

Perspective

Unlocking the societal potential of engineered living materials

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SUMMARY

Engineered living materials (ELMs) are an emerging class of materials with the potential for transformative impacts in sustainability across sectors (e.g., water, energy, health). Progress toward producing ELMs with tailorable and/or stimuli-responsive functionalities has occurred in recent years, along with advances in materials manufacturing with increased complexity and scale. While a few ELMs have been commercialized, important barriers must be surmounted before their broader integration into society. These social, ethical, legal, and regulatory barriers, as well as barriers to collaboration between stakeholders, were identified in a workshop combining academic, industry, and government agency participants that was convened as part of the annual Montana Biofilm Meeting (Bozeman, MT) in July 2023. The ELM research community finds itself at a defining moment. Urgent action is needed to realize the societal benefits of ELMs while decreasing the likelihood of negative perception, and actual consequences, of their commercialization.

INTRODUCTION

Engineered living materials (ELMs) are an emerging class of materials that have additional or unique functionalities resulting from the inclusion of living biological cells on or within the material during at least one part of the material life cycle.¹ Living cells enable these materials to have useful primary or secondary functionalities, such as self-assembly, self-repair, sensing, increased resilience, conversion of compounds (e.g., bioremediation), biomaterial/feedstock production, drug manufacturing, and energy generation or storage. Therefore, the novel functionalities of ELMs have the potential to make transformative progress toward solutions for highly impactful challenges (e.g., National Academy of Engineering's 14 "Grand Challenges"), such as restoring and improving aging infrastructure, carbon sequestration, providing access to clean water, and engineering better medicines.²

ELMs have the potential to address seemingly intractable challenges in human health, environmental health, and sustainability. For example, ELMs could be utilized to sense and report the presence of toxins and pathogens that are not easily detected with traditional sensing mechanisms. A notable analogy to this approach is the addition of mercaptan to natural gas to track the presence of dangerous leaks in gas lines. Based upon sensitive and specific capabilities of biological systems, an ELM could potentially detect an odorless or colorless compound and respond with a visible readout (i.e., pigment production). Through utilizing microorganisms as biosensors, producing or delivering compounds, or interfacing with the host

PROGRESS AND POTENTIAL

Engineered living materials (ELMs) offer promising solutions to grand challenges in sustainability, energy, and healthcare but face significant challenges in terms of deployment in society. A dedicated ELM workshop was held as part of the Montana Biofilm Meeting in July 2023. This workshop brought together academic, industry, and agency researchers and stakeholders to identify significant barriers to the societal adoption and deployment of ELM technologies, as well as potential solutions to these barriers.

microbiome, ELMs are poised to increase the toolbox of healthcare materials and approaches.³ Regarding sustainability, the manufacturing of engineering materials has an outsized carbon footprint—accounting for an astounding 25% of worldwide carbon emissions.^{4,5} As much as 80% of engineering materials are made for long-term applications, including construction, vehicles, and machines.⁴ ELMs have the potential to greatly reduce carbon costs associated with material manufacturing by using living organisms to aid material manufacturing via less carbon-intensive processes. ELMs can also be manufactured on demand, thereby reducing carbon costs associated with material transportation. Furthermore, ELMs with self-healing capacities could extend the service life of materials used in durable devices, thereby reducing the frequency at which replacement materials are manufactured.^{6,7} A recent analysis substantiated that a 20% increase in the service life of buildings can reduce carbon emissions associated with their replacement by 30% per year,⁸ highlighting an opportunity for self-healing ELMs to yield significant environmental benefits.

The momentum behind ELM research is rapidly growing, as indicated by an exponential increase in the number of ELM-related publications (Google Scholar, keyword: “engineered living materials”). Public investment in ELM research is also increasing through at least the United States National Science Foundation, Department of Defense, Department of Energy, and National Institutes of Health programs, as well as the European Commission (e.g., Horizon Pathfinder). However, the translation of research progress to industry and application in society is currently hindered by a limited exchange of findings, ideas, and innovations between and among multidisciplinary teams working in this area. One of the principal challenges is that ELM research is highly interdisciplinary and integrates techniques from multiple domains, including materials science, engineering, microbiology, and synthetic biology, along with social, legal, and ethical fields of study. Currently, investigators rely on special symposia in established conferences in these principal fields to communicate their work (e.g., Materials Research Society, American Chemical Society, Synthetic Biology: Engineering, Evolution, and Design). As is often the case for emerging fields, none of these events currently capture the breadth of the ELM community nor catalyze much-needed, specific interactions and conversations between multiple stakeholders from academia, government, and industry.

As a first step toward fulfilling this unmet need, an ELM workshop was held on July 13, 2023, in Bozeman, Montana, in conjunction with the Montana Biofilm Meeting (MBM). The MBM is an established meeting of the Montana State University-Center for Biofilm Engineering (MSU-CBE), a graduated NSF Engineering Research Center sustained by relationships with more than 100 industry associates during a 33-year history. The meeting was chosen as the venue for the first US-based ELM workshop because (1) biofilms are arguably the best-known and most widely studied class of ELMs and (2) the meeting allowed the ELM community to leverage the MSU-CBE’s existing relationships between academia and industry related to biofilm-related technologies. This full-day workshop was comprised of spotlight talks, small-group discussions, large-group moderated discussions, an industry panel, and a government agency panel. Workshop attendees included 140 participants, representing 16 universities, 24 companies, and 4 governmental agencies. Attendees self-reported as 41% group leaders (principal investigator/professor/manager, etc.), 15% postdoctoral researchers, 26% graduate students, 7% undergraduate students, 2% administrators, and 11% other. Moreover, of the responding participants, 36% identified themselves as a member of a historically marginalized or underrepresented group.

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Figure 1. The transformative potential of engineered living materials requires surmounting critical barriers to their commercialization and societal implementation

The purpose of the workshop was to identify key barriers and potential solutions to progress in ELM research and technology development (Figure 1). Here, we report areas of momentum within the ELM research community but also existing and emerging challenges to scientific progress, partnership with industry, and adoption of ELM technologies by society. These insights will enable the ELM community to “look around the corner” to better enable ELM research progress and commercial translation.

RECENT ADVANCES IN ELM RESEARCH AND TECHNOLOGY DEPLOYMENT

The workshop included summaries of current research progress within the ELM community. This section summarizes the presentations and arguments that were posited by the invited speakers.

ELM advances via programming bacteria (C.A.-F. and M.C.)

ELMs can leverage the abilities of living cells to impact the physical and mechanical properties of materials from inception to use. This approach uses genetic circuits to conditionally synthesize structural biopolymers and/or enzymes that confer material properties of interest without the need for exogenous addition of functional enzymes, synthetic polymers, or postprocessing. For example, researchers have created ELMs that, from inception, have tailored color,⁹ electrical conductance,¹⁰ and stiffness.^{11,12} Details of genetic engineering to tailor the physicochemical properties of ELMs are reviewed elsewhere.^{13–15} Molinari et al. showed that changes to the domains in the structural protein responsible for bottom-up assembly of an ELM resulted in significant changes to the microscale structures and macroscale stiffness.¹¹ Likewise, Gilbert et al. found that the material properties of a cellulose-based ELM could be altered by secreting cellulase into the material.¹⁶ Wielding the ability to exert spatiotemporal control over properties, Wang et al. demonstrated that mineralization in engineered biofilms can be optogenetically patterned to allow

for structural property gradients.¹⁷ As genetically coded sense-and-respond abilities are becoming more common in ELMs, it is not difficult to imagine that material properties could be altered in response to stimuli. Thus, the potential for ELMs for “smart” material properties surpasses that of most other materials.

ELM advances in bottom-up fabrication of materials (N.J.)

While industrialized microbial fermentation has produced foodstuffs, commodity chemicals, drugs, and other products for many decades, the extension of this paradigm into materials has been limited. Apart from polyhydroxyalkanoates, and excluding fuel feedstocks (e.g., ethanol, lipids), there are few biopolymeric substances that are produced this way, and they are viewed exclusively as raw building blocks to be purified and incorporated directly into existing manufacturing paradigms (e.g., thermo-injection molding).¹⁸ ELMs present a unique opportunity to use living cells to manufacture, from the bottom up, material products that are more refined, have specialized functions, or exhibit enhanced performance characteristics. Examples include biodegradable bioplastics, three-dimensional (3D)-printable bioinks, affinity membranes, and therapeutic/diagnostic capsules for ingestion.^{19–22} Many approaches thus far have focused on developing material scaffolds based on variants of known structural proteins, including functional amyloids (e.g., *Escherichia coli*, *Bacillus subtilis*), S-layer proteins, and others.^{23–25} Strategies employed in this area span length scales and disciplines, from molecular engineering to macroscopic materials fabrication and characterization to industrial scale-up. Frontiers in this area involve the genetic programming of higher-order hierarchical assemblies and autonomous pattern formation.

ELM advances in additive manufacturing (A.S.M.)

The ability to create ELMs with higher-order functionalities will critically depend on the development of technologies to spatially pattern these living materials into complex, 3D shapes. Progress has been made in developing inexpensive, accessible 3D-printing technologies to produce living materials. Conventional 3D printers, originally designed to extrude plastic filament, can be converted into printers that deposit cell-containing bioinks by replacing the plastic extruders with syringe pumps attached to the printheads.^{26,27} These 3D bioprinters have been applied to print biofilms—communities of single-celled bacteria living a quasi-multicellular lifestyle—through secreting a thick extracellular matrix that surrounds and embeds the cells. 3D-printed microorganisms can survive for days to weeks^{28,29} and are able to respond to inducers to produce biological products of interest.²⁶ As an example of the utility of this approach, 3D-printed biofilms containing bacteria strains expressing curli fibers enabled the discovery that curli fibers contribute more to biofilm antibiotic resistance than other components of the extracellular matrix, such as cellulose.^{26,28–30} Future applications for 3D-printed biofilms could include the production of model biofilms-on-a-chip for the development of therapeutics, as well as the development of biologically and physically robust living materials with applications for environmental detoxification, the fabrication of environmentally responsive materials, environmentally friendly biocatalytic materials processing, and much more.³¹

ELM advances via stimuli-responsive polymer matrices (A.N.)

The engineering of the polymer matrix is also vital to the processability, mechanical properties, and stimuli responsiveness of ELMs. Synthetic polymer matrices in ELMs afford two different modalities of stimuli-responsive behaviors. The first is represented by stimuli-responsive behaviors that enable the processing of ELMs into 3D form factors (shapes). Stimuli-responsive triblock copolymer hydrogels have

been used in immobilized cell bioreactors, where engineered microorganisms serve as cellular factories for on-demand bioproduction of chemical products.^{32–34} Representing an interesting departure from traditional hydrogels used in ELM research, triblock copolymer hydrogels are temperature responsive, exhibiting a reversible gel-to-sol transition at 17°C that enables the cells to be homogeneously incorporated into the solution form and then shape formed at warmer temperatures. These same hydrogels also exhibit a shear-thinning response, which is ideal for extrusion-based 3D printing. Photocuring the hydrogels induces cross-linking of the hydrogel matrix. Thus, the multi-stimuli-responsive behaviors of these hydrogels enable 3D processing of these ELMs into arbitrary form factors. The second modality of stimuli-responsive ELMs is represented by ELMs that can sense and respond to environmental stimuli. Inducible CRISPR transcriptional activation (CRISPRa) programs were implemented to regulate the expression of enzymes in a pteridine biosynthesis pathway.³⁵ In one demonstration, enzyme production occurred in response to tetracycline in the medium and maintained the ability to sense and respond over multiple cycles that lasted nearly 1 month. The engineering of microorganisms and synthetic extracellular matrix in this way could lead to a wide spectrum of new material properties and capabilities.

ELM advances in construction (W.V.S.)

The conceptualization and commercialization of engineered living building materials (LBMs) serve as a template for ELM deployment within and beyond the built environment.³⁶ As reported in Heveran et al., engineered LBMs are produced by combining biomineralizing microorganisms with a sand-hydrogel scaffold, thereby creating a strong, tough, living structural composite.³⁶ LBMs have been produced using a wide variety of engineered and wild-type microorganisms that enable biomineralization (e.g., urea hydrolysis, photosynthesis).^{36,37} In the right conditions, LBMs have been shown to self-propagate and self-heal.^{36,37} LBMs are an example of a hybrid living material that combines living organisms with a non-living substrate to overcome the ELM grand challenge of scale.¹ A central advantage of LBMs compared with conventional building materials is the potential for lower-energy and lower-emissions manufacturing. The living component of LBMs can provide other advantages, such as carbon capture and self-healing.³⁸ Current disadvantages include lower strengths and higher prices of these materials compared with conventional building materials. LBMs have seen recent commercialization by Prometheus Materials and Biomason. Other companies, such as Biosqueeze, Basilisk, and Ecovative, have also brought products and technologies to market within the construction and infrastructure space, although not all of these materials are designed for load-bearing applications. These early commercialization endeavors demonstrate that well-known barriers to market entry can be overcome and may serve as a blueprint for other startups seeking to commercialize nascent ELM technologies.

BARRIERS TO ELM PROGRESS AND TECHNOLOGY DEPLOYMENT

Barriers to scientific and technical progress

Despite the rapid growth of ELM research activity and growing governmental investment, there are important challenges that must be addressed to sustain the continued growth and maturation of this field. Furthermore, critical deployment barriers must be overcome to accelerate the integration of these materials into society. Several common themes emerged from the workshop discussions.

Scale and production volumes

Scale remains a grand challenge for ELM technological advancement. Most research is conducted on the benchtop, rendering small quantities on the order of milligrams

available for testing. For most ELM technologies that are being designed to replace traditional materials, production volumes must increase from milligrams to kilograms, even for simple prototype testing. In other industries, such as construction, quantities must be scaled to metric tons. Researchers have invoked various top-down design approaches to address the challenge of scale. For example, hybrid ELMs, in which a living component is combined with a non-living substrate, enable the production of larger volumes of the final product without the burden of scaling the living component to comparable volumes.³⁹ Deployment efforts would be streamlined if existing infrastructure and applications were used for scale-up. For example, designing and manufacturing drop-in replacements for existing unsustainable material products (e.g., concrete, conventional plastics) would be a strategically beneficial approach for some technologies and lead to near-term breakthroughs since this strategy does not necessarily require the development of new codes, standards, or application methods. However, the scalability of some ELMs may necessitate concomitant innovation in manufacturing paradigms. Examples of such new manufacturing approaches might be found in the solid-state fermentation used to make mycelium-based materials or the greenhouse-based cultivation of biobricks.

Control of cellular viability

The living component of ELMs confers specific functionalities and benefits to the structure. Control over this living component over time is essential for reliable material performance and societal acceptance. On the one hand, concerns about microbial overgrowth or mutation need to be addressed. Engineering robust “kill switches” or synthetic auxotrophies into materials can help mitigate this concern. The living component of deployable ELM systems should be engineered to allow enough reliable control over the return to a stable state after the target response has been achieved. On the other hand, for some applications (e.g., stiff or self-healing materials, sensors), the ability to maintain microbial viability is not yet sufficient to generate a material that stays alive for more than a few weeks.⁷ Progress is being made to surmount the limitation of cellular viability. For example, while typical hydrogel-encapsulated microbes require continual input of nutrients to extend their viability beyond a few days,^{26,29} the fabrication of ELMs featuring self-sustaining photosynthetic microalgae boosted the lifespan of these materials to weeks or months.²⁸ In some settings, ELM innovations designed for extended cellular viability may require the co-development of fluidic systems to enable them, akin to the circulatory systems of some natural living systems.⁴⁰ The viability of ELMs will also benefit from judicious selection of the environments in which they are deployed, as well as future research related to additives, preservatives, and microfluidic nutrient systems that could prolong viability.

Improved performance, cost, and design of materials

In some cases, the performance and prospective cost of ELMs are not yet competitive enough to replace established materials, especially those in commodity markets (e.g., plastics, construction materials). Even the most robust naturally occurring materials do not have the strength and stiffness to match commonly used engineering materials, limiting the application of materials synthesized by living organisms.⁷ For instance, while biomineralized ELMs can currently achieve stiffness and strength comparable with some mortars, these materials do not yet achieve properties that allow substitution for concrete. Increasing the mineral fraction of these materials or using hybrid ELMs can help to surmount these challenges.⁴¹ The use of enzymatic methods to induce mineralization to stiffen these types of materials can also be useful. Enzymatic mineralization has achieved some of the highest mineral contents and stiffnesses to date for sand-hydrogel

composites.⁴² The durability characteristics of ELMs intended to replace engineering materials also have important limitations. For example, ELMs that utilize hydrogels suffer decreased strength in humid environments.³⁶ Improving the viability, material properties, and durability characteristics of ELMs will benefit from the collaborative efforts of materials scientists, engineers, and biologists.

In other cases, uniformity of performance is important to maintain. A material containing a living component with prolonged viability might have variable effectiveness over time with regards to production, biosensing, etc. In addition, design tools governed by appropriate standards are required to facilitate the design and engineering of ELMs for targeted applications.

Predictability and standardization

To achieve the predictive design that drives the development of traditional materials, ELM researchers will need to elucidate genotype-to-phenotype relationships at cellular, population, and community levels to build and improve structure-property relationships.^{43,44} Currently there is a lack of standards and practices employed by ELM researchers to thoroughly characterize and compare materials across length scales. At the smallest scale, genetic sequences, as well as protein sequences and levels, should be confirmed, and as synthetic biologists are the most prevalent ELM developers, this is common. However, biophysical assessment using techniques like dynamic light scattering, fluorescence resonance energy transfer, and differential scanning calorimetry are needed but uncommon.⁴⁵ From there, spatio-temporal visualization of multiscale structures is key, and the 2018 Genome Engineering for Materials Synthesis Workshop report provides technical recommendations.⁴⁶ At the macroscale, mechanical properties should be assessed through techniques such as rheology and flexural tests. Using all of these methods, comparisons of variants will confirm the effect genetic changes have on final properties. Additionally, current standards, such as those provided by the American Society for Testing and Materials (ASTM) and/or the International Organization for Standardization (ISO), will need to be applied to ELMs. These standards are not currently designed for ELMs; therefore, discussions with federal agencies such as the National Institute of Standards and Technology, the U.S. Food and Drug Administration, and the U.S. Environmental Protection Agency are needed.

Barriers to societal adoption of ELM technologies

Most ELM products and technologies are still at low technology readiness levels (TRLs). As these TRLs advance, there are social, legal, and ethical challenges that need to be surmounted for ELMs to be fully deployed in society. Some of these challenges may arise because stakeholders are unfamiliar with these emerging technologies or may have misperceptions about risks and impacts. In such cases, efforts to address these risks and impacts should include engagement efforts aimed at increasing public understanding of the science and technology, including the development of education and training materials at all levels (kindergarten–college, as well as for the general public “K-gray”). Other challenges, however, may point to genuine ethical concerns about safety, cost, and accessibility or conflicts with moral or ethical worldviews. In these cases, challenges may need to be addressed in the design and development phase or may guide development of particular applications or regulations.⁴⁷ To identify the range of challenges, stakeholder input should be solicited early in the process, before ELM products reach higher technology readiness.^{48–51}

Several of the ethical, legal, and social barriers and potential solutions discussed here could be relevant to other materials systems that involve microorganisms.

However, ELMs require unique considerations. Workshop participants anticipate a possible future where ELMs are ubiquitous, through a combination of building materials, bioplastics, medicines, and likely other products. The level of potential interaction between the public and these technologies may be much greater, and harder to avoid, than with other biotechnologies (e.g., genetically modified organism [GMO] foods). To meet their potential for impacts in sustainability, healthcare, and other domains, it is essential to establish public acceptance of these materials.

Social

The public perception of living materials is anticipated to be negative in some sectors, as there are aspects of ELMs that may provoke disgust, or what is known as the “yuck factor.”^{52–54} End users may experience disgust at the idea of interacting with materials that contain microbial communities for a variety of reasons, including widespread views about hygiene and bacteria, despite the fact that surfaces in homes and workplaces already have resident microbial flora. The yuck factor can also be provoked by moral disgust or disgust that occurs when an emerging technology appears to conflict with deeply held moral convictions, such as the view that “nature” should not be altered or engineered.^{55–57} Countering moral disgust will require different strategies, including efforts that effectively communicate the prospective environmental and social benefits of ELMs, especially in the context of offering new solutions to persistent challenges. Moral concerns that might be triggered might also be alleviated through regulation, selective applications, or design choice. As an example, hospital-acquired infections are currently at an all-time high. ELMs have the potential to manufacture and deliver antibiotics in new ways, which could address this need better than current methods. Faced with the alternative (i.e., persistent infections or other challenges), the public may be receptive to unfamiliar technologies. An important strategy will be emphasizing examples of currently commercialized products where resistance to novel technologies can be overcome by convincingly demonstrating that they safely address a societal need as well as, or better than, existing alternatives.^{58,59} Improving the social acceptance of ELMs will also benefit from utilizing non-toxic material components and verifying the non-toxicity of these materials over time. For example, there has been considerable progress in designing polymer or biopolymer matrices that support ELM functionalities and are also non-toxic.^{3,11,22,23,25,29,34} Additionally, ELMs that use wild-type organisms may be the most suitable candidates to commercialize first, potentially paving the way for materials containing engineered organisms.

Legal

The regulatory environment surrounding ELM use is unclear at best. It is uncertain which regulatory agency or agencies will oversee the prospective use of ELMs within the United States and beyond. ELMs may need to achieve certain material properties, such as appropriate strength and durability, to perform a structural task while harboring living cells that may perform another function, such as the production of a useful chemical. Concerns were expressed regarding the regulatory frameworks for ELMs that serve a healthcare purpose, as ELMs are unlikely to have 510(K) precedents for some time and may be seen as combination drug/device products, depending on the application. The cost involved in bringing these materials to market may be substantial. Other legal considerations may include the containment of ELMs. The history of legal challenges involving the migration of genetically modified crops to neighboring fields may be instructive for what might happen if the living component on an ELM installation does not stay contained. If ELMs in society contain genetically engineered organisms, or organisms with the potential or the perception to potentially threaten human or environmental health, legal challenges may be likely.

Ethical

There are numerous important ethical considerations to deploying ELMs in society. Risks might include harm to individual, public, or environmental health due to failure to contain the living component of the material. Improving the ability to contain microorganisms within ELMs or engineering “kill switches” in these materials may substantially mitigate these concerns and improve acceptance of these materials. Further, it will be important to control the possibility of lateral gene transfer from genetically engineered components to environmental organisms. ELMs with potential for dual use (e.g., civilian and military applications) must be subject to much stricter oversight. There may also be safety concerns if the living component of the material is not maintained properly, such that it loses its functionality in particular ELM applications. For example, if biofilms are not properly maintained, then they may lose their ability to clean, trap, or filter harmful particles in water or air, which could impact health if not detected immediately. Thus, proper maintenance and monitoring of ELMs will be needed.

Another important ethical consideration is access to ELMs and whether any risks and benefits they involve will be equitably distributed. If ELMs cost significantly more than traditional materials, then this may mean that their use will be restricted to those who can afford them. This will be particularly problematic if their safety risks are imposed on all of society, even those who cannot afford them. If the cost of ELMs is kept low, then the materials may be more accessible. However, there is also a risk that certain underserved populations will be more skeptical of embracing novel materials. Communities of color and poor communities have historically been put at risk with cheap materials with known negative health impacts (e.g., lead pipes, asbestos). Such communities may be particularly distrustful of novel materials. In the absence of clear regulatory guidelines for ELMs, self-regulation by ELM researchers may emerge in a manner analogous to what has occurred for genetic engineering. Workshop participants voiced a need for continued discussion about ethical considerations of these materials and supported introducing, or expanding, ethics training for researchers in this space.

Several of these ethical, legal, and social barriers, and potential solutions, could be relevant to other materials systems that involve microorganisms. However, ELMs require unique considerations. Workshop participants anticipate a possible future where ELMs are ubiquitous, through a combination of building materials, bioplastics, medicines, and likely other products. The level of potential interaction between the public and these technologies may be much greater, and harder to avoid, than with other biotechnologies (e.g., GMO foods). To meet their potential for impacts in sustainability, healthcare, and other domains, it is essential to establish public acceptance of these materials.

Barriers to collaboration between academia, industry, and government agencies

A strength of this ELM workshop was the participation of representatives from academia, industry, and government. Current and anticipated challenges to collaboration between teams working in ELM research across academic, industry, and government laboratories were explored through industry and agency panels as well as open, facilitated discussions.

Knowledge regarding ELMs is nascent within industry

While most industry workshop attendees work in biofilm research and development in some capacity, few had prior knowledge of ELMs. There was a shared sentiment

between academic and industry attendees that creating more opportunities for exchange of ideas between these groups is essential for moving the ELM field forward toward commercialization and deployment. Dialogue between industry and academia is necessary for identifying the products and/or processes that are best suited to benefit from ELM-enabled attributes. It is recommended that conferences should include sessions focused on product development of ELM technologies, with an emphasis on the critical issues facing application and commercialization, including regulation, manufacturing readiness, and public perception.

Need to expand collaborations between academic, industry, and government agency teams

Early engagement with practitioners, industry professionals, government entities, and other key players can be a critical factor in the eventual success of technology advancements and implementation.^{60,61} A variety of funding mechanisms already exist (e.g., NSF programs including Engineering Research Centers, GOALI, INTERN, Regional Innovation Engines, Tech Hubs, SBIR/STTR, and others) to launch collaborations between teams working in each domain, and some of these could be leveraged more extensively to pursue fundamental and translational ELM research. More broadly, increasing opportunities for academic, industry, and agency researchers to congregate and share results and challenges can begin filling this gap in collaboration across teams in ELM research.

Technological readiness levels are currently low for most ELMs

It was expressed by industry attendees that a willingness to externally invest in ELM technologies will improve as TRLs increase. For some government agency interests, these challenges are also applicable. Drop-in replacements of existing products will facilitate the incorporation of ELMs into applications that interest potential industry and government stakeholders. However, acceptance within the market of such drop-in replacements may require the demonstration of improved product performance or sustainability profile for the market to accept the potential of higher costs. Importantly, several products for packaging, textiles, and food made from fungi that are no longer alive are currently on the market. Non-living paving tiles made from bacteria-biocemented crushed granite are also available. These types of products help prove the market potential for new ELM technologies. To increase the awareness of ELM technologies and capabilities, the ELM community should continue to communicate past and recent successes to educate industry, government, and the general public on the benefits of these products.

Training a workforce to participate in ELM development in industry is essential

In this “century of biology,”⁶² students need to receive special training at the interface of biology, materials science, and engineering to lead the ELM industry forward. Internship programs are critical for students to gain industry-relevant experience. Nurturing the collaboration between academia and industry within the ELM discipline will surely create more meaningful opportunities for students’ exposure to industries with a focus on developing products with ELM-embedded technologies.

DISCUSSION

The development of ELMs is poised for continued rapid growth, but this growth will not meet its potential efficiency or effectiveness without working to surmount important barriers. Some of these barriers, especially regarding ethical and legal considerations, are likely to increase as the first ELMs are deployed. Barriers, if not identified and resolved beforehand, may at the very least become bottlenecks to

bringing ELMs to society or become ingrained roadblocks to societal acceptance. For example, if the ethical ramifications of deploying an ELM within a community are not appropriately considered, then there may be regulatory pushback that further challenges their deployment, even for uses that benefit many. History teaches that public acceptance of new technologies may be a more challenging hurdle even after regulatory acceptance has been received and the societal benefits have been clearly presented. Past examples of technologies that faced difficult public acceptance with clearly defined societal benefits include agricultural GMO technologies. More recently, technologies employing AI-embedded capabilities have faced similar public acceptance challenges. Implementation of commercialized ELM products should consider transparent public outreach strategies to educate on the societal benefits of such technologies.

Among the barriers most frequently discussed during the workshop was the lack of a regulatory framework for ELM technologies. Defining the regulatory landscape will improve societal acceptance of ELMs and also help potential industry partners understand risks and rewards in ELM technology investment and development. As with other technologies that have the potential to cause harm if improperly tested, deployed, or monitored (e.g., healthcare, construction/infrastructure materials), regulation surrounding ELMs will likely differ across countries and regions. Development of industry-specific standards that can be adopted by interested entities will help promote acceptance and innovation.

An interesting question is whether self-regulation by the ELM community will precede governmental regulation, such as what occurred with CRISPR-Cas9 technologies. This sort of development of ethical standards within the ELM community as pertaining to developing, testing, and deploying ELM standards may be advantageous. The ELM community may be able to address some or all concerns in ways that ease public concern. Well-developed professional guidelines might serve as a starting point for frameworks later codified by governments.

Important for surmounting barriers to bringing ELMs to society is recognizing who is missing from the ELM research community, and there was consensus that experts in the social, legal, and ethical implications of ELMs are not yet adequately represented in the community. Encouragingly, recent funding mechanisms (e.g., NSF Emerging Frontiers in Research and Innovation program) have valued the inclusion of researchers with these areas of expertise on interdisciplinary ELM teams. It will be beneficial to dedicate conference sessions, journal special issues, or other venues for communication to these topics. Experts in communication are likely needed to understand and overcome potentially unjustified concerns of the public regarding living materials. Additionally, experts in regulatory development and compliance are likely needed to work toward widespread, safe usage of these materials in society.

To summarize, the ELM research community currently finds itself at a defining moment. Separate, often isolated, efforts are beginning to coalesce and converge as progress in ELM research necessitates collaboration beyond the benchtop. Potential barriers to bringing ELMs to society are no longer hypothetical. Now is the time to work toward solutions to these barriers to improve the likelihood of accelerating ELM commercialization and maximizing the societal benefits of ELMs while decreasing the likelihood of potential negative impacts. It is of utmost importance to assemble people across the ELM community and include necessary voices that are not yet part of the community to increase progress toward surmounting these key issues.

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DECLARATION OF INTERESTS

W.V.S. is a listed co-inventor on a patent application (PCT/US2020/020863) filed by the University of Colorado on April 3, 2020, related to biomineralized building materials. W.V.S. is a co-founder and shareholder of Prometheus Materials, Inc. and Minus Materials, Inc. and a member of their scientific advisory boards.

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