Chapter 2
Low Energy Adaptive Biological Material Skins from Nature to Buildings

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Abstract This chapter reviews emergent work in large-scale interactive building skins that use biological materials derived from abundant, renewable, biodegradable sources like silk, algae, wood, cellulose, chitin, fungi, or bacteria. They are surveyed as new interactive systems for material-driven environmental sensing and response within the outer layer of architectural applications. Programmed at the molecular scale, they respond to their surroundings at the building scale by; self-healing cracks, performing programmed decay, tuning flexibility and opacity depending on sunlight and rain, changing color to diagnose health markers, shapeshifting with humidity changes, digesting waste into structure, cooling and cleaning air, or transforming city pollutants into fuel and aliments. Demonstrators are often in testing phases, but critical in signaling a future for sustainable material systems offering adaptive solutions at the intersection of building construction and biotechnology that are elegant in both their efficiency and new aesthetics.

Keywords Bio-composites · Adaptive materials · Programmed matter · Responsive skins

2.1 Introduction: Nature to Buildings

Biomimicry in architecture—in other words, design inspired by how functional challenges have been solved in biology (Pawlyn, 2019)—has broadened its scope in recent year's research. Solutions in buildings emerge that expand beyond traditional advances in technology inspired by biological strategies, and towards including living and bio-based matter itself. This is because bio-based, biological, or even living material solutions present a dual advantage to common construction materials such as glass, concrete, ceramics, steel, or aluminum. On one hand they involve much

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J. Wang et al. (eds.), *Advanced Materials in Smart Building Skins for Sustainability*,
https://doi.org/10.1007/978-3-031-09695-2_2

lower construction waste and energy consumption in extraction, synthesis, and end-of-life (Ashby, 2021). On the other hand, they are programmable with new function enhancing sustainability as well as multiplicity of unprecedented function as reviewed later in the text (Shtein & Shoseyov, 2017). New man-made composites from synthetic materials also present large ecological footprints in their production and are difficult to disassemble for recycling (Bechthold & Weaver, 2017). Many naturally grown materials like cellulose, silk, or chitin are lightweight but strong, stiff, and tough, while made at ambient conditions, processed with low energy and low waste, and composed of simple molecules that biodegrade without toxicity (Vincent, 2012; Wegst & Ashby, 2007). Not only these materials present desirable environmental friendliness, but they also have inherent capacity to interact and adapt to their surroundings with passive strategies able to be programmed for specific functions. Today, in the field of building construction, and following similar avenues in materials science and biomedical engineering, mimicking Nature's intelligence will ensure superior function and efficient reuse of resources.

Biological materials are indeed gaining interest in the architectural community with large-scale solutions being developed as demonstrators of a new paradigm. A paradigm observing matter as a design element to be described to the molecule (Mogas-Soldevila, 2021), a task enabled by the fact that natural matter is in constant re-design during growth by responding to the environment and to the forces acting upon it, making material properties vary across species, within the same species, and throughout the same organism. For instance, organic composite materials give living tissues the ability to adapt by rearranging their material configurations towards optimized ones. The leaf closing of *Mimosa pudica* in response to touch, heliotropism in sunflowers following sunlight, skin color changes in *Loliginidae squid*, catapult seed actions of some fruits, variable-stiffness collagen in marine animals, opening and closing of pine cones, and the hinged operation of ice plant seed capsules, are just a few examples of this extraordinary ability (Ball, 2012; Bechthold & Weaver, 2017; Jeronimidis, 2009).

Such adaptation that helps trees, insects, and humans survive, can be re-programmed to solve specific building problems, or deliver desired signals as described next. Reviewed below, recent solutions show efforts to invent systems that respond to changes in the environment performing adaptation of mechanical, optical, and chemical material properties. Examples chosen are larger than meter-scale, geared towards façade implementation, and made of raw bio-based materials derived from wood, silk, or chitin, or made of living organism assemblies like fungi networks, bacterial colonies, mosses, or microalgae.

2.2 Methodologies in Practice: The Active Skin

The function of a building skin is to shelter and enclose human activity by filtering light, radiation, dirt, moisture, temperature, and pathogens. This emphasis in protection, renders traditional buildings static for decades hardly interacting with their occupants and the environment. Mechanically responsive facade systems are emerging in the field and typically poses some of the following features embedded within man-made actuated technology; energy storing, natural ventilation, radiation control, or automated management of plants on the building skin (Romano et al., 2018). In nature, skin, shell, or cuticle do protect organisms by filtering light, radiation, dirt, moisture, temperature, and pathogens, and do store energy and manage systems automatically like these new facades do, but they perform outstanding added functions of self-repair, shape-shift, sensing, and color change to adapt to their changing surroundings.

It is the goal of many of the solutions presented in this section to achieve these superior levels of interaction by mimicking naturally grown skins. Biological material systems and biology-driven strategies in the demonstrator examples reviewed below aim to create buildings that respond to their surroundings while being environmentally friendly (Sandak et al., 2019). Proposals can perform programmed decay, change flexibility and opacity responding to sunlight and rain, self-heal cracks using bacteria, change color in response to health markers, curl and shapeshif with humidity changes, capture carbon dioxide, digest waste into structural members, react to hot weather with evaporative and radiative cooling, clean city air, or transform air pollutants and water contaminants into fuel and food (Figs. 2.1 and 2.2).

2.2.1 Wood

Most advanced large scale biological material solutions for building skins are based on timber and wood composites and are a promising resource because of their renewability, sustainability, and versatility. Producing wood for buildings uses about 10% of the energy required to produce equivalent amount of steel. It is transformed with much simpler tooling while enabling prefabrication, fast installation, favorable weight-to-load-bearing capacity ratio, and low thermal conductivity increasing its applicability in façades (Sandak et al., 2019). However, many efforts aim at keeping wood systems static and avoiding their natural tendency to deform and interact with environmental humidity. Examples below harness that ability, instead of suppressing it, to achieve higher order of performance.

In nature, structural anisotropy in the organization of cellulose wood fibers can induce movement through water absorption and differential swelling, as observed in pinecones when they passively open their seed pods. Larger scale hydromorphic effects can be programmed in plywood selecting and arranging wood in specific grain directions using its expanding behavior as an actuator. The ICD at the University of

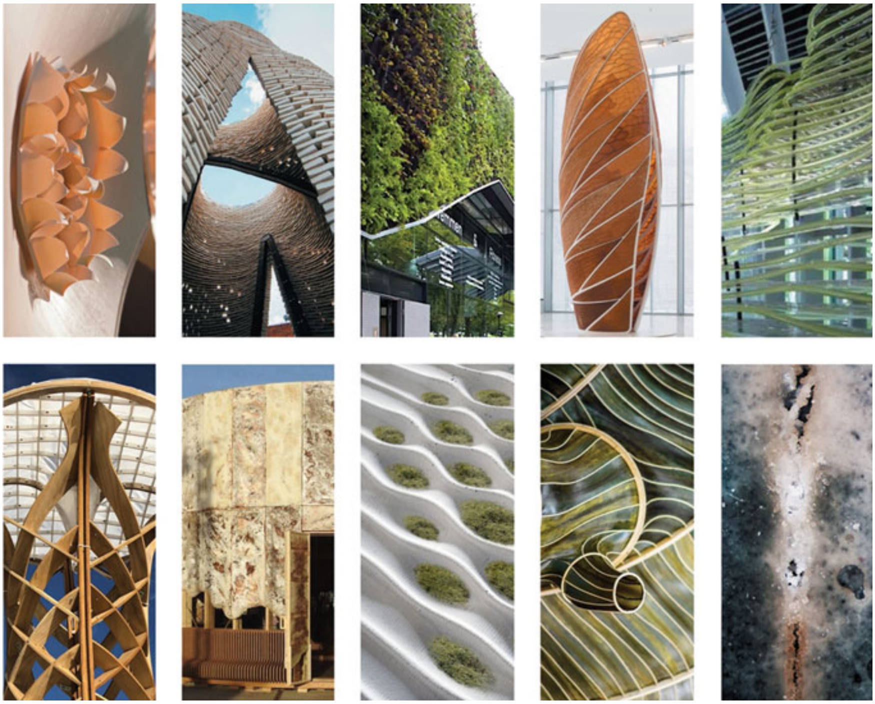

Fig. 2.1 Column one; (top) Hygroskin by the ICD (Menges & Reichert, 2015) and (bottom) Hydroculus by Thermal Architecture Lab (Aviv et al., 2020). Column two; (top) HiFy by The Living (The Living NY, 2014) and (bottom) Growing Pavilion by Company New Heroes (Biobased Creations, 2019). Column three; (top) Sportplaza Mercator by VenhoevenCS (VenhoevenCS architecture + urbanism, 2006) and (bottom) Bioreceptive concrete by BiotA Lab (Cruz & Beckett, 2016). Column four; (top) Aguahoja1 by The Mediated Matter Group (Duro-Royo et al., 2018) and (bottom) Hidaka Ohmu by Julia Lohmann (Lohmann, 2017; Toivola, 2020). Column five; (top) HORTUS XL by ecoLogicStudio (Valenti & Pasquero, 2021) and (bottom) Bioconcrete by Jonkers Lab (Jonkers, 2011)

Stuttgart has developed a series of studies for thin wood veneer façade systems that shape-shift with humidity changes during building use. For instance, Hygroskin uses flat petal-like units arranged in pentagons of about half a meter wide that stay stiff and closed in dry weather but become flexible and open in high humidity situations to ensure ventilation. Their deformation is reversible in several thousand cycles. (Krieg & Menges, 2013; Menges & Reichert, 2015) (Fig. 2.2, column one). New prototypes by the same group envision; additively-manufacturing wood-like systems using cellulose and other biopolymers to match similar motion rates with larger design freedom, or obtaining doubly-curved 9 m-tall assemblies using the same principle during panel formation (Correa et al., 2015; Grönquist & Bechert, 2020).

Also made of wood and in partnership with water, a recent project called Hydroculus by the Thermal Architecture Lab at the University of Pennsylvania can

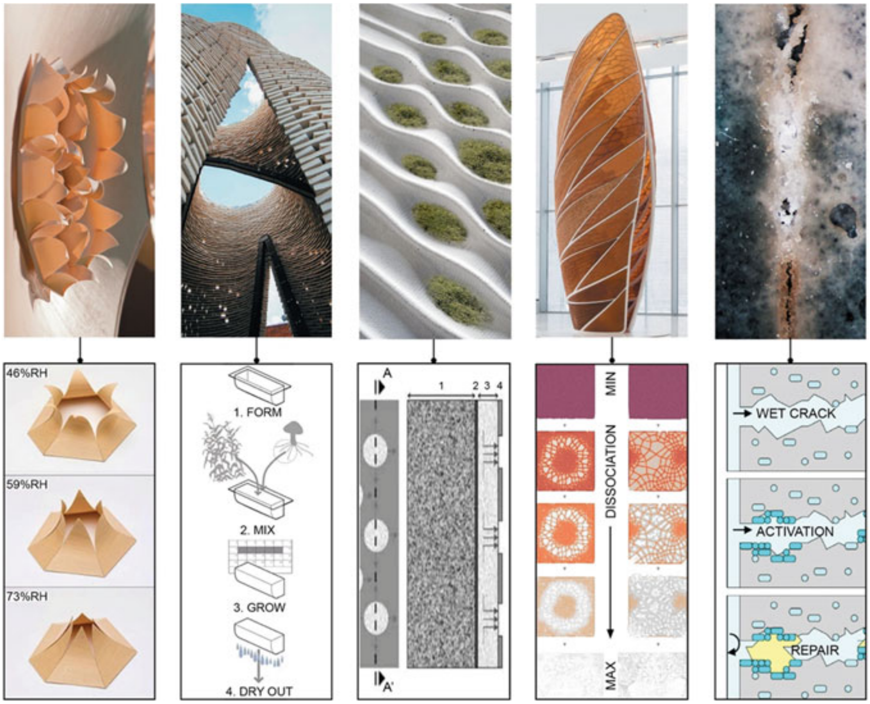

Fig. 2.2 Column one; (top) Hygroskin structure by ICD, Institute for Computational Design at the University of Stuttgart (Menges & Reichert, 2015) and (bottom) Hygroskin veneer-composite unit shape changing by hygroscopic response to relative humidity change (adapted from (Correa et al., 2015)). Column two; (top) HiFy by The Living (The Living NY, 2014) and (bottom) mycelium brick formation steps including 5-day agricultural waste digestion and heat treatment before use (adapted from (Holcim Foundation Awards, 2015)). Column three; (top) Bioreceptive concrete by BiotA Lab and (bottom) section of bioreceptive panel depicting (1) structural Portland Cement, (2) anchoring and sealing interface, (3) bioreceptive mortar with water retention capabilities, (4) water absorbing coating (adapted from (Cruz & Beckett, 2016)). Column four; (top) Aguahoja1 by The Mediated Matter Group (Duro-Royo et al., 2018) and (bottom) simulation of swelling and decay by effects of weathering based on measurements of printed patches following Aguahoja's materialization technique (adapted from (Tai et al., 2018)). Column five; (top) Bioconcrete by Jonkers Lab (Jonkers, 2011) and (bottom) steps of crack-healing by concrete-immobilized bacteria (in teal) activated due to water penetration through cracks and precipitating repairing minerals (in yellow) to protect the steel reinforcement from further external chemical attack (adapted from (Jonkers, 2007))

cool air in hot-dry climates by tapping into new technology and vernacular knowledge. Hydroculus is a prototype for a combined evaporative and radiative cooling chimney integrated into a building's envelope in hot-dry climates. It uses hygroscopic materials to generate cooled airflow: a hydrogel membrane is embedded in the wooden funnel-shaped top of the chimney, which acts as a wind catcher. The hydrogel stores water, which is diffused into the incoming wind, inducing evaporative cooling and downdraft flow (Aviv et al., 2020). The chimney structure constitutes waffle timber ribs covered with a thinly coated membrane that reflects shortwave solar radiation, protecting high-thermal-capacity liquids stored in the envelope from overheating during the day. During the night, when the night sky temperature drops to below freezing, the photonic properties of the membrane allow for radiation exchange between the liquids and the sky in the longwave range, thus providing additional free cooling to be stored by the chimney's envelope across a diurnal cycle (Aviv et al., 2020).

Additionally, exposure to wood in living and working environments is linked to reduction of stress-related illness and improved moods. Using wood in skins with human interaction certainly creates positive psychophysiological effects and health impacts that we must not neglect (Burnard & Kutnar, 2020; Mcsweeney et al., 2015).

2.2.2 Plants and Mosses

Live plants on building skins -or vertical gardens- are inherently interactive with their surroundings and introduce numerous applications providing a single-material multiple-solution paradigm, as Nature does. Some benefits of vertical gardens include water retention, air filtering, wind gust dampening, heat gain reduction, and if positioned in front of openings, they can provide shading and noise protection as well as light-filtering. Wonderwall by Patrick Blanc is a vertical garden design applied to the Sportplaza Mercator building in Amsterdam (VenhoevenCS architecture + urbanism, 2006). The wall consists of a steel frame attached and separated from the roof construction of the building, then a 'growing wall' system made of metal, plastic and a felt fleece with notches and small buckets for each plant to grow. A significant number of different plants is maintained by a rain and feeding system with hoses and sensors. The authors explain that every wall has its own climate and demands therefore different kinds of plants (VenhoevenCS architecture + urbanism, 2006). This technology has vibrant aesthetic effects, indoor comfort benefits, and contributes to the thermoregulation and carbon sink capacities of the city.

There are other organisms like mosses or lichens that form what is called the cryptogamic crust and reproduce with spores, without flowers or seeds providing minimal root systems thus accounting for low weights. They cover large surfaces in forest substrates, and over bark or rock, and fix carbon dioxide and nitrogen from the atmosphere. Compared to vertical gardens, moss façade systems present low tech and low maintenance advantages while providing similar benefits. Mosses in building skins have been proven to increase outdoor air quality, provide indoor insulation, and help cool the city. They provide efficient solutions for large-scale applications due to their low requirements in substrates, nutrients, and water, and to their high desiccation tolerance. They do not need maintenance and irrigation is provided by rainfall (Cruz & Beckett, 2016; Perini et al., 2020). Bio receptive surfaces for moss and microalgae have been explored at the BiotA lab Bartlett School of Architecture, UCL. A series of projects aim at growing microorganisms directly on the surface of façade panels to overcome many of the limitations of existing green walls, particularly the need for mechanical irrigation systems and expensive maintenance as mentioned above (Cruz & Beckett, 2016). Low pH magnesium phosphate concrete is used instead of traditional Portland cement which would be too acidic to allow mosses, lichen, or algae to grow. Via digitally designed molds, surfaces made of layered concrete casting acquire fissures and depressions emulating tree bark and produce shaded areas as well as channels to guide rainwater to specific growth areas. Then panels are seeded with a mix of algae cells and moss spores, photosynthetic organisms that collect water from weather events, absorb radiation, $CO_{2,}$ and other pollutants and produce oxygen (Fig. 2.2, column three). Researchers identify future work on moss façade systems towards water distribution and retention during dry periods and adhesion of moss mixture onto facade materials (Birch, 2016).

2.2.3 Fungi

Combining living biological systems with methods in materials science and nanotechnology is enabling superior tuning of material properties by guiding growth instead of de-novo engineering matter from atoms and molecules (Niemeyer, 2001). An example is engineered fungi materials. Fungi can provide function beyond the repertoire of plant-derived materials, and they have been studied to make pigments, construction materials, packaging, or paints. Mycelia, the vegetative tubular filament networks of fungi, contribute to circular economies by transforming local residual flows into fibrous, natural composite materials with controllable physical properties that can be produced in large quantities for carbon-negative buildings and applicable to architecture facades (Almpani-Lekka et al., 2021; Haneef et al., 2017).

The following two examples use mycelium to make compression-based building skins with bricks and panels manufactured under Ecovative's license and method (Fig. 2.2, column two) (Bayer & McIntyre, 2012; Holt et al., 2012). The method entails mixing local agricultural waste, such as stumps and branches, with *Gonoderma Mushroom* spores kept in a dark room in a covered mold ensuring minimal oxygen supply. After one week, spores have broken down the agricultural mass forming a lightweight solid using a natural digestion process that is then halted with heat (Leboucq et al., 2019). The heat treatment of mycelial composites stops growth of mycelium in the mold rendering an inert material (Almpani-Lekka et al., 2021), however, controlling living fungi materials on skins could offer new active properties such as self-healing, self-repairing, and partial self-organization.

The Hi-Fy tower by The Living and Arup for MoMA PS1 uses grown-to-shape fungi roots that digest waste into structure. It is the largest construction project with mycelium composite materials to date forming a 13 m-tall structure made of 10,000 lightweight bricks combining corn stalk waste and living mushrooms, and a timber substructure framing to ensure stability. The structure provides shade and cooling through openings and reflective brick coatings at the coronation. After use, it was biodegraded by shredding and soil composting during two months (The Living NY, 2014; Attias et al., 2019).

The Growing Pavilion a collaboration of Company New Heroes, the Dutch Design Foundation, and Eric Klarenbeek (Biobased Creations, 2019), is an entirely bio-based cylindrical structure made of wooden frame and mycelial cladding panels measuring 2 × 0.7 m each. Panels are coated to increase their weather resistance and demonstrate their use as façade elements. During the life of the structure, mycelium mediated the sound qualities of the pavilion's interior environment by insulating indoor musical performances from outdoor noise (Almpani-Lekka et al., 2021).

2.2.4 Biopolymers

During their life cycles, green plants, animals, bacteria, and fungi produce biopolymers. They are easily biodegradable and include; animal protein-based biopolymers - such as wool, silk, casein, gelatin, and collagen-, as well as polysaccharides - such as chitin, cellulose, pectin, and starch-, or carbohydrate polymers produced by bacteria and fungi -such as xanthan, dextran or cellulose (Yadav et al., 2015). Biopolymers systems called biomaterials are used emergently in advanced research within life sciences and biomedical disciplines to improve human health in drug delivery and tissue scaffold applications for regenerative medicine (Ratner, 2013). In this section, biopolymers are defined as based on naturally occurring polymeric materials (Plank, 2005) and pioneer projects made entirely of them are reviewed.

As the architecture field has become more aware of the impacts of plastic products in human safety (Faircloth, 2015), promising research has emerged in the last decade identifying strategies and material opportunities to replace man-made fuel-based polymers with bioplastics synthesized by organisms. For instance, Julia Lohmann inspects the capacity of brown kelp to form large-scale skins (Lohmann, 2017). She borrows a Japanese cuisine ingredient—a natural soup glutamate—as a material for "making instead of eating". It is not unusual that designers look at food industry and biomedical fields for plastic-like materials that our body can naturally digest with the hope that our planet will too (Mogas, 2018; Mogas et al., 2021). This seaweed can make fertilizer and turn into bioplastic, biofuel, dyes, veneer, and textiles. It grows yearly up to 6 m long and 30 cm wide while cleaning the ocean by filtering toxic farm run offs and fish feces from sea water. Hidaka Ohmu is a six-meter-wide structure with a seaweed skin in tension within a birch plywood and rattan frame. Seaweed has been treated with an environmental method to remain flexible (Toivola, 2020) by trapping water within its molecule chains. This is key, as most biopolymers, like kelp, lignin, or collagen, are hydrated in nature within the living bodies of organisms, plants, or animals, and will inevitably dehydrate when becoming non-living materials for buildings.

Tunning of intramolecular water absorption can be made interactive by programming the behavior of biopolymers. In Aguahoja1, a six-meter tall chitin and cellulose composites tower by The Mediated Matter Group at MIT (Duro-Royo et al., 2018), we observe control of mechanical, optical, and chemical properties within the system's skin. This is because biopolymer blend compositions are graded differentially throughout it. Opacity, color, and strength can be varied in correspondence to chitin-cellulose and pectin-calcium mixtures that are 2.5-dimensionally printed in large panels assembled onto a biodegradable polymer skeleton. Interestingly, the interaction of this system with its environment allows for programmed decay based on two design parameters: the hydrophilic property of biopolymers which swell in the presence of high humidity and ultimately disintegrate, and their density in the structure enabled by geometric distribution via computational tool pathing accounting for open and closed cell configurations (Fig. 2.2, column four).

Water and geometry were also crucial in the development of Lachesis by The Silklab at Tufts University (Mogas, Matzeu & Omenetto, 2018; Matzeu et al., 2020). Lachesis are a series of silk fabric tapestries imprinted with silk protein-based inks that embed a chemical reporter able to sense and diagnose its environment. Inks are water-based and formulated for screen-printing applications by combining an algae biopolymer as thickener, a plasticizer, and regenerated silk fibroin which is the fibrous protein found in silk cocoons. This formulation is made responsive through the addition of pH sensing molecules that are encapsulated within the fibroin matrix, making them interactive with their surroundings and able to change color in rich accurate palettes in the presence of weather events like saturation or rain. By changing color, the tapestries display the acidity of rain, for instance. This system is derived from biomedical research where such sensors work over a reduced pH range, with low sensitivity, and with local sensing restricted to small patches. However, Lachesis 3 m-tall tapestries can withstand repeated wetting, dry cleaning, and reversibility to diagnose their surroundings. Screen-printing of robust bioactive inks like these on a large scale opens a promising direction toward mass-production of responsivee interfaces for distributed environmental sensing in buildings with applications in façade or roof canopies (Matzeu et al., 2020).

2.2.5 Microorganisms

Engineered Living Materials (ELMs) merge the fields of materials science and synthetic biology and study generation of biologically active materials with tailorable properties providing new function across fields in, for instance, medical, electrical, and construction applications (Srubar, 2021). There are a few examples of successful engineered building materials where living cells both give structure and modulate performance. BioMASON makes bacterial derived mortars and bricks (Dosier, 2011), Henk Jonkers group at TU Delft and Basilisk produce concrete able to self-heal its cracks by selectively activating its bacterial composition (Roy et al., 2020), the Srubar Research Group at UC Boulder derives cementitious materials that regenerate themselves by using photosynthetic microorganisms to biomineralize inert sand-gelatin scaffolds (Heveran et al., 2020), or ecoLogicStudio investigates photosynthetic living microalgae building skins and products (Valenti & Pasquero, 2021).

Self-healing bio-concrete is made of concrete infused with dormant bacteria. These microorganisms allow it to self-heal its cracks and prevent steel rebars from corroding. This is enabled by certain strains of bacteria that metabolically mediate the precipitation of minerals such as limestone when exposed to the right environmental conditions. In this case, when dormant spores of alkali-resistant bacteria are in contact with outside water entering concrete through a crack, they multiply and precipitate minerals such as calcite thus sealing small cracks and autonomously remediating concrete before steel reinforcement is damage (Fig. 2.2, column five). In order to bring living concrete to industry, Basilisk is continuing research on robust bacteria able to withstand construction times for longer than a few months, and evaluating if bio-precipitation can be sustained over decades (Jonkers, 2007, 2011).

BioMASON's bio-cements are assembled and cured at ambient conditions by bacteria reducing energy costs and resulting in zero carbon emissions. In particular, the technology uses sand aggregate, infused with calcium ions and water, and then seeded in cycles with a broth of robust bacteria strands that produce urease enzymes. Molded bricks or parts are allowed to harden to ASTM specification. Hardening is mediated with the help of bacteria in the creation of calcium carbonate from calcium ions which fills the bonds between loose pieces of aggregate forming a solid construction material (Dosier, 2011). Interestingly, matter can be tailored to different requirements of porosity, lightness, or insulation, and still maintain properties comparable to traditional masonry materials.

In the IBA Hamburg in 2013 Arup and SSC built the BIQ five-story housing building, the first algae-powered building in the world. Bioreactor panels fill the south façade and autonomously cultivate photosynthetic microalgae -by feeding them CO_2 and nutrients- to generate energy and biofuel as renewable energy resources (Elrayies, 2018). Several ecoLogicstudio implementations look at distribution and maintenance of similar photosynthetic microalgae systems in soft building skins. Photo.Synth.Etica, installed in Dublin in 2018 is perhaps the largest system they have investigated. It features a bioplastic envelope façade with aqueous solution pockets filled with living microalgae and nutrients. The architects explain that city air enters the system and CO_2 molecules and atmospheric pollutants are captured and stored by algae before being transformed into biomass, which can be then collected and used in the production of new bioplastics. In the meantime, oxygen expelled by photosynthesis is free to leave and return into the city (Valenti & Pasquero, 2021). These living microorganism systems can produce outputs in the form of biomass for human nutrition, biofuel for green energy, or inputs for other organisms to perform new functions in symbiosis. In all these examples, replenishment and survival of living systems is critical, and comprises most of the groups' future research.

2.3 Outlook: Challenges in Disguise

The aim of this text is to inspire consideration of a future for biological and living material building skins at the intersection of construction and biotechnology. A future where facades interact and adapt to changes in their environments providing passive cooling and autonomous ventilation, health diagnostics and programmed decay, and even embedding and supporting other organisms able to perform sophisticated functions of self-healing, biomass production, and air cleaning. All of this by inherently increasing resource efficiency when using abundant local materials instead of global supply chains, shifting from fossil-fuels to solar power, and from linear materials and energy use to a circular economy producing more growth and no waste.

It is true that, compared with traditional building materials, biological materials possess properties that have traditionally been difficult to control, however, mastering strategies applied to these properties can spark solutions to old problems.

Water absorption in wood and natural fibers (5 to 40% of their dry weight) can lead to deformation via shrinkage and swelling and to fungal growth and decay (Sandak et al., 2019). Paradoxically, hygroscopicity is one of the most interactive properties of bio-based materials as it enables autonomous hydration-dehydration cycles in tune to daily and seasonal changes. For instance, laminar wood surfaces can curl and relax linked to atmospheric humidity, which can be harnessed to tune light and ventilation through building skins (Krieg & Menges, 2013).

Deformation in response to changing loads are characteristic of living bone or wood, and generally penalized in building code. However, this property could help existing building structures, for instance, “grow” more matter where highest wind or traffic forces are applied. Such beneficial dynamics are yet to be regulated in architectural handbooks, but they are part of ancient techniques making living root bridges in Meghalaya (Ravishankar & Ji, 2021), or grown-to-shape wood chairs by Full Grown (Munro and Munro, 2006), and are becoming within reach as designers and architects push for their implementation (Joachim & Silver, 2017).

Time scales can be a limiting factor to produce engineered living materials for construction applications as organisms output matter at different time scales, from hours to make bacterial cellulose, to decades to make wood (Srubar, 2021). However, it is also true that time cycles can help bio-based material systems achieve their optimal outputs, such as programmed decay in biopolymers (Duro-Royo et al., 2018), self-repair in bacterial cements (Dosier, 2011; Heveran et al., 2020; Jonkers, 2011), or self-regulation in cooling hydrogels (Aviv et al., 2020).

Replenishment is another challenge of biological and living materials systems in building construction applications. Research is advancing so that mosses adhere to bio receptive concrete for decades without intervention (Cruz & Beckett, 2016), bacteria powering self-healing concrete wait dormant for years before being activated by water penetrating the cracks (Roy et al., 2020), or photosynthetic microalgae in façade bioreactors receive enough nutrients to perform their function. In nature, when something stops working, death and new life is preferred. Ensuring that our buildings, codes, and aesthetic expectations account for autonomous cyclical renewal is key to the adoption of active and adaptive biological material construction.

Current industrial certification processes sustain biological material solutions to traditional testing methods and compliance rates in deformation, fire, or water resistance. However, biological function such as self-regulation, adaptation, autonomous growth, and self-repair, create an alternative paradigm requiring consideration of material properties over the entire building's life cycle, and accounting for the advantages of not relying in energy-intensive solutions to building adaptation problems (Almpani-Lekka et al., 2021; Mogas-Soldevila, 2021; Yadav et al., 2015).

In the next decade, industry will aim at high-quality, labor-friendly, minimum waste, low emission products demonstrating no harm to humans and the planet. Biobased, biological, and living material systems in construction will certainly contribute to achieving these goals, and while doing so, will derive multifunctional, passive, adaptive, responsive, and aesthetically shifting solutions to old and new challenges.

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