Materials come alive

The dissemination of synthetic biology into materials science is creating an evolving class of functional, engineered living materials that can grow, sense and adapt similar to biological organisms.

Nature has long served as inspiration for the design of materials with improved properties and advanced functionalities. Nonetheless, thus far, no synthetic material has been able to fully recapitulate the complexity of living materials. Living organisms are unique due to their multifunctionality and ability to grow, self-repair, sense and adapt to the environment in an autonomous and sustainable manner. The field of engineered living materials capitalizes on these features to create biological materials with programmable functionalities using engineering tools borrowed from synthetic biology. In this focus issue we feature a Perspective and an Article to highlight how synergies between synthetic biology and biomaterial sciences are providing next-generation engineered living materials with tailored functionalities.

As the name implies, living cells are an integral constituent of engineered living materials[1,2]. But beyond that, in engineered living materials, cells actively contribute to the formation, maintenance and properties of the material, utilizing energy from the environment to fabricate building blocks or to modulate bulk responses. These materials can be composed entirely of living cells or biocomposites with synthetic and living components. Genetically engineered bacteria, fungi and eukaryotic cells are used as functional modules to endow programmability and desired responses. Some examples include wound-healing gels containing spores of genetically engineered bacteria that produce antibiotics when detecting a pathogenic bacteria[3]; bacterial cellulose-based biosensors for hormones made from engineered bacteria and fungus[4]; or regenerative living building materials fabricated from a sand–hydrogel matrix toughened by cyanobacteria-mediated biomineralization[5].

The blossoming of engineered living materials has been facilitated by a deeper understanding of the molecular mechanisms that drive and regulate biological material assembly and functions. Equally important has been the development of molecular engineering tools to repurpose those natural processes to create biological circuits and systems with artificial functions. In a Perspective in this issue of *Nature Materials*, Allen Liu, Nicholas Stephanopoulos, Ovijit Chaudhuri and colleagues provide an overview of recent advances in the fields of synthetic biology and biomaterials and discuss how collaborative research at their interface will lead to programmable biomaterials with advanced functionalities. They review how synthetic biology has evolved into a truly engineering science, enabling the programming of mammalian cells and even the construction of customized cell-free systems and fully synthetic cells. They also discuss developments in biomaterial design, namely for the fabrication of stimuli-responsive hydrogels with tunable viscoelastic properties for the fine tuning of cell–biomaterial interactions and modulation of cellular and tissue behaviour. Using synthetic biology tools, the functions and properties of these biomaterials can be tailored for a specific function. Nonetheless, the most exciting direction is the fabrication of engineered living biomaterials that establish bidirectional interactions with the cells, that is, biomaterials that adapt their properties and functions according to cellular responses. While the development of such materials is still in its infancy, the researchers predict possible applications for engineered living biomaterials in medicine, biotechnology and sustainability.

Wood-decay fungi are being used to create living materials from agricultural waste. Credit: Nature Picture Library / Alamy Stock Photo.

Not considering energetic needs, biomaterials and living organisms are fully recyclable through their life cycle, thus, being prime examples of sustainable materials. In an Article in this issue, Damen Schaak, Harris Wang and colleagues describe fungal–bacterial biocomposites grown on lignocellulosic waste that can be moulded, folded and assembled into human-size living structures with self-healing and sensing functionalities. The authors add white-rot bracket fungus (pictured) to raw hemp herd particulates inside plastic moulds to grow a fungal mycelium that binds the lignocellulosic particulates into brick-sized living building blocks. Origami-inspired flat moulds in combination with fabrics are also used to create foldable blocks for kinematic assembly and complex three-dimensional structures. These living materials can self-repair, grow and repopulate other raw feedstocks, when supplemented by the appropriate growth media. The authors engineered a bacteria found on the raw feedstocks to create a prototypical sender–receiver signalling system in the living composites and demonstrated their ability to produce, sense, amplify and transmit molecular signals. As discussed in an accompanying News & Views article by Matthew Chang and colleagues, these sustainable living building materials may become an alternative to concrete-based constructions, thus contributing to efforts for global emissions mitigation. Likewise, by growing on agricultural by-products, these engineered living materials could also aid in worldwide efforts in waste reduction and recycling.

Engineered living materials have enormous potential to address real-life challenges. For instance, multifunctional water purification living materials that sense, report and even neutralize toxins and pollutants can be envisioned. To reach that stage, a better knowledge of the molecular rules determining biological assembly and improved biological engineering tools are still required. Likewise, the long-term robustness, viability and overall safety of engineered living materials need to be studied and optimized. These issues can only be solved with further collaboration between synthetic biologists and materials scientists. ❐

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