PAPER

Engineered Living Materials (ELMs) for the Built Environment

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Over the past decade, the field of Engineered Living Materials (ELMs) has emerged, combining synthetic biology and material science to mimic the properties of natural living materials. ELM research aims to produce novel materials with tailored functions using genetically engineered organisms coupled with synthetic or biological polymers to create desirable features like self-repair and enhanced mechanical properties. ELMs have been applied in regenerative medicine, therapeutics, electronics, device engineering, computing, and construction in the built environment. ELMs are a rapidly growing field that is based on the convergence of synthetic biology with polymer science.

The authors of this study are part of a National Science Foundation (NSF)-funded project, in which we define ELMs as composite materials of engineered living cells encapsulated within a polymeric matrix. Our interdisciplinary research team comprises chemists, biochemists, bioengineers, mechanical engineers, and architects who develop ELMs for the built environment, which includes 3D-printable resins with engineered living cells that exhibit different functionalities. The focus of our lab-based research focuses on three main issues around innovative ELMs: (1) the ability to thrive in changing hydration levels (outdoor environment) and survive periods of low hydration levels, (2) the integration of photosynthetic active, productive cells in high-tech building membranes, and (3) the creation of ELMs clusters as resilient bioreactors for bioproduction.

This study reports on the structure of this research project and the state of the science of ELMs research in general. It highlights the need for disciplinary collaboration on ELM research between chemistry, molecular biology, bioengineering, material science, architectural design, and beyond. The multidisciplinary discussion offered by this paper juxtaposes the science, built environment, and design perspectives on ELMs and touches on essential questions in this emerging field.

INTRODUCTION

Today, architects have a plethora of opportunities to replace non-renewable, energy and carbon-intensive construction materials with biogenic or biobased materials, which reduce the environmental footprint and potential health risks of conventional construction materials in buildings (Göswein et al. 2022). In addition to traditional building materials, such as wood, straw, and hemp, much research has been conducted on how to industrially cultivate, breed, farm, and grow biogenic construction materials (Hebel and Heisel 2017) and how to successfully integrate them in construction details, wall sections, and building designs (Lewis et al. 2022).

To further advance materials inspired by nature, the field of Engineered Living Materials (ELMs), which combines synthetic biology and material science, has emerged over the past decade (Table 1). The nascent field aims to recapitulate desirable properties of natural living materials, such as self-assembly from simple raw materials, self-repair, and the ability to sense and respond to environmental stimuli to create novel, productive materials with tailored functions using genetically engineered organisms. The research activities and available funding opportunities in this field have significantly grown over the last ten years. As Lantada and coauthors point out, the rise in publications in the emergent ELMs field corresponds with the first published use of the term "engineered living materials'' (Nguyen 2017), illustrating the growing need for a classification system for such materials. ELMs have been applied to a broad range of applications that include regenerative medicine, therapeutics, electronics, device engineering, computing, and built environment construction (Srubar et al. 2020). The growing list of innovative technologies have the potential to revolutionize sustainable engineering by creating systems capable of performing tasks that are not accessible to existing engineered systems, such as self-replication, self-regulation, self-healing, and environmental responsiveness.

The application of advanced ELMs in the built environment (BE) is challenging since many promising ELM materials are still in the proof-of-concept stage, untested in the field, available only in minimal quantities, and a long way away from being commercially viable for the construction industry. However, the emerging innovations and possibilities are so intriguing that more BE experts should get involved in contributing to the field. Additionally, the more end-users –architects and engineers in this case– are involved in the research development, the more likely these materials will be developed with useful functionality in commercial settings. Only interdisciplinary teams are able to identify pressing issues that ELMs might advance. Furthermore, how will ELMs transform the future of design and the construction of buildings? The National Science Foundation (NSF)-funded project "Autonomous Engineered Living Materials for Construction and Repair of Outdoor Built Environments" introduced in this investigation attempts to develop ELMs specifically for BE application and answer some of the above questions from a multidisciplinary perspective.

The interdisciplinary emergent field of ELMs is an umbrella for various technological approaches, material subcategories, and research combining different domains. Given the large number of subfields, ELM research has yet to establish a consistent nomenclature to distinguish between different classifications of ELMs. Some defining questions are still open and might be answered differently by various disciplines. For example, do embedded living organisms need to be genetically engineered for a material to qualify as an ELM? Do these organisms need to remain alive and functional throughout the lifetime of the material (Srubar 2022)?

ELM CATEGORIES

On the most abstract level, an ELM is made up of a living component – a lineage of cells, microorganisms, or multicellular tissues and a matrix – a biological or abiotic substance (such as a synthetic polymer, cellulose, alginate, etc.) as scaffolding structures for the living cells. Optionally, some ELMs include additional inorganic salts and minerals. ELMs are commonly based on living, engineered, or genetically manipulated bacterial or eukaryotic cells. Bacterial genera used in ELMs include Escherichia coli (E. coli) and Cyanobacterium (photosynthetically active bacteria). Saccharomyces cerevisiae (Brewer's yeast), Yarrowia lipolytica (beneficial yeast species used to synthesize valuable metabolites), and Ganoderma lucidum (fungal mycelia) are eukaryotic organisms used in ELMs (Figure 1). Sometimes, ELMs use a consortium of multiple synergetic cell types, including cross-domain combinations (Lantada et al. 2022). Commonly, the living components of ELMs are engineered to sense chemical and optical inputs that then activate a response (Gilbert et al. 2021; Molinari et al. 2021).

The following overview highlights a selection of ELM categories that have or could be implemented in the BE. The definitions of these categories are primarily derived from three review articles and proposed taxonomies of current developments in the ELMs field (Nguyen et al. 2018; Srubar et al. 2021, Lantada et al. 2022).

Table 1. Different types, terminology, and definitions of "living materials" (by the authors).

name	*definition*	*source*
Biogenic materials	materials produced by living organisms	(Lewis et al. 2022)
Biobased materials	materials that are made in whole or in part from renewable biogenic material	(Göswein et al. 2022)
Engineered Living Materials (ELMs)	Engineered Living Materials (ELMs) combine synthetic biology and material science to further advance materials inspired by nature. They recapitulate the desirable properties of natural living materials, such as self-assembly, self-repair, and sensing, to create novel, useful materials with tailored functions using genetically engineered organisms.	(Gilbert et al. 2021; Molinari et al. 2021)
	"Engineered materials composed of living cells that form or assemble the material itself, or modulate the functional performance of the material in some manner"	(Nguyen et al. 2018)
Biological ELMs	Biological ELMs consist of cells embedded in cell-generated extracellular matrices. They are grown from genetically encoded cells through cell proliferation. This method is considered a **bottom-up approach.**	(Lantada et al. 2022, Jones et al. 2022, Molinari et al. 2021)
Hybrid ELMs	Hybrid ELMs consist of living cells and an abiotic scaffold (for example, polymers, carbon-based, and noncarbon-based). They are considered a **top-down creation.**	(Lantada et al. 2022)
Composite ELMs	Composite ELMs are a type of hybrid ELMs. They are engineered to create additional functionalities by synergistically growing, assembling, mixing, or layering microorganisms with other materials, such as organic or abiotic substances (synthetic polymer, cellulose, alginate, etc.) These composite materials "exemplify the cooperative programmed action of living cells with externally provided building blocks, pushing the boundaries of performance" of ELMs and "can be used for a variety of applications, including sensing, remediation, bioenergy production, microorganism encapsulation, release of functional molecules, and soft robotics."	(Nguyen et al. 2018)

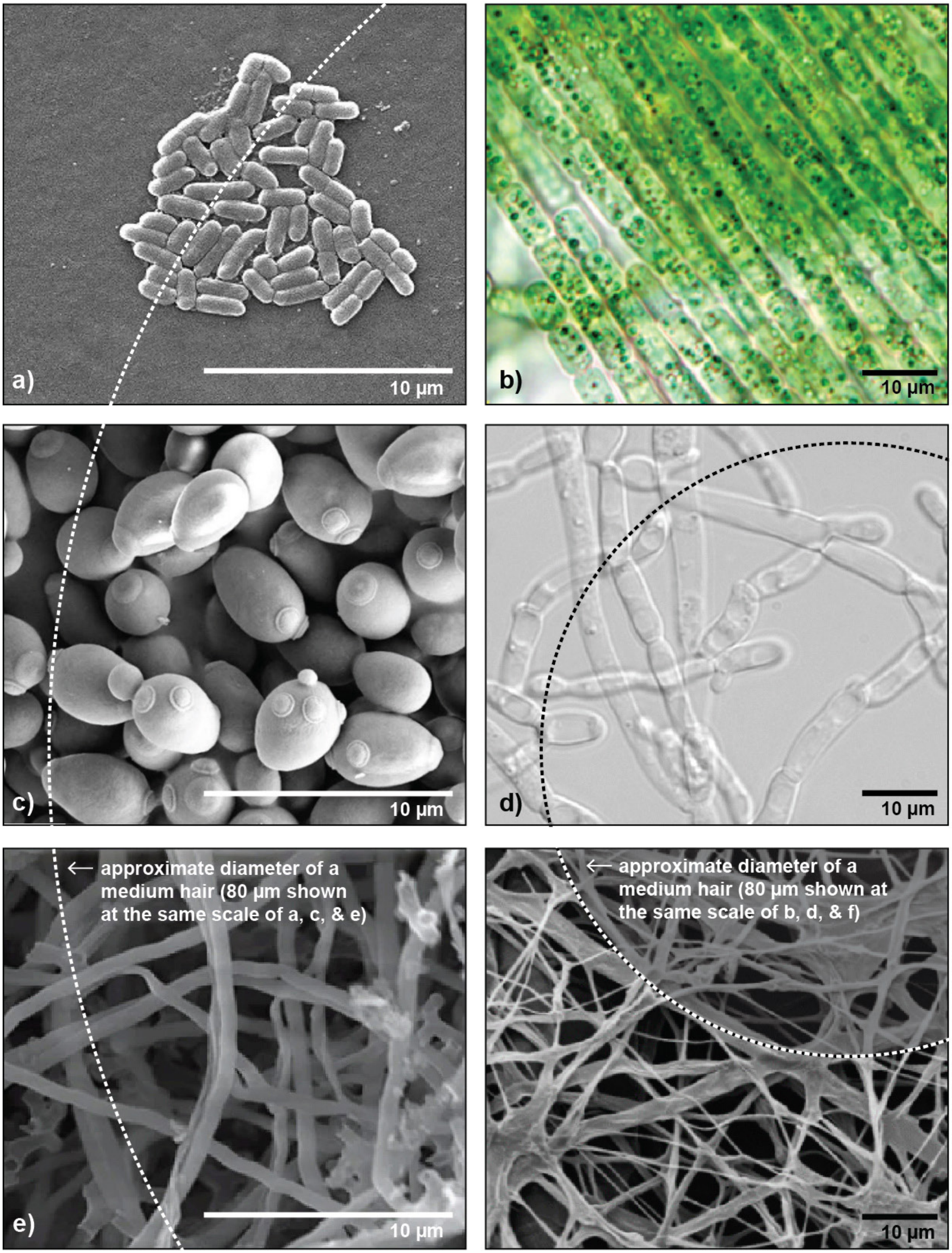

Figure 1: Living cells used in ELMs: a) Escherichia coli (E. coli bacteria),[1] b) Cyanobacterium (bacteria),[2] c) Saccharomyces cerevisiae (Brewer's yeast, eukaryotic organism),[3] d) Yarrowia lipolytica (eukaryotic organism),[4] e) Ganoderma lucidum (fungal mycelia) (Haneef et al 2017) and f) Pleurotus ostreatus (mycelial network)[5] (Karana et al. 2018) and scale comparisons to the size of the average diameter of a human hair.

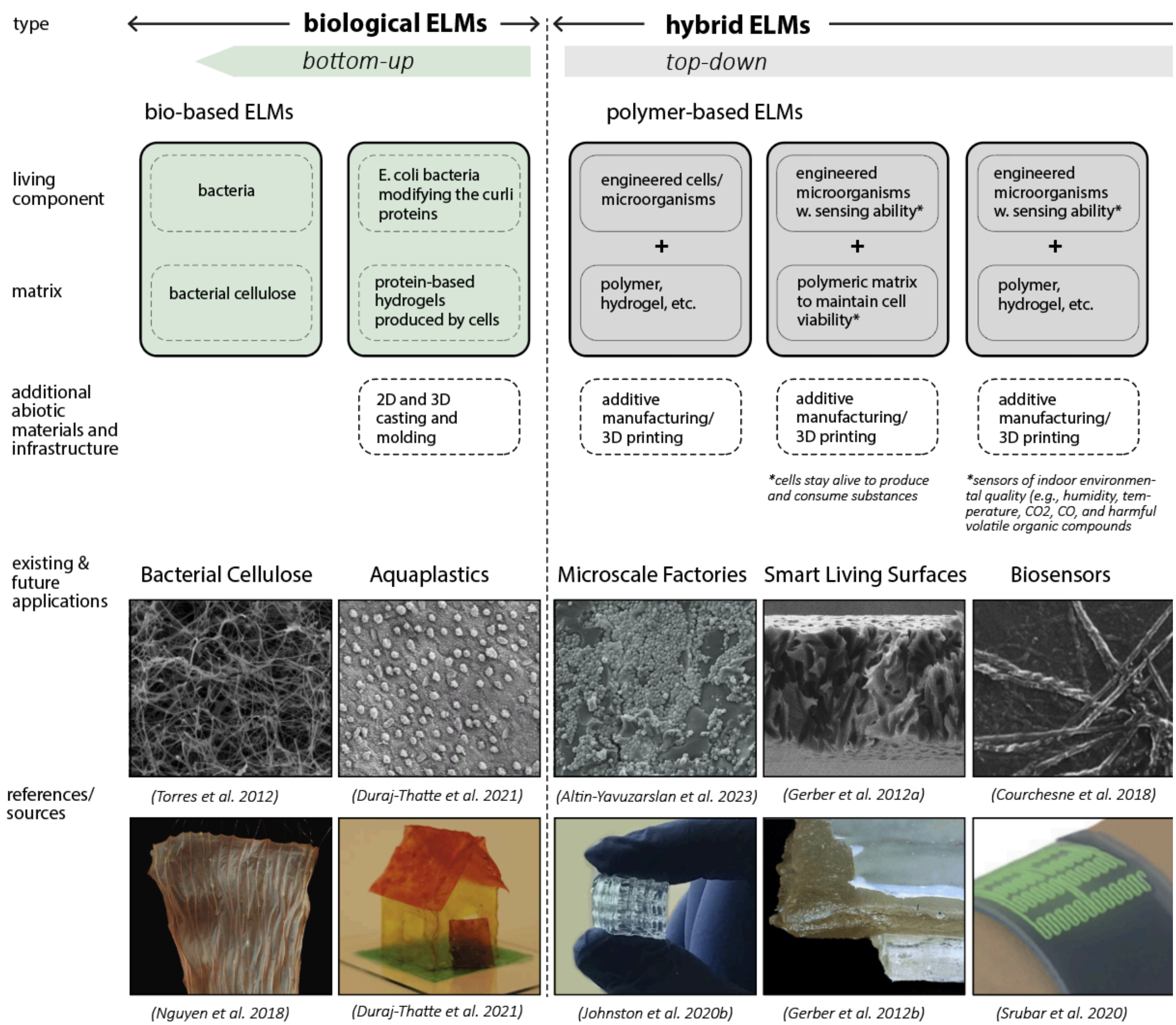

Figure 2: Overview of different types of ELMs, their components, and existing and future applications (chart and categorization by the authors).

From the chemical, biochemical, and bio–inspired engineering perspective, two primary ELMs systems must be differentiated: biological and hybrid ELMs (Figure 2). The overview juxtaposes these two types with systems that engineer large-scale multicellular tissues and assesses how these approaches are relevant for existing and future BE applications.

Biological ELMs consist of cells embedded in cell-generated extracellular matrices. They are grown from a genetically encoded single cell (equivalent to a seed) through cell proliferation (Lantada et al. 2022, Jones et al. 2022). This method is considered a bottom-up approach (Molinari et al. 2021). This category of ELMs is usually based on bacterial systems that may generate extracellular matrix materials and, therefore, can grow their own scaffold, often in the form of bacterial cellulose (BC) (Nguyen et al. 2018). The embedded living cells are engineered to create substances that modify this cellulose. While the primary use of BC has been in tissue engineering and specialized material production, several commercial specialty applications for the BE have emerged. The strong mechanical properties of BC have been used to create high-strength paper, textiles, and environmentally friendly architectural materials (Nguyen et al. 2018). Other biological ELMs focus on the production of specialized biofilms that provide a different kind of biological matrix for this type of ELM. At the proof-of-concept level, researchers have demonstrated that genetically manipulated E. coli can enable biofilms to be both a functional material in its own right and a materials synthesis platform. (Chen et al. 2014). By modifying the curli proteins in E. coli, the cells produced protein-based hydrogels, which are cast and dried to create aquaplastics that can form three-dimensional architectures using water (Duraj-Thatte et al. 2021).

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Hybrid ELMs are living materials with additional functionalities in which microorganisms are grown, assembled, mixed, or layered synergistically with other materials. The second component can be an engineered or natural material, however, the ELM's living cells cannot produce it. Many prefabricated materials used in hybrid and composite ELMs are synthetic polymers or inorganic materials and serve as a scaffold to direct cell growth and behavior. Since the two primary components of ELMs (living cells and matrix) are brought together during the engineering process, this method is considered a top-down approach (Nguyen et al. 2018). To be considered an ELM, the living cells must transform the material performance or characteristics of the ELM. Composite ELMs strive to establish novel properties enabled by living cells while retaining desirable functionalities of the matrix materials (Chen et al. 2015). Polymer-based ELMs consist of engineered living cells encapsulated within a polymeric matrix. They offer diverse applications from bioreactors for on-demand production and their expanded storage capacity (Yuan et al 2021, Brooks et al. 2023), co-culture of cells (Johnston et al 2020), advanced 3D printability of ELMs (Smith et al 2020; Butelmann et al 2021). Promising applications of composite ELMs in the built environment are smart surfaces and biosensors (Inda and Lu 2020), wearable devices, and living electrodes (Freyman et al 2020). While originally developed in different domains, electrochemical biosensors, for example, could be integrated as indicators of indoor environmental quality and for structural health monitoring (Srubar 2020). There is a growing body of work directed toward encapsulating cells in polymeric matrices that can sustain the viability and metabolic activity of these microorganisms. However, there is still a need for developing physically robust structures for extended use under the harsh demands of the outdoor built environment.

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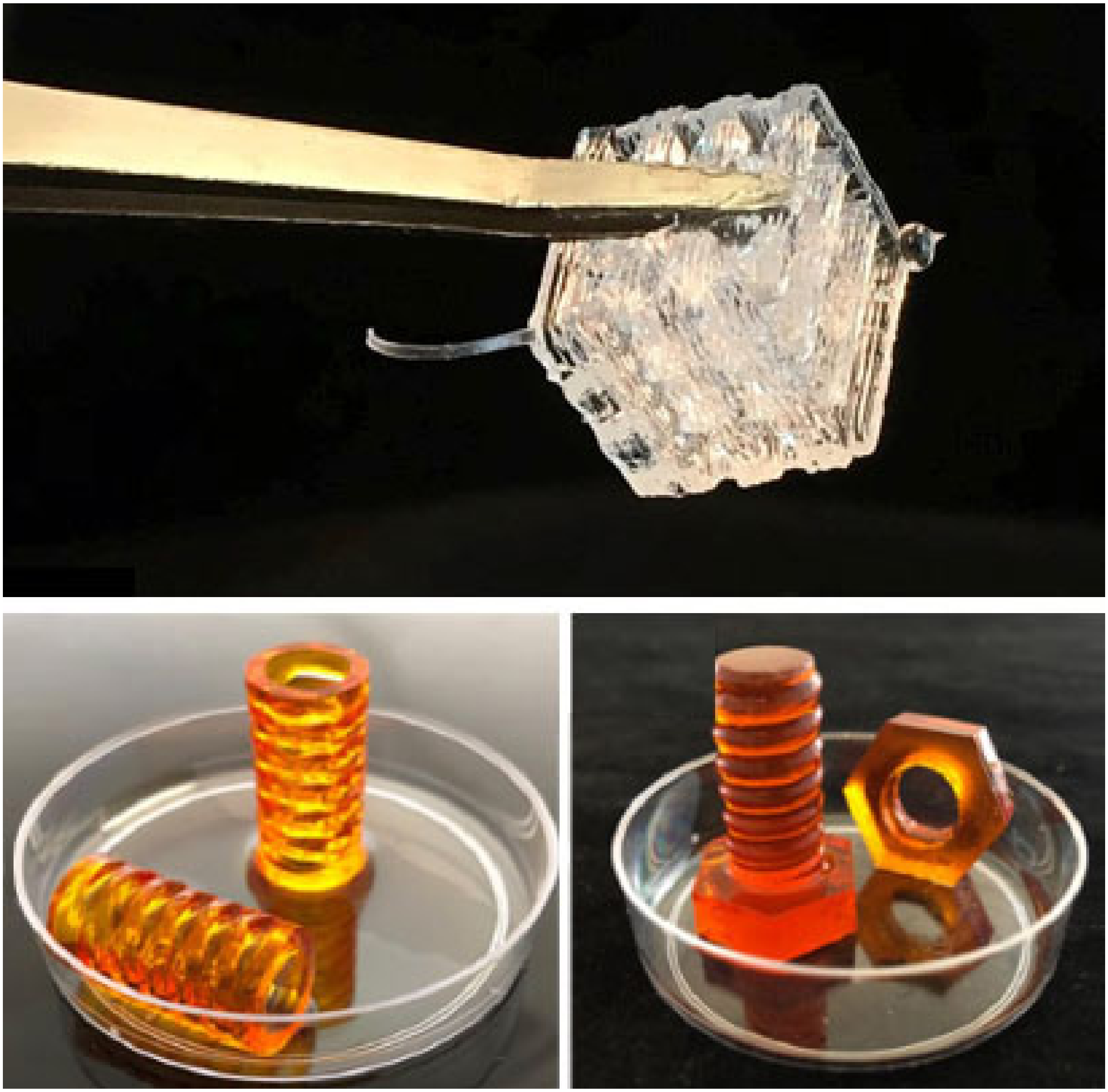

Figure 3:a) Samples of polymer-based ELMs with cyanobacteria embedded in different polymers tested for cell viability (Johnston et al. 2020b); b) cell-laden 3D printed hydrogel (Altin-Yavuzarslan et al. 2023), c) high precision 3D-printed objects from hydrogels (Altin-Yavuzarslan et al. 2023)..

Biomineralization and multicellular tissues -- Composite ELMs can also comprise living cells with biomineralized components, and these materials are of significant interest for construction materials production. Biologically fabricated bricks or biologically fabricate concrete masonry units (bio-CMUs) have seen some commercial success, while self-healing concrete, biologically cemented concrete, or Living Building Materials (LBMs) are still in the development phase (Srubar 2021, Ednie-Brown, Pia. 2013, Jones et al. 2022, Heveran et al. 2020). Engineering of large-scale multicellular tissues, especially the production of mycelium materials, has been of increasing interest in architecture and the construction material industry. Commercially viable products include insulation materials and experimental applications as lightweight, load bearing materials (Ecovative). The fungal mycelium cells can be genetically manipulated to create specific material characteristics. However, the living cells must be rendered nonviable before the mycelium materials are used for construction, usually through heat exposure (Nguyen et al. 2018). In the future, ELMs could be inspired by even larger organisms, such as trees, through tree shaping or Baubotanik, in which woody living plants or small trees are trained with temporary scaffolds into a load-bearing structure through mechanical manipulation.

ERFI ELIS RESEARCH DESIGN

Our four-year-long interdisciplinary research project is funded by NSF's Emerging Frontiers in Research and Innovation (EFRI) program. It focuses on polymer-based composite ELMs and will advance the next generation of sustainable materials, processes, and products in this material category for the built environment. This project aims to address three significant challenges around innovative ELMs. (1) The ability of engineered living cells to thrive in changing hydration levels, as typical in the outdoor environment, and survive periods of low hydration levels. Most ELMs so far have been developed and tested under optimal lab conditions that support the viability of the cells. (2) The integration of photosynthetic active, productive microorganisms, such as cyanobacteria, in high-tech building-membranes. Photosynthesis allows cells to produce energy, which, in the case of ELMs can be used to activate and support their functionality. (3) The living cells embedded in the ELMs can be considered microscale factories. 3D-printed ELMs can operate as resilient bioreactors for enhancing the construction material.

The project builds on the foundational research by Alper and Nelson on the additive manufacturing of cell-laden hydrogels (Johnston et al. 2020a, Johnston et al. 2020b, Myers 2018). For this research project, the team added three investigators with expertise in mechanical engineering, microfabrication, additive manufacturing, cyanobacteria, and the integration of living systems into the built environment. This project requires the in-depth expertise of each investigator's discipline and the innovative synthesis of the different domains in the interdisciplinary creation of new living materials. Domain-specific tasks include (1) the genetic manipulation of productive living cells through bioengineering as the living component of ELMs. The manipulated cells produce, for example, substances that modify the material characteristics of the new living material; (2) the development of polymers as the matrix of ELMs that are 3D-printable, and support the viability, longevity, and specific functionality of the engineered living cells. The viability of the microorganism, such as cyanobacteria, embedded in the matrix must be tested throughout the development process, (3) mechanical engineering of the high-precision 3D printing of ELMs. Additive manufacturing is based on 3D modeling of the intended spatial configuration with computer-aided design (CAD), similar to the architectural design process (Figure 3), and (4) the assessment of the BE integration through testbeds that simulate the outdoor environmental condition at the scale of the sample size.

In addition to the development of ELM components and composites, the EFRI ELiS project also includes a significant outreach and education component to inform the larger public and support the development of a diverse, interdisciplinary workforce in the ELMs field. As educational components, the team offers opportunities in the NSF Research Experience for Undergraduates, graduate research seminars, and studios for architects, BE disciplines, and design-related fields. An open student competition to work with ELMs is planned in the second half of the project. Overall, the research team aims to support the creation of a diverse workforce of researchers, architects, and built environmental experts in the field.

RESEARCH PROGRESS

This project is still at the beginning of its investigations that will address pressing issues around developing polymer-based ELMs for the built environment. Our experimental work on the project started in early 2023. First lab-based experiments continue foundational ELMs research to (1) seamlessly integrate the biotic (cellular) and abiotic (polymer) components into printable resins (Altin-Yavuzarslan et al 2023), (2) advance the viability and longevity of photosynthetic active cells in resin, and (3) advance the precision of 3D printing at the capillary scale. Collaboratively, we work on outreach projects, such as ELMs research seminars and studios. The first course sequence started in January and aims to introduce an interdisciplinary cohort of graduate students in architecture to the state of research around ELMs in the BE. The seminar is supported by discipline-specific presentations of all fields contributing to the research grant. The seminar is followed by an advanced graduate research studio in architecture. The architecture students will have access to the same (off-the-shelf) 3D printers used by the chemistry and mechanical engineering labs and ongoing opportunities for exchanges with the graduate students working on the lab-based research. An important outcome will be the cross-discipline relationships that will be developed between architects, engineers, and scientists for the future ELMs workforce.

CHALLENGES

While the possibilities of future ELMs are enticing, the emerging field faces several challenges. These problems include technical difficulties, such as the long-term viability of the living cells, issues around scaling up, and advancing economic feasibility. Environmental concerns also lead to problems around biocontainment and regulatory frameworks.

Manufacturing – The form factor of ELMs must be addressed through advanced manufacturing technologies. Additive Manufacturing, or 3D printing, is a promising fabrication method to obtain ELM constructs such as bioreactors, medical devices, and sensors. This fabrication platform has become ubiquitous in many disciplines for prototyping, model making, architecture construction, and bioprinting (Nguyen et al. 2018). The process of bioprinting deposits the hydrogel in a previously determined shape based on a digital 3D model. The hydrogel also works as a matrix containing the living cells and preserving their viability. The accuracy of the 3D printers – even of affordable off-the-shelf models – allows the creation of 3D living composites with micrometer resolution (Nguyen et al. 2018; Narupai and Nelson 2020).

Figure 4: Publications addressing the creative design integrations of living materials, ELMs, and other biological innovations. a) (Imhof and Gruber 2016), b) (Myers 2018), c) (Mitchell and Aiolova 2019), d) (Mitchell and Silver 2016), e) (Armstrong 2015), f) (Trubiano et al. 2024), and g) (Nguyen et al. 2018).).

Long-term viability – One of the main challenges of all ELMs, but especially of hybrid ELMs that use an encapsulation approach, is to achieve compatibility and long-term viability of the living organism during the production phase and beyond, which ultimately depends on the conditions that can be maintained within the artificial scaffold (Srubar 2020). Some ELMs aim to keep the cells alive throughout the material's life cycle to sustain self-repair and sensing capabilities. In contrast, others utilize the functionality of the living cells only during the production phase. In some cases, the existence of the living component becomes a liability for the long-term stability of the material. In these materials, the cells need to be rendered nonviable for optimal product performance, or due to safety concerns. In other cases, the living cells – the microscale factories – might be separated entirely from the desired material product (Nguyen et al. 2018).

Biocontainment and regulatory frameworks – The question of viability also comes with the dimension of biocontainment concerns of genetically-manipulated cells. How can engineered cells be prevented from escaping and proliferating in the natural environment? What containment methods are appropriate that won't impede the functionality of the ELMs? What level of containment is needed to be registered as safe for commercial use? Regulatory framework for applications, ethical guidelines, and material safety protocols are essential for further developing the ELM fields (Ebbesen et al. 2024).

Scaling-up – Production rates, volumes of ELMs, and high capital cost in industrial biotechnologies, regardless of the ELM type and production approach, are currently limiting factors in this emerging field. More specifically, living organisms produce materials at a variety of time scales that are dependent on various factors, from the health of the organism to nutrient availability and cellular environment. The selection of active cells, their production rate, and the material needs for the target application need to be aligned. For example, the material footprint of biosensing ELMs is much smaller than the quantities required for structural or construction materials, though the technical requirements of these ELMs maybe much higher (Srubar 2020). ELMs with highly specialized functionalities might be a good target for the initial scaling-up ELMs implementation. The development of most ELMs requires interdisciplinary teams, which increases their R&D expenses even further.

Economic feasibility – In the realm of construction materials, emerging ELMs often compete with the well-established market of commodity construction materials. While materials like concrete and steel are currently considered cheap and accessible, their price does not consider their carbon and environmental footprint. As environmental regulations change and the actual cost of conventional construction materials is considered, sustainable ELMs (especially those that utilize waste streams and industrial byproducts) will gain feasibility and become more economically competitive. In the meantime, the commercial success of some ELM technologies provides a roadmap for the commercialization and large-scale production of ELMs for the BE (Jones et al 2022).

DESIGN INTEGRATION

While the development of most ELMs is still in its infancy, architects and designers have responded with great interest and various speculative projects to the innovations of this emerging field. Creative disciplines have been fascinated for a long time by nature-inspired materials, biomimicry, and the integration of living systems into the built environment. Advances in synthetic biology, therapeutic medicine, material science, and bioengineering have sparked the interest of various creative fields to combine biology and technology at multiple scales, integrate science into art, and connect living systems and architecture as documented in recent publications (Figure 4). MoMA's publication Bio Design: Nature, Science, Creativity documents how biological science, synthetic biology, and the aesthetic of biological innovations inspire artists and architects (Myer 2018). The edited volume focuses primarily on prototypes and proof-of-concept installations that are advanced by interdisciplinary collaborations and the synergy between science and design.

Architects have also researched and speculated on innovative, living materials that can self-assemble and self-repair and their integration into architectural design and built environment adaptations. Terraform One has developed speculative projects that investigated the implementation of ELMs at the building scale, such as the In-Vitro Meal Habitat and Fab Tree Hab – Living Graft Prefab Structure (Mitchell and Aiolova 2019, Joachim and Silver 2017). Rachel Armstrong's research investigates how multiple living materials could be synthesized into a building as next-generation sustainable architecture. As a regenerative approach to architecture, this type of construction would significantly improve sustainable building performance and reduce the environmental footprint of the BE (Armstrong 2023, Armstrong 2015). The edited volume Bio Matter Techno Synthesis juxtaposes twenty-three visions on how to approach biology, new materials, technology, science, and their relation to design theory (Trubiano et al. 2024). While investigating cutting-edge material science, the publications mentioned above offer reflections on emerging innovations from the perspective of the architectural designer, often with the budding generation of architects in mind.

ELMS IN ARCHITECTURE EDUCATION

Several universities have started to integrate ELM investigations into their research labs and architecture programs. The project Built to Grow: Blending Architecture and Biology takes an innovative approach to getting architects involved in the field. Two faculty members at the University of Applied Arts (die Angewandte) in Vienna, Austria, transformed one of their architecture design studio spaces into a biology lab (Imhof and Gruber 2016). Connecting physical lab-based research with design, architectural students experimented with slime mold, mycelium, algae, mobile 3D printing, and the integration of the grown materials into design projects. The interdisciplinary Hub for Biotechnology in the Built Environment (HBBE) at Newcastle University in the UK is co-led by architecture professors and conducts research on ELMs and their integration into sustainable construction processes. The Centre for Information Technology and Architecture (CITA) at the Royal Danish Academy's research focuses, among others, on Biohybrids –which include ELMs– as well as digital simulation and fabrication.

CONCLUDING THOUGHTS

Engineered Living Materials offer a transformative approach to innovative material development, sustainable architecture, and fabrication, integrating self-repairing and adaptive capacities into building materials. However, the real-world applications of these materials require further interdisciplinary research, a transformation of the building industry, and an evolution in architectural education and interdisciplinary workforce training. Recognizing the potential of ELMs to revolutionize our relationship with the built environment, the focus shifts towards fostering collaboration across scientific, engineering, and architectural domains. The journey toward sustainable, regenerative materials and novel architecture applications is a shared endeavor, demanding collective effort and expertise to navigate the complexities ahead.

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ENDNOTES/ PHOTO CREDITS FIGURE 1

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