By observing the character-animations on the screen, we can respond to the needs of microbial cyborgs—so they are more like pets than ‘slime’—and will keep on producing the electrons that power the whole system producing 200 mW/L urine.



Screen shot from the <https://alice-interface.eu> webpage where a live feed from an MFC biofilm in a laboratory setting informs microbial data in the characterisation of ‘Mobes,’ 2020.



Another graphical view of “Mobes,” from the ALICE website (<http://alice-interface.eu>) showing dynamic, interactive, graphical representations of microbes, courtesy the ALICE consortium, 2021. © ALICE, screen shot from website.

ALICE is more than images on a screen, it exists as an installation, which takes the form of a transparent orb powered by microbes that animate LEDs and iPads. By uniting mechanical components (computer, LEDs, electronics, MFCs) and natural biofilms in the MFCs, ALICE

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has become an entity called a *cyborg* that is neither entirely biological, nor exclusively mechanical, which can be trained and domesticated like a pet.



The ALICE installation you see here, is a version of the interface that was exhibited during the Digital Design Week at the Victoria & Albert Museum last year. Courtesy of the ALICE consortium: Ioannis Ieropoulos, Julie Freeman, & Rachel Armstrong. © ALICE, photograph by Julie Freeman.

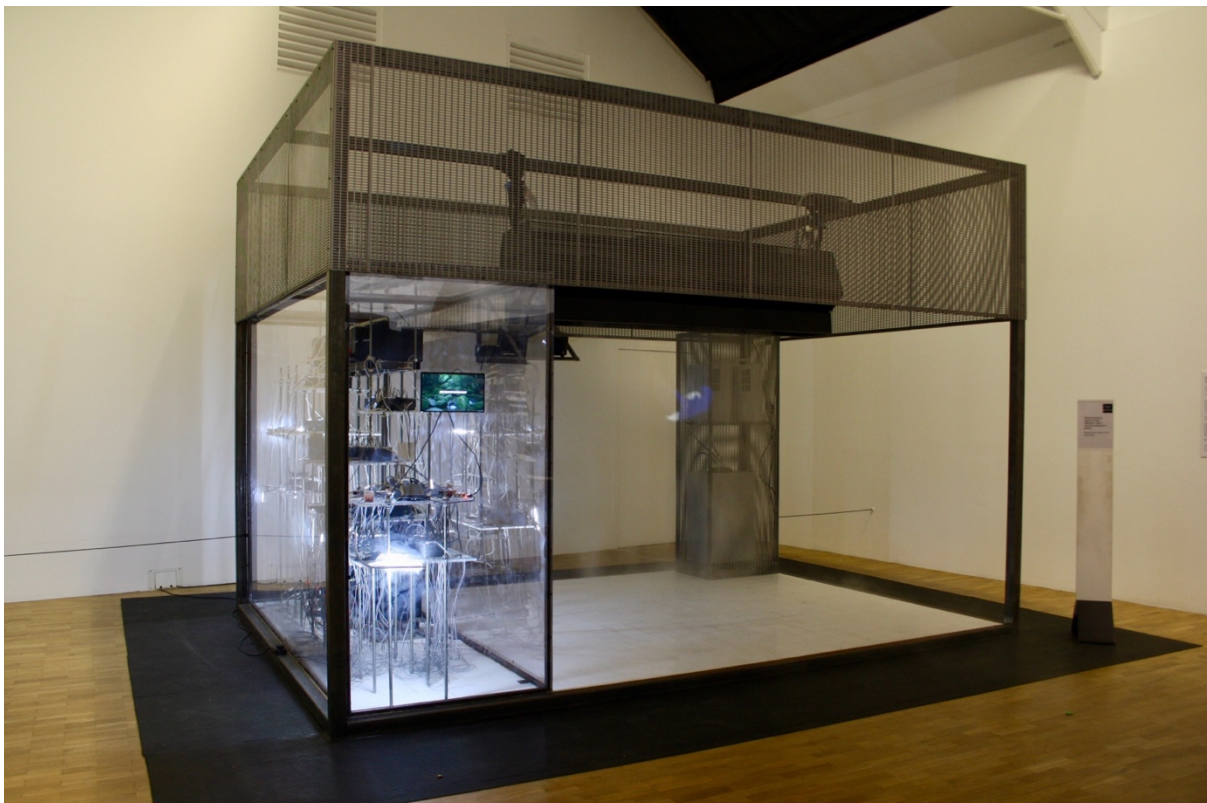


ALICE at the Electro Magnetic Festival Courtesy of the ALICE consortium: Ioannis Ieropoulos, Julie Freeman, & Rachel Armstrong. © ALICE, photograph by Rachel Armstrong.

The ALICE installation has been installed at the Victoria and Albert Museum for the Digital Design Weekend in September 2021 and at the Electromagnetic Field festival, Eastnor, in June 2022, embodying the bio-digital platform through the integration of microbial and artificial intelligences with biological and technical bodies.

9. *How might microbial ‘cyborgs’ inhabit our living spaces to provide building operations?* If we are to live in spaces where the building operations are (at least in part) performed by creatures such as microbes, then we need to establish a good relationship with them. In the installation *999 years 13sqm (the future belongs to ghosts)*, dedicated space was given to housing resident microbes in a stack of MFCs that formed a power-producing installation, which generated around 200 mW/L urine. The feeder tanks contained 20 litres of feedstock and were topped up and drained once a week.

The work was developed for the *Is this tomorrow?* exhibition at the Whitechapel Gallery, in collaboration with artist Cecile B Evans for a group show that was themed on the Whitechapel Gallery’s former landmark exhibition *This Is Tomorrow* in 1956. The original exhibition featured 37 British architects, painters, and sculptors, including Richard Hamilton, Eduardo Paolozzi and Alison and Peter Smithson, working collaboratively in small groups. *Is this tomorrow?* was a showcase of experimental propositions from contemporary leading architects and artists responding to 21st century issues at a time when humanity is facing new challenges posed by big data, bioengineering and climate change. As one of the ten invited artist/architect pairs, Cecile and I were invited to offer our vision of the future in the technological world of tomorrow. Our experimental project took the form of a future apartment space, where the only human presence was in the digital “ghosts” displayed on the screens, suggesting that this apartment exists at a time long after people had gone, when perhaps homes and cities are only inhabited by microbes (see Timmis and Hallsworth (2021) for a cautionary tale about what might happen if we don’t establish good relationships with microbes and other life forms).



999 years 13 sqm (the future belongs to ghosts), installation by Rachel Armstrong and Cecile B Evans at the Whitechapel Gallery for the “Is This Tomorrow” group show, Photograph courtesy Rolf Hughes, 2019.

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a. **Energy.** For MFCs to be installed in buildings, the units need to be smaller, and more efficient. Currently, scientists like Ioannis Ieropoulos are aiming to produce MFCs with a high energy density of 1mW/L feedstock. This means that soon MFCs will be portable, and you will be able to carry them to recharge your phone, or power an LED torch if you are out late.

While the overall electrical outputs are much lower than compared with fossil fuels, from an ecological perspective, setting these limits on energy consumption at source are creative and invites us to do things that require lots of energy differently. The unlimited energy offered by fossil fuels encourages wasteful patterns of behaviour, which accelerates consumption. Perhaps the most radical advance suggested by using microbes in our homes is to challenge our basic assumptions about the baselines of what we need to live comfortably and healthily. Imagine the reduced impact of human development if every home that is now connected to a 230V grid, could operate comfortably on a 12V battery supply. While this would require innovation in some of the things that we do every day that we solve by consuming a lot of energy, like washing machines and fridges, these same tasks could be done differently, such as using advanced new materials to help with refrigeration and finding alternatives to mechanical agitation like ultrasound to carry out this housework.

b. **Services Integration.** Perhaps the most interesting aspect of microbial solutions, is they can link previously separate realms. The electricity produced by anaerobic biofilms can be thought of as a kind of microbial “intelligence,” which can be combined with artificial intelligence (and machine learning) in hardware like Living Architecture, 999 years 13sqm (the future belongs to ghosts) and ALICE, so that nature comes into conversation with technology. More than just being a natural way of providing electrical energy, these ‘living’ microbial technologies are establishing the foundations for a Green Digital Revolution, where using our computers can help bioremediate our environment.

10. *What next for microbially powered building operations?* For microbially-produced materials and building operations to be adopted into mainstream building practices, the new kinds of services and buildings, typologies and structures must be figured out in detail. One way of doing this is to take established kinds of building typology (a way of categorising buildings based on their function, form, and how they are constructed) and to completely challenge our assumptions using what we have learned from microbial materials and building operations.

A good starting point is to take the idea of a toilet and consider how, rather than a waste chute that is flushed with water, it can become a different kind of system that processes the organic matter from our bodies into bioelectricity, cleaned water and a range of microbial ‘goods’ that we can use to make things, or return the microbially-transformed substances safely to the soil. If we are to take this challenge seriously, then new kinds of structures must be designed to help this system function properly, so that our going to the toilet helps reduce the impact of human development while bioremediating our surroundings.

The following images are based on new structures for housing MFC stacks, which encourage a different attitude towards, and expectations of our toilets and other sanitary spaces like bathrooms.

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MFC toilet structure made from recycled wood, inspired by the harbour ship hulls. Concept for the Estonian Maritime Museum, Tallinn, rendering by Anna Vershinina, 2023.

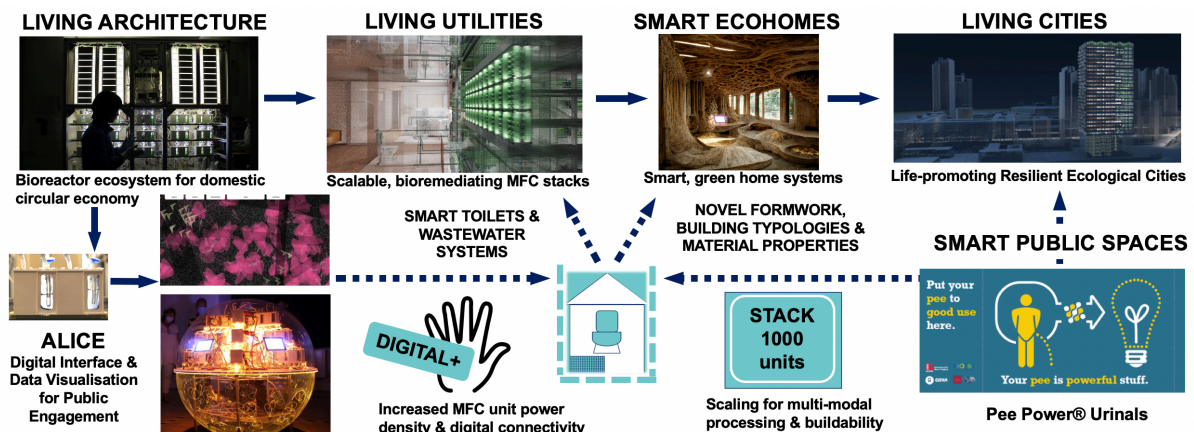


MFC toilet structure made from recycled wood, incorporated into a precision gardening unit with robot-farmed hydroponically grown plants. Concept for Nova Gorica GO! 2025 festival, rendering by Anna Vershinina, 2023.



MFC toilet structure made from recycled wood, inspired by biofilm formations, as the structure for a bioelectrically powered data centre. Concept for Laboral Centre for Art and Industrial Creation, Gijón, rendering by Anna Vershinina, 2023.

11. *Towards “Living” cities powered and produced by microbes.* The implications of using microbially-produced materials and building operations means that we can start to re-imagine how we live and work in our cities. Below is a diagram how all the different developments in microbial applications can build together to generate a city that is good for the planet, good for people and good for nature too.



The installation of microbial applications into our homes and cities can give rise to Resilient, Ecological “Living” cities that are produced (in part) by microbially-made materials and enabled by microbial technologies that: i) perform *building operations* (based on an ecology of scientific and technical advances achieved by the consortium—PeePower®, Living Architecture (LIAR), 999 years 13sqm (the future belongs to ghosts), Active Living Infrastructure: Controlled Environment (ALICE) which provide ecosystem services & energy for low powered electronic devices e.g. 5G WIFI transmitters, to keep communities connected by digital devices, and provide LED lighting, which are powered by green energy sources. These are used in concert with ii) *microbially made materials* (e.g., mycelium biocomposites), that reduce embodied energy and increase comfort (thermal and sound insulation, and fire resistance). The integration of systems and materials within the project’s constructions, enables further exploration of novel structures, aesthetics, and user experiences.

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In architecture, there is still some way to go before we can integrate all these solutions in a single house or building. But that time is not far away if we change our strategic priority. One day we will come home to a “living” building of our own – that will greet us through digital signals that have been produced by our waste, which turn on the LEDs that make our living space seem welcoming, clean up after us and make sure that our living space is just the way we like it.

The hardest part to altering our impacts is changing our thinking, our habits, and our ideas about what living a “good life” means. Whether we like it, or not, the rules for living on this planet have changed. The good news is that by rethinking how we can live alongside and work with microbes helps us make the necessary adjustments to work within the carrying capacity of our lands, draw on our collective creativity and help us find much, much, ways of better working alongside nature.

The impacts of working anew with microbes are fundamentally political, in that they make a difference to how our cities work – the term ‘polis’ was used by the ancient Greeks to indicate activities related to the affairs of the city. An eco-political benefit (one that addresses ecological and political issues) of finding new relationships with microbes is that we re-establish a relationship with land fertility, even in cities, as the biofilms that turn the soil over and make the ground productive, are now our close companions again.

While this does not solve the political issues of land ownership (where, in the first section of this document we saw wealthy landowners stealing the common land from peasants), we have access to new kinds of fertile spaces that we can tend to with precision gardening (which uses technology to increase the productivity of food-growing spaces), micro-gardening (the cultivation of very small spaces) and via the production of fertile techno soils (where citizens actually start to make their own soil using recycled construction and demolition waste, with the addition of home-grown biofilms and organic garbage).

The bad news is that, so far, nobody has demonstrated at scale that this is possible in Western communities and, therefore, requires the participation of adventurous and bold pioneers. Despite the present challenges, microbial technologies are here to stay and are helping us make a paradigm shift in how we live. Getting to know what microbes are and what they can do, is key to establishing an ecological era of human development, where the human species can become a fundamentally bioremediating and enlivening force within the biosphere.

Relevance for Sustainable Development Goals and Grand Challenges

The incorporation of microbes into building operations and microbially-made materials – whether locally applied within the household, or scaled to community and city dimensions – relates to several SDGs (*microbial aspects in italics*), including

- **Goal 3. Ensure healthy lives and promote well-being for all at all ages** (*improve health, reduce preventable disease and premature deaths*). Incorporating biopositive substances that are typical of microbially-made materials and bioreactors, which actively cultivate beneficial microbes into our homes and cities, are likely to have overall beneficial effects on human health, specifically via the probiotic balance between the *human microbiome*, the *microbiome of the built environment* and the *urban microbiome*. By re-enriching these ecological communities, life-promoting interactions and environmental services can be fostered that promote the health of soils, increase biodiversity beyond the conventional focus on plants and animals to improve the overall health of cities and their human inhabitants. All of these beneficial environmental effects

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promote well-being and good health, including mental health, with economic consequences for health budgets.

- **Goal 6. Ensure availability and sustainable management of water and sanitation for all** (*assure safe drinking water, improve water quality, reduce pollution, protect water-related ecosystems, improve water and sanitation management*). Microbial Fuel Cells (MFCs) play a crucial role in simultaneously biodegrading organic matter in wastewater, removing pathogen loads, bioremediating toxins (e.g., heavy metals), while converting the chemical energy within the bonds into electrical energy to provide low power renewable bioelectricity, which reduces the cost overall cost of wastewater treatment through safe and local effluent disposal.

- **Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all** (*ensure access to clean, renewable and sustainable energy, and increase energy use efficiency*). MFCs generate low-power renewable energy, which is more than a natural way of providing electrical energy, but also establishes an off-grid emergency communications platform through powering 5GWi-Fi networks in the immediate term. As the MFC platform is further refined, new units for construction will become increasingly available being stackable, lightweight, and versatile in their design enabling new kinds of structures and, ultimately novel building typologies. Currently, a 1000-unit MFC stack comprises 46 modules of 5L geometrical volume each, which is 230L total volume. With a 50L header tank and peripherals, this volume becomes 300L. With smaller MFC modules, 2 tiers of 22 MFCs/module can be produced reducing the total number of modules to 23, which would be 115L total volume (~190L with tanks & peripherals). The power density of MFC modules is also set to reach 1mW/mL feedstock. Scaled to 1,000-MFC units at 1-2mW/MFC, 1-2W, 24Wh-48Wh can be reasonably expected for 1 day, with 168Wh-336Wh per week, 720Wh - 1.4kWh for 1 month and 8.7kWh-17.5kWh for 1 year, taking a significant step towards resource circularity for human settlements raising the possibility of 12V domestic lifestyles that go beyond survival and bioremediate our surroundings, while meeting - and perhaps one day surpassing - the basic expectations of a modern existence (*see Gadja et al., 2018*). In the medium to longer term a 'living' utilities system based on smart toilet networks that generate bioelectricity are possible, which, when coupled to low power electronics enable a Green (bioremediating) Digital Revolution.

- **Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all** (*promote economic growth, productivity and innovation, enterprise and employment creation*). Since the work of life generates feedstock for microbes (urine, black water, grey water, liquid organic wastes) this forms a domestic currency of electrons. By exchanging our 'wastes' for electrons, cleaned water, biomolecules and detoxification processes within the home, even those who are not economically productive within a capitalism value system can make valuable contributions within a domestic economy.

- **Goal 9. Industry and innovation** (*promote economic growth, productivity and innovation, enterprise and employment creation*). The development of new microbially-based construction materials and building operations processes is pure innovation in industry and will lead to the creation of new enterprises likely to become a major driver of economic growth. Crucially, it will be economic growth in a key area of sustainability and in response strategies to the global warming crisis: *necessity is the mother of invention!*

- **Goal 11. Sustainable cities and communities** (*build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*). MFCs in particular form the basis for 'smart' sewerage and plumbing systems with biosensing potential i.e. they can detect the composition of their liquid contents, and provide electrical signals that linearly correspond with targeted contaminants. From a microbially-produced materials perspective, the ability to use local organic wastes as cost-effective fabrics reduces reliance on fossil-fuel derivatives while increasing

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the value of waste streams that are available to all (owing to the base value of all raw materials). In combination microbial solutions establish the potential of **paradigm shifting building technologies (services and materials)** that are cultured and grown, rather than mined, burned, or extracted, fundamentally changing the impact of the built environment on our living world to reach new levels of sustainability and resilience against climate change.

- **Goal 12. Responsible consumption and production** (*ensure sustainable consumption and production patterns*). By valorising waste streams, microbial technologies (materials and systems) enable an implementable system for a circular economy founded on zero waste, renewable energy and where ‘customers’ become ‘users,’ which does not exclusively rely on, or is defined by, human actions alone.

- **Goal 13. Take urgent action to combat climate change and its impacts** (*reduce greenhouse gas emissions, mitigate consequences of global warming, develop early warning systems for global warming consequences, improve education about greenhouse gas production and global warming*). The incorporation of microbial technologies (materials and systems) into our homes, communities and cities can **improve resilience, preparedness & responsiveness of the built environment for climate adaptation through resource circularity, bioremediating waste streams, setting limits to energy consumption and inviting innovation for low powered solutions for carrying out the activities of daily life**. Forming the operational basis for community transactions through access to the microbial commons, such microbial technologies establish a platform for a circular resource economy enabling new kinds of urban exchanges.

- **Goal 15. Life on Land** (*protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation and halt biodiversity loss*). Outputs from microbial technologies (materials and services) can be integrated with established building systems in retrofit, new build, or cultural heritage buildings and connected to existing utilities such as rainwater collection systems, and regenerative energy sources via the smart energy grid (solar, wind). The resultant versatile ‘Living’ buildings systems infrastructure is bioremediating and can be deployed across a range of vital services from hydroponics to sanitation, green energy, and environmental sensing. In this way, microbial technologies can be implemented to form a ‘Living’ utilities system optimising energy consumption, while having regenerative impacts on soil health, land fertility, biodiversity, thereby, rendering urban spaces more bio-positive—i.e., life-promoting.

- **Goal 17. Partnerships for the goals** (*strengthen the means for implementation and revitalize the Global Partnership for Sustainable Development*). Offering a range of new materials, building services and modes of producing work, microbial technologies establish the principles for breakthrough innovation at all stages within the built environment with benefits to producers, and consumers through a bioremediated, low energy environment that ultimately replenishes land fertility, increasing biodiversity. **Heralding an era of change** the potential of **paradigm shifting building technologies** based on microbial technologies that are cultured and grown in our homes and communities alongside us, fundamentally change the impact of the built environment on our living world to reach new levels of sustainability and resilience against climate change through new sources of bioenergy, sanitation, circularity for natural resources, increased soil and water health. Neither optional extras nor an architectural fashion, installing microbial technologies in our homes, buildings, and cities will, literally, save lives and invite partnerships from all levels of the building industry, utilities and land management services. At a time of climate emergency, escalating fuel prices and the displacement of peoples from war, having access to basic utilities as a combined processing system can provide clean water, shelter, power, and sanitation, which maintains a basic liveability made possible through the microbial commons to generate freely-available materials, even *in extremis*.

Potential Implications for Decisions

1. *Individual*

a. Weighing up the relative benefits of various microbial and non-microbial materials, systems and sources of energy and aligning them with personal convictions (do the personal positive low cost, low power benefits outweigh the convenience and speed of high-power energy systems? Do soft microbial materials perform an adequate function for the time they will actually be used for, compared with the idea/illusion of permanence).

b. Range of choice (variety of applications will be influenced by locally available materials, microbes, artisan skills and vernacular building styles)?

c. One solution does not fit all challenges (choosing a microbial system or material for implementation will be highly dependent on context, intended purpose, social acceptability and relative costs of the microbial solution)?

d. *Non-microbial parameters: value systems, shared vision of home and community, ability to work alongside and co-exist with global capitalism, creativity and imagination in developing new possibilities, legislation, education, literacy and raising awareness of the potential of microbial technologies, vested interests in keeping the status quo, etc.)*

2. *Community policies*

a. Local environmental consequences (pollution of land and rivers from domestic and community effluents, and local water bodies with faeces, nitrogen, phosphorus), provision of clean soil, detoxification of contaminants and use of local materials, Urban versus rural applications.

b. Production and training costs associated with altering established supply chains and building designs and practices. Business models based on user groups, stakeholder needs to strengthen supply chains and the workforce to implement the solutions.

c. Demonstrate cost-effectiveness of innovative solutions for the end users and mainstream life cycle costing approaches

d. *Non-microbial parameters: support of local businesses – builders, landowners, property developers, architectural practices, real estate companies, material suppliers, plumbers and utilities services, etc. – local policy regarding health and safety guidelines and the environmental regulation of microbes.*

3. *National policies relating to uptake of microbial technologies into the built environment*

a. Sustainability targets e.g. the EU's Decarbonization Pathway 2030, Net Zero 2050, including forecast/scenarios for built environment quality of living and working

b. Environmental pollution reduction e.g. bioremediation of waste streams, reuse of organic agricultural wastes, upcycling and reuse of household waste.

c. Adoption and implementation of Circular Economy principles through affordable and clean (low power) energy provision for e.g. LED street lighting, charging mobile phones etc.

d. Business models based on user groups, households and stakeholder needs with the potential for job creation

e. Increased citizen awareness and empowerment creating a user-centric knowledge based to catalyse community action and enable the global transition to climate neutrality through a resilient economy

f. Industrial leadership in key and emerging technologies that work for people.

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g. Non-microbial parameters: policies relating to circular economy: patents, licensing of the novel solutions. Resistance from established sectors and utilities that are renewables (don't perform bioremediation) and fossil fuel-based providers? An integrative energy approach can help address these challenges but industry is fundamentally protectionist and needs policy support to break the deadlock by providing incentives (or penalties).

Pupil Participation

1. Class discussion of the issues associated with growing your own home

- a. What would you make your house from?
- b. Can you draw, design or model your own-grown home? How long does it take to make?
- c. What things would you need to do differently in your home?
- d. Can microbes do everything that you need in the home? What can they not do?
- e. Is the inconvenience of working or doing things differently worth the benefits in environmental impact? Why?

2. Pupil stakeholder awareness

a. How different are microbes and machines in making materials or providing services? How similar are they? Clue, they both use energy, work at very different scales (microbe and human) and use resources in very different ways – machines have a very distinctive form (shape) while microbes are generally slimy. Also, machines process one thing at a time, while microbes are parallel processors (able to pat their heads and rub their tummies at the same time)! The idea here is to think from first principles how we might perform work differently and instead of using a machine, maybe we can ask nature to help us for certain tasks – not everything. This video imagines what would happen if we re-designed a plumbing system to provide energy for an entire apartment block:
https://www.youtube.com/watch?v=t_QdQiXBJn8

b. Can you think of any materials or services that could be provided by microbes in the home or in the community? Remember, we already have microbial practices which are mostly in making food e.g., cheese, bread, beer. Perhaps it would be good to think of the bathroom or kitchen as a starting point and use the Philips Microbial Home 2011 project as a talking point for inspiration which, for example uses microbes to provide lighting, generates biogas from kitchen compost and then uses that to grow herbs. Maybe the tables and chairs could be made from using organic waste turned into a solid biocomposite using fungi etc.

c. Can you think of anything you might personally do that uses microbes to reduce the environmental footprint of your home?

3. Exercises

a. In most homes, food waste is either ignored or handled as regular garbage. What other alternatives to disposing food waste can you envision? Also, urine is regarded as a contaminant that is flushed (with fresh water) down the toilet. What other uses for urine can you imagine (fertilizer, power source, etc.)

b. Furnishings often use fossil-fuel produced materials. What sustainable options are there for soft, foamy materials in a home? How might you formulate a sustainable microbially-produced material (e.g. mycelium biocomposite) and produce it for your city/town/region?

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c. Looking at the SDGs, how can we change our approach to the re-use of the substances we call waste to bring them into sustainable living? What are the challenges and opportunities? Create a sustainable city plan for waste streams and their associated environmental impacts.



Future microbial settlement, Mid Journey drawing by Rolf Hughes, 2022

The Evidence Base, Further Reading and Teaching Aids

Architecture that repairs itself (TED Talk):

https://www.ted.com/talks/rachel_armstrong_architecture_that_repairs_itself?language=en

Children of the Industrial Revolution (TEDx Danubia):

<https://www.archdaily.com/199069/tedx-danubia-children-of-the-industrial-revolution-rachel-armstrong>

Living Buildings:

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<https://www.itsnicethat.com/articles/rachel-armstrong-university-of-the-underground-architecture-040817>

https://www.youtube.com/watch?v=t_QdQiXBJn8

Press Articles on microbial materials

BioCouture: Suzanne Lee on microbial cellulose

<https://www.dezeen.com/2014/02/12/movie-biocouture-microbes-clothing-wearable-futures/>
Bioconcrete

<https://edition.cnn.com/2015/05/14/tech/bioconcrete-delft-jonkers/index.html>

BIQ building: The first algae façade

<https://www.internationale-bauausstellung-hamburg.de/en/projects/the-building-exhibition-within-the-building-exhibition/smart-material-houses/biq/projekt/biq.html>

The Quest to Grow Cities from Scratch

<https://www.fastcompany.com/3068583/the-quest-to-grow-cities-from-scratch>

Architecture and the microbiome (the microbial ecosystems all around us)

https://www.architectmagazine.com/technology/think-small-architecture-and-the-microbiome_o

Towards the engagement of microbes in the arts: Jens Hauser

<https://lab.cccb.org/en/toward-a-bacterial-turn-in-art-architecture-and-design/>

MediaLab: BioLogic materials

<https://www.dezeen.com/2015/11/04/mit-media-lab-tangible-media-group-biologic-material-bacteria-fashion-design/>

Ecovative and BioMASON collaborate

Accent table Fully Grown From Mushroom® Materials and Microorganisms Introduced at Biofabricate, by BioMASON and Ecovative, 2016

<https://grow.bio/blogs/press-releases/ecovative-and-biomason-collaborate-to-advance-biofabricated-furniture-for-the-home-and-office>

Use of melanin in design, 2019

<https://www.dezeen.com/2019/04/04/neri-oxman-totems-technology/>

Books

The need for a new architecture that welcomes microbes. Armstrong, R. (2021). *Safe as houses: More-than-human design for a post-pandemic world*. London: Lund Humphries.

Outline of a discipline called ‘experimental architecture’ and a collection of experimental/research practices with relevance to architecture. Armstrong, R. (2020). *Experimental Architecture: Designing the Unknown*. London: Routledge.

The role of microbes in establishing sociability. Hird, M. (2009). *The Origins of Sociable Life: Evolution after Science Studies*. New York: Palgrave Macmillan.

How a re-reading of the planetary condition can lead to new insights into our values and how we live. Tsing, A.L., Swanson, H.A., Gan, E. and Bubandt, N. (2017). *Arts of Living on a Damaged Planet: Ghosts and Monsters of the Anthropocene*. Minneapolis: University of Minnesota Press.

Academic Articles

Importance of microbes in ecosystems services in cities

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King, G. 2014. Urban Microbiomes and Urban Ecology: How Do Microbes in the Built Environment Affect Human Sustainability in Cities? *The Journal of Microbiology*, 52(9), pp. 721-728.

MFCs underpinning 'living' architecture. You, J., Rimbu, G.A., Wallis, L., Greenman, J. and Ieropoulos, I. (2019). Living Architecture: Toward Energy Generating Buildings Powered by Microbial Fuel Cells. *Frontiers in Energy Research* 12 (Bioenergy and Biofuels): <https://doi.org/10.3389/fenrg.2019.00094>.

Establishing the interface between microbes and the digital realm. You, J., Mendis, A., Greenman, J., Freeman, J., Armstrong, R., Hughes, R., and Ieropoulos, I. A. (2022). Development of a Bio-Digital Interface Powered by Microbial Fuel Cells. *Sustainability* 14, 1735: <https://doi.org/10.3390/su14031735>

Smart, biohybrid Materials, which change shape when wet

Wang, W., Yao, L., Cheng, C-Y, Zhang, T., Atsumi, H., Wang, L., Wang, G., Anilionyte, O., Steiner, H., Ou, J., Zhou, K., Wawrousek, C., Petrecca, K., Belcher, A.M., Karnik, R., Zhao, X. and Wang, D.I.C. (2017). Harnessing the hygroscopic and biofluorescent behaviour of genetically tractable microbial cells to design biohybrid wearables. *Science Advances* 3(5): <https://doi.org/10.1126/sciadv.1601984>

Heat absorbing fungal pigment

Casadevall, A., Cordero, R.J.B., Bryan, R., Nosanchuk, J. and Dadachova, E. (2017). Melanin, Radiation, and Energy Transduction in Fungi. *Microbiology Spectrum* 5(2): <https://doi.org/10.1128/microbiolspec.FUNK-0037-2016>; [10.1111/1751-7915.12807](https://doi.org/10.1111/1751-7915.12807)

Cordero, R.J.B. and Casadevall, A. (2019). Melanin. *Current Biology* 30(4): <https://doi.org/10.1016/j.cub.2019.12.042>

Mattoon, E.R., Cordero, R.J.B. and Casadevall, A. (2021). Fungal Melanins and Applications in Healthcare, Bioremediation, and Industry. *Journal of Fungi* 7(6), 488: <https://doi.org/10.3390/jof7060488>

Cordero, R.J.B., Dragotakes, Q., Friello, P.J. and Casadevall, A. (2022). Melanin protects *Cryptococcus neoformans* from spaceflight effects. *Environmental Microbiology* 14(4); 679-685: <https://doi.org/10.1111/1758-2229.13078>

Timmis, K. and Hallsworth, J.E. (2021). The darkest microbiome—a post-human biosphere. *Microbial Biotechnology* 15(1); 176-185: <https://doi.org/10.1111/1751-7915.13976>

Gajda I, Stinchombe A, Merinao-Jimenez I, Pasternak G, Sanchez-Herranz D, Greenman J and Ieropoulos IA (2018) Miniaturized Ceramic-Based Microbial Fuel Cell for Efficient Power Generation from Urine and Stack Development. *Frontiers Energy Research* 6(84): <https://doi.org/10.3389/fenrg.2018.00084>

Exhibitions

Whitechapel Gallery. (2019). Is This Tomorrow? 14 February to 12 May 2019. [online]. Available at: <https://www.whitechapelgallery.org/exhibitions/is-this-tomorrow/>.

The Idea Laboratory, April 2015

<https://freshartinternational.com/2016/02/26/fresh-talk-rachel-armstrong/>

Future Venice 2, 2015.

<https://nextcity.org/urbanist-news/experimental-architect-explores-biologys-role-in-the-urban-design>

June 2017 'Living Brick' installation featured as part of the Living Architecture project and exhibition of the developmental work carried out by the Experimental Architecture Group

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during this pioneering project. Shown as part of the Great North Museum Collection, The Great North Museum. <https://my.ncl.ac.uk/staff/nuconnections/item/living-bricks-exhibition>.

September-October 2017 Living Brick Series, Exhibitor in group show for 4th Tallinn Biennale, Estonia. Overall curator Claudia Pasquero <http://2017.tab.ee/programme/curatorial-exhibition/> and SEEM[N]EST with StudioUnseen <https://3dclayprinting.com/3dclayprinting/seemnest-by-studio-unseen-estonia/>

Companies making microbial materials

BIOHM—specialising in sustainable, organic materials and new ways of making buildings <https://www.biohm.co.uk>

BioMason—specialising in biobricks

<https://biomason.com>

Ecovative—specialises in mycelium biocomposites

<https://www.ecovative.com>

Grown.Bio—specializing in a range of mycelium products

<https://www.grown.bio>

Modern Meadow—specialising in victimless leather

<https://www.modernmeadow.com>

MOGU—specialising in mycelium biocomposites for home interiors

<https://mogu.bio>

Innovative art gallery working with the future of microbes in technology: Kersnikova Institute

<https://kersnikova.org>

Glossary

3-D printing—or additive manufacturing is the construction of a three-dimensional object from a CAD model or a digital 3-D model.

999 years 13sqm (the future belongs to ghosts)—is an installation by Cecile B. Evans and Rachel Armstrong at the Whitechapel Gallery at the group exhibition “Is this Tomorrow?”, London (2019) was possible with contributions by: Bioengineering team: Ioannis Ieropoulos (lead; University of the West of England), Simone Ferracina (University of Edinburgh), Rolf Hughes (Newcastle University), Pierangelo Scravaglieri (Newcastle University), Jiseon You (University of the West of England), Arjuna Mendis (University of the West of England), Tom Hall (University of the West of England), Patrick Brinson (University of the West of England); Microbial Fuel Cell Bioreactor Brick Installation Design: Pierangelo Scravaglieri and Jiseon You, under the guidance of Ioannis Ieropoulos; Structure Designer: Dominik Arni; Structure Fabricator: Weber Industries; Contributing Writer: Amal Khalaf; Animator: Tom Kemp; Composer: Mati Gavriel; Research and production assistance: Anna Clifford; Installation team: Richard Hards, Hady Kamar; Sponsorship from Personal Improvement Ltd. and Living Architecture (EU Grant Agreement no. 686585). In-Kind support provided by Andrew Hesketh; Audioviz (UK FogScreen); the Bristol BioEnergy Centre at the Bristol Robotics Laboratory and their research into alternative, sustainable sources of power for the home and infrastructure.

Absorption—is a chemical or physical phenomenon in which the molecules, atoms and ions of the substance getting absorbed enters into the bulk phase (gas, liquid or solid) of the material in which it is taken up. Absorption is the condition in which something gets mixed or absorbed completely in another substance.

Actuate—is to cause (a machine or device) to operate.

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Active Living Infrastructure: Controlled Environment, or ALICE project—is the first example interface for real-time digital exchanges between human and microbes. It is funded by an EU Innovation Award for the development of a bio-digital ‘brick’ prototype, a collaboration between Newcastle University, Translating Nature, and the University of the West of England (2019-2021) under EU Grant Agreement no. 851246.

Aggregate—is a whole formed by combining several separate elements.

Agrarian—relates to cultivated land or the cultivation of land.

Agricultural waste particles—are left over fragments from harvesting crops like sugarcane bagasse, rice husks, cotton stalks, straw.

Algae—a large class of plants that mostly live in water.

Anaerobic—is a process that does not need oxygen.

Anode—is the positively charged electrode by which the electrons leave an electrical device.

Artificial intelligence—is when computer algorithms can perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages.

Artificial leaf—are designed materials that resemble some of the functions of natural leaves. For example, The Silk Leaf by Julian Melchiorri, is the first man-made leaf that can survive in outer space. The leaf consists of chloroplasts extracted from real plant cells suspended in silk fibres with revolutionary molecule-stabilising properties.

Bacteria (plural), or bacterium (singular)—are members of a large group of unicellular microorganisms which have cell walls but lack organelles and an organized nucleus.

Bacterial cellulose—is cellulose that is produced by bacteria.

Battery—is a container consisting of one or more cells, in which chemical energy is converted into electricity and used as a source of power.

Battery cell—refers to the basic electrochemical unit that provides a source of electrical energy by direct conversion of chemical energy and consists of an assembly of electrodes, separators, electrolyte, container, and terminals.

Benthic microbial fuel cells (BMFCs)—are the potential sources for energy generation in which the chemical energy stored in the bonds between organic and non-organic materials are turned into electricity using microorganisms as the catalysts.

Black water—is the wastewater from bathrooms and toilets that contains faecal matter and urine. Water from kitchens and dishwashers are also considered blackwater due to the contamination by pathogens and grease

Big data—are extremely large data sets that may be analysed computationally to reveal patterns, trends, and associations, especially relating to human behaviour and interactions.

Biobricks—are bricks that are not fired from clay using a kiln but are hardened using MICP (see Microbial Induced Calcium Precipitation).

Biocellulose—(or microbial cellulose) is a natural fibre with a diameter of only 20 nanometers – 1000 times thinner than human hair. This superfine fiber is an eco-friendly, biodegradable alternative to fibres produced through commercial manufacturing processes.

Biochemical reactions—are chemical reactions that take place inside the cells of living things. The field of biochemistry demonstrates that knowledge of chemistry, as well as biology, is needed to fully understand the life processes of organisms at the level of the cell.

Bioconcrete—is a self-healing form of concrete designed to repair its own cracks by triggering a mineral-producing microbial metabolism (MCIP).

Bioelectricity—is the electrical currents and electrical potentials generated by or occurring within living cells, tissues, and organisms.

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Bioengineering—is a discipline that applies engineering principles of design and analysis to biological systems and biomedical technologies.

Biofertilizer—is a biological preparation of efficient microorganisms that promote plant growth by improving nutrient uptake.

Biofilm—is a soft, formless, complex structure formed by microbial colonies, which can be thought of as ‘microbial cities.’

Biofuel—is any fuel that is derived from biomass—that is, plant or algae material or animal waste.

Biogeochemical cycle—is the pathway by which a chemical substance cycles the biotic and the abiotic compartments of Earth.

Biohybrid—is a material that contains or is composed of both biological and non-biological substrates.

Bioink—is a gel containing microorganisms which thrive in the medium and are used in 3-D printing to create the final shapes of different applications like artificial leaves, photosynthetic skins, or photosynthetic bio-garments.

Bio-inspired - the geometry of a plant or animal is copied to make an “organic”—or nature-based design statement

BioMason—is a company that aims to remove 25% of carbon emissions from the concrete industry by 2030. [<https://biomason.com>]

Biomass—is organic material that comes from living organisms, such as plants and animals.

Biomolecules—are a molecules that are produced by living organisms.

Bioplastics—are plastic materials produced from renewable biomass sources, such as vegetable fats and oils, corn starch, straw, woodchips, sawdust, recycled food waste, etc.

Bioreactor—is an apparatus in which a biological reaction or process is carried out, especially on an industrial scale.

Bioremediating/ bioremediation—is the use of naturally occurring or deliberately introduced microorganisms to consume and break down environmental pollutants, in order to clean a polluted site.

biosphere—is the regions of the surface and atmosphere of the earth or another planet occupied by living organisms. It is another word for our living world.

Bill & Melinda Gates Foundation—is an organisation committed to tackling the greatest inequities in our world. [<https://www.gatesfoundation.org>]

Brundtland Report—a landmark report on sustainable development called “Our Common Future” published in 1987.

[<https://www.are.admin.ch/are/en/home/media/publications/sustainable-development/brundtland-report.html>]

Building regulations—are statutory instruments or statutory regulations that seek to ensure that the policies set out in the relevant legislation are carried out. Building regulations approval is required for most building work.

Building operations—these are all the active functions performed by buildings

Carbon dioxide (CO₂)—is a chemical compound made up of molecules that each have one carbon atom covalently double bonded to two oxygen atoms. It is found in the gas state at room temperature. In the air, carbon dioxide is transparent to visible light but absorbs infrared radiation, acting as a greenhouse gas.

Carbon emissions/ CO₂ emissions—are emissions stemming from the burning of fossil fuels and the manufacture of cement; they include carbon dioxide produced during consumption of solid, liquid, and gas fuels as well as gas flaring.

Carbon footprint—is a measure of the amount of carbon dioxide released into the atmosphere as a result of the activities of a particular individual, organization, or community.

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Carbonate—is a type of salt that is formed when carbon dioxide is dissolved in a liquid.

Cathode—is the the negatively charged electrode by which electrons enter an electrical device.

Cellulose—is an insoluble substance which is the main constituent of plant cell walls and of vegetable fibressuch as cotton. It is a polysaccharide consisting of chains of glucose monomers.

Chloroplasts—are inclusions in green plant cells which contain chlorophyll where photosynthesis takes place.

Cladding—is a covering or coating on a structure or material.

Colonies—are communities of animals or plants of one kind living close together or forming a physically connected structure.

Concrete—is a building material made from a mixture of broken stone or gravel, sand, cement, and water, which can be spread or poured into moulds and forms a mass resembling stone on hardening.

Cement—is a powdery substance made by calcining lime and clay, mixed with water to form mortar or mixed with sand, gravel, and water to make concrete.

Circular system— is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature. decouples economic activity from the consumption of finite resources. It is a resilient system that is good for business, people and the environment.

Crystallize—is form or cause to form crystals.

Cyanophyte—is a microorganism of the division Cyanobacteria.

Cyborg—is a fictional or hypothetical person whose physical abilities are extended beyond normal human limitations by mechanical elements built into the body.

Digital interface—is is the medium through which humans interact with computers. Interfaces represent an amalgamation of visual, auditory, and functional components that people see, hear, touch, or talk to as they interact with computers (digital devices).

Direct Current (DC)—is an electric current flowing in one direction only.

Eco-political—is the study of the interrelation between political and ecological issues and problems.

Ecosystem—is a biological community of interacting organisms and their physical environment.

Ecovative—is a company that unlocks the power of mycelium to grow better materials
[<https://www.ecovative.com>]

Electricity—is a form of energy resulting from the existence of charged particles (such as electrons or protons), either statically as an accumulation of charge or dynamically as a current.

Electrons—are stable subatomic particles with a charge of negative electricity, found in all atoms and acting as the primary carrier of electricity in solids.

Embodied carbon—is the carbon dioxide (CO₂) emissions associated with materials and construction processes throughout the whole lifecycle of a building or infrastructure.

Embodied energy—is a calculation of all the energy that is used to produce a material or product, including mining, manufacture and transport.

Enclosure acts—are now usually spelt "enclosure" (formerly The Inclosure Acts, using an archaic spelling of the word), create legal property rights to land previously held in common.

Engineered microbes—or, genetically modified bacteria, were the first organisms to be modified in the laboratory, due to their simple genetics.

Environmentally-friendly—something that does not harm the environment.

Environmental services—are those that include the provision of raw materials and energy used to produce goods and services, the absorption of waste from human activities, and the basic roles in life support and the provision of other amenities such as landscape.

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Escherichia coli—is also known as E. coli, which are Gram-negative, facultative anaerobic, rod-shaped, coliform bacteria of the genus Escherichia that are commonly found in the lower intestine of warm-blooded organisms.

Exoskeleton—is an external skeleton that supports and protects an animal's body

Exponential rate—is an increase that is becoming more and more rapid.

Eutrophication—is the process by which an entire body of water, or parts of it, becomes progressively enriched with minerals and nutrients, particularly nitrogen and phosphorus.

Façade—is the main front of a building, that faces on to a street or open space.

Field study/trial—is an experiment that occurs in a natural setting. Researchers examine how the manipulation of at least one independent variable leads to a change in a dependent variable in the context of the natural environment.

Feeder tank—is a vessel that is designed to hold liquid for release into another system.

Feedstock—is raw material to supply or fuel a machine or industrial process.

Formless—lacking a recognisable shape, or geometry.

Fossil fuels—are hydrocarbon-containing materials formed naturally in the Earth's crust from the remains of dead plants and animals that are extracted and burned as a fuel. The main fossil fuels are coal, oil, and natural gas

Foster + Partners—is an architectural firm founded by Norman Foster.

[<https://www.fosterandpartners.com>]

Free radicals—are unstable atoms that can damage cells, causing illness and aging

Fungi—are organisms that resemble plants but, biologically speaking, they are much more like animals and have an insect-like shell, which stiffens their cells. Their reproductive bodies are recognised as 'mushrooms' or 'toadstools.'

Glastonbury festival—is a five-day festival of contemporary performing arts that takes place in Pilton, Somerset, England.

Green Digital Revolution—is a vision for the near future when electronic systems are powered by biological metabolism rather than fossil fuel, or renewables, so that the use of computers is bioremediating and helps restore environmental health.

Greywater—is the wastewater that comes from sinks, washing machines, bathtubs and showers. It contains lower levels of contamination, making it easier to treat and process.

Herzog & De Meuron—is a Swiss based architecture firm with its head office in Basel, Switzerland, founded by Jacques Herzog and Pierre de Meuron.

[<https://www.herzogdemeuron.com>]

Homogeneous—is when things are of the same kind; alike.

Hydration—is the process of causing something to absorb water.

Hybrid—is something made by combining two different elements.

IDEA Laboratory—was held in the Azerbaijan Pavilion where the exhibition Vita Vita took place during the 56th Venice Biennale.

[<https://artwisescurators.com/exhibitions/10/overview/>]

Industrial sector—is mostly made up of companies involved in the manufacturing and distribution of capital goods, transportation services, or the provision of commercial services and supplies.

Inert—is when something is non-reactive.

Installation—is an artistic genre of three-dimensional works that are often site-specific and designed to transform the perception of a space.

Insulated—is when something is protected by interposing material that prevents the loss of heat or the intrusion of sound.

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Kombucha tea—is a fermented drink produced by symbiotic fermentation of sugared tea using a symbiotic culture of bacteria and yeast (SCOBY) commonly called a "mother" or "mushroom".

Land ownership—land ownership regulates the relationship of the people to the land, specifically the power of disposition over land and the right to use the land.

Light Emitting Diode (LED)—is a semiconductor device that emits light when current flows through it.

Limestone—is also known as (calcium carbonate CaCO_3) and is a type of carbonate sedimentary rock which is the main source of the material lime.

Living Architecture—is a modular bioreactor-wall, based on the operational principles of microbial fuel cell technology and synthetic 'consortia' of microbes. It demonstrated the proof of principle that different bioreactors could be sequenced in a domestic setting to generate a microbially-enabled circular economy. It is Funded by the EU Horizon 2020 Future Emerging Technologies Open programme (2016-2019) Grant Agreement 686585 a consortium of 6 collaborating institutions—Newcastle University, University of Trento, University of the West of England, Spanish National Research Council, Explora Biotech and Liquifer Systems Group.

Living cities—are those that are fundamentally life-promoting, which is greatly assisted by the uptake of microbial materials and technologies.

Milliwatts(mW)—are one thousandth (10^{-3}) of a watt.

Melanin—is a broad term for a large group of related molecules found in most organisms that are responsible for many biological functions, including pigmentation of skin and hair and protection of the skin and eye from sun damage by UV light.

Metabolism – is the process by which the body changes food and drink into energy and comprises all the biochemical reactions performed by a cell, or organism.

MFC-microbial fuel cell—is a type of bioelectrochemical fuel cell system that generates electric current by diverting electrons produced from the microbial oxidation of reduced compounds (also known as fuel or electron donor) on the anode to oxidized compounds such as oxygen (also known as oxidizing agent or electron acceptor) on the cathode through an external electrical circuit.

MFC stack—is when MFC arrays are stacked in trays and loaded above each other, as in a cafeteria.

Mobes—relatable animations that represent those actions of microbes developed by data artist Julie Freeman.

Microalgae are microscopic algae that are invisible to the naked eye, which exist as individual cells, or form chains or groups, which we often encounter as 'pond scum.'

Microbes—are tiny living things that are found all around us and are too small to be seen by the naked eye.

Microbial 'goods'—are the molecules and processes performed by microbial metabolism that can be used or harvested.

Microbial Induced Calcium Precipitation (MICP)—is an active process of mineralisation produced by microbes that results in the deposition of insoluble calcium salts e.g. calcium carbonate.

Microbial intelligence—is inherent to microbes as they monitor their environment, process information, and intelligently make a decision. These decisions can be made through various mechanisms and networks such as gene-expression regulation, signaling pathways, transport, metabolism, etc.

Microorganisms—are tiny creatures that cannot individually be seen with the naked eye and include bacteria, archaea, fungi, protists, viruses.

Micro gardening—involves planting vegetables, fruits, and flowers in a small space where plants would not ordinarily be found. This hobby is also referred to as tiny gardening.

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Microscope—is a laboratory instrument used to examine objects that are too small to be seen by the naked eye.

Mesh—is a fabric that is usually made from polyester, nylon or spandex. These synthetic materials last a very long time.

Microbiome—(*human*) comprises bacteria, archaea, viruses, and eukaryotes which reside within and outside our bodies. These organisms impact human physiology, both in health and in disease, contributing to the enhancement or impairment of metabolic and immune functions—(*of the built environment*) refers to the microbial communities harbored by the environments that humans have constructed, including houses, offices, public buildings (such as schools), cars, roads, and public transport, but also drinking water treatment plants and other human-built spaces—(*urban*) consists of microbial consortia inhabiting regions throughout the body (i.e., the gut, skin, lungs, etc.), urban microbiomes are a collection of microbial communities that occupy diverse reservoirs throughout city landscapes, from the depths of sewers to the tops of buildings.

Mimic—is when something is copied or resembled to produce an effect inferred by the original object or system.

Minerals—are naturally occurring inorganic substances.

Mycelium—is a fine filamentous system that forms the vegetative body of fungi, which is a root-like structure

Mycelium biocomposite—is a solid material formed when fungal mycelium grow into agricultural wastes, binding them together with novel properties e.g. lightweight, heat and sound insulating.

National power grid—is composed of power generators – such as dams, coal plants or wind turbines – and million miles of power lines carrying electricity all over the country.

Nature-based—solutions are those that are inspired and supported by nature.

Net-positive—is something that puts back more into society, the environment and the global economy than it takes out.

New generation of sustainable buildings—these buildings are much more ambitious than net zero and aim to benefit the natural world by not only using natural energy to run their operations, but also by growing their materials and re-using them at the end of their lifespan.

Nutrient—is a substance used by an organism to survive, grow, and reproduce.

Operating energy—the total energy needed to run building operations

Organic—is something relating to or derived from living matter.

Pathogens—are organisms that cause disease to their host.

PeePower®—is an electricity-generating sanitation solution for decentralized areas. PeePower®—is a prototype that uses urine as a source of power to produce electricity.

Photobioreactors—are any cultivation system designed for growing photoautotrophic organisms using artificial light sources or solar light to facilitate photosynthesis.

Photosynthetic bio-garments—are clothes that can photosynthesise like plants.

[<https://www.dezeen.com/2019/10/02/biogarmentry-roya-aghighi-living-clothes-photosynthesis/>]

Photosynthetic skins—are building skins or coverings that can photosynthesise, often by the inclusion of chloroplasts or microalgae.

Political—is the set of activities that are associated with making decisions in groups, or other forms of power relations among individuals, such as the distribution of resources or status. Politics (from Greek: Πολιτικά, politiká, 'affairs of the cities').

Precision gardening and precision agriculture—are methods of farming (gardening= small scale; agriculture= large scale) that use technological innovations - including GPS guidance, drones, sensors, soil sampling and precision machinery - to grow food/crops more efficiently.

Proton-exchange membrane—is a semipermeable membrane generally made from ionomers and designed to conduct protons while acting as an electronic insulator and reactant barrier, e.g. to oxygen and hydrogen gas.

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Renewable sources—are those that are replenished at a higher rate than they are consumed.

Saccharomyces—are yeasts (e.g. Brewer's or Baker's yeast) that convert the chemical energy of sugar into electrons

Sandstone—is a clastic sedimentary rock formed through transportation, deposition, compaction and cementation of different mineral composition of sand grains

Sediment—is fine solid matter that settles to the bottom of a liquid.

Self-healing materials—are are polymers, metals, ceramics, and their composites that when damaged by an operational use has the ability to fully or partially recover its original set of properties.

Spores—are units of sexual or asexual reproduction that may be adapted for dispersal and for survival, often for extended periods of time, in unfavourable conditions.

Sustainable architecture/buildings—are those that are designed to help reduce the overall impact on the environment and human health during and after construction.

Sustainable development—sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (see Brundtland Report)

Sustainable resources—are ones that can be repeatedly harvested e.g., biofuels and biomass

Symbiosis—is any type of a close and long-term biological interaction between two different biological organisms,

Synthetic bioreactors—are environments that allow biological and/or biochemical activities within or between genetically modified organisms, to take place under highly monitored and regulated environmental and operational conditions.

Tapestry—is is a woven structure that has threads running in both directions.

Technosols—is a Reference Soil Group, according to the World Reference Base for Soil Resources, that combines soils whose properties and pedogenesis are dominated by their technical origin. They contain either a significant number of artefacts, some sort of geotechnical liner, or are sealed by technic hard rock.

Tenants—are people who occupy land or property rented from a landlord.

Tendrils—is a slender whiplike or threadlike strand, produced usually from the node of a stem, by which a vine or other plant may climb. Its anatomy may be of stem tissue or of leafstalk tissue.

Textile—is a material made from fibers, thin threads or filaments that are natural or synthetic or a combination of both.

Thrombolites—are microbial formations that have a clotted internal organisation as opposed to stromatolites that have a laminated organisation.

TU Delft—a university in the Netherlands called the Technical University of Delft

Typology—a way of categorising buildings based on their function, form, and how they are constructed.

Urine—is a liquid by-product of metabolism in humans and in many other animals

Ultraviolet (UV) light—is a form of electromagnetic radiation with a wavelength that falls in the range of the EM spectrum between visible light and X-rays and is powerful enough to break chemical bonds.

Vegetative body, or structure—is the structure that is not associated in reproduction.

Ventilation system—is the mechanical system in a building that brings in "fresh" outdoor air and removes the "contaminated" indoor air.

Versatile—is when something can adapt or be adapted to many different functions or activities.

Zero impact—buildings that effectively do not consume any energy from the national power grid