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The Biomaterial Age: The Transition Toward a More Sustainable Society will Be Determined by Advances in Controlling Biological Processes

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A dramatic transformation is necessary to reach a sustainable society revolving around the control and use of biological materials and designs. This biomaterial age ushers a completely new technological paradigm favoring the development of circular economic models and sustainable societies.

Sustainable Materials: A Scientific Issue

The history of humanity is often associated with epochs named after advancements in the technology of materials. Stone, bronze, and iron are early examples of materials that transformed the world. A counterpart to those primitive materials nowadays can be found in the vast range of man-made synthetic polymers commonly known as plastics[1]. In contrast to their predecessors, plastics are genuinely artificial and in complete disconnect from ecological cycles on Earth. They depend on human action to be both produced and recovered. Since human action in reclaiming the resources embodied in plastics is often piecemeal at best and practically nonexistent at worst, most plastic produced is accumulating in landfills, the oceans, and in places and forms we are still discovering.[2]

In the last few decades, we have developed broad social awareness for the impact of our actions on the environment. Part thereof is now attributed to the impact of plastics. Yet, this new awareness has crystalized into timid regulations because there are few to no available alternatives for such a fundamental material on which our economy and current way of life depends. It is thus practically impossible to strongly regulate the overuse of plastics, and currently, most solutions deployed are focused on recovery primarily via recycling practices. However, as the World Bank Group recently confirmed, current recovery processes connected to an uncontrolled production are technologically unfeasible for developing countries while giving rise to increasingly unaffordable and oversized waste management systems in the developed ones.[3] As a result, despite the clear understanding that recovering strategies are not enough and the use of plastics must be limited globally, there is nothing indicating that this may ever be implemented. Instead, the gross production of plastics only accelerates: If in the 1950s we produced half a million tons a year, we now produce almost five hundred million tons, and at the current rate, by 2050 we will double that amount, requiring one-fifth of the world's oil production to manufacture plastics.

The rapid transition of plastics from being the future of manufacturing to an environmental issue has somewhat caught materials scientists off guard. Examining general science journals reveals that the primary source of articles related to the impact of plastics are studies produced by environmental scientists describing the immeasurable magnitude of the problem and the imperativeness of its solution. While interest in the scientific community for understanding and raising awareness is evident, it is also in sharp contrast with the minimal scientific attention given to solutions, which are completely absent from the same reference journals. This is because the field of materials science remains fixated in paradigms of the last century, where improvement of mechanical and electrical properties is the primary and almost sole driver of research and development. Meanwhile, advancements in new materials with a broader understanding of their ecological behavior and environmental impact are still largely ignored. Times are changing; rare is the university that does not have one or several courses focused on sustainability these days. However, the current generation of materials scientists should acknowledge their key role in sustainability and establish this aspect as one of the main research motivations with the recognition that mechanical and electrical material properties currently have.

Beyond Bioinspiration: Linking Biological Components and Designs

Solutions for sustainable alternatives to plastic are invariably targeting scanty biomolecules with thermoplastic properties or relying on the transformation of abundant biomolecules toward properties exhibited by plastics, such that they can be easily adopted and integrated with minimal investment in retooling. While using renewable sources to produce plastics is a positive step forward, it is ultimately not a profoundly sustainable solution but rather a piecemeal mitigation. This is because the transformation of biological

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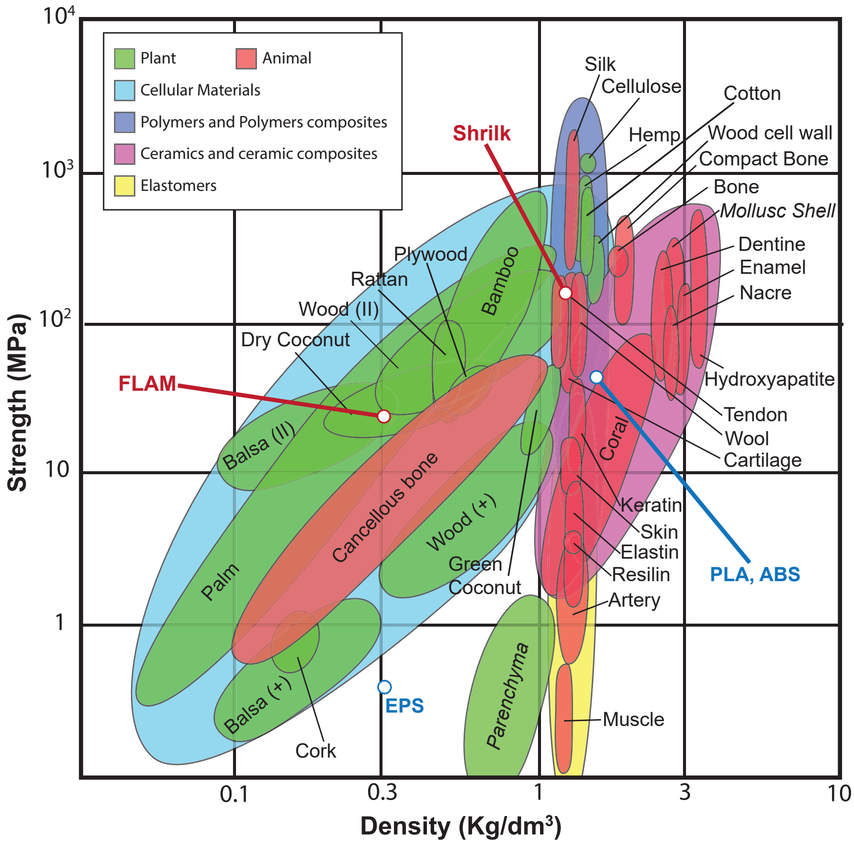

Figure 1. The Mechanical Diversity of Biomaterials

Ashby plot of the tensile strength of biological composites and their density. Biological materials are generally characterized by a low density, predominantly around that of water. On the plot it is highlighted the relative location of the bioinspired and fully biological fungal-like adhesive materials (FLAM)[6] and insect cuticle mimic (i.e., Shrilk),[5] as well as the most common synthetic 3D printing materials acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and Expanded Polystyrene (EPS) low-density foams.

molecules to fit the behaviors of plastics is often in detriment to their ability to integrate into the ecology of Earth, requiring similar recovery strategies as those for conventional plastics. With such approaches, we continue to fail to see past the horizon of plastics; the problem is the current paradigm, not the lack of materials capable of integrating seamlessly into the ecology of Earth. In fact, we are surrounded by those materials. The solution to the sustainability of our materials is less likely to come from an invention of an exotic new synthetic material, but from the control of materials that have been invented by nature since the Cambrian Period.

Take, for example, the strength of silk, the mollusk shell's ability to absorb impact, and the lightness of balsa wood—extraordinary properties with broad uses in engineering applications (Figure 1). The secret behind those astonishing properties is in the hierarchical structure of biological materials.[4] From human bones to the wings of a butterfly, nature uses this strategy of extremely complex hierarchical designs to produce remarkable structures using very little energy and the most common and unassuming primary components. The intrinsic design intelligence in biomaterials, crystalized after millions of years of evolution, is today a recurrent source of inspiration in materials sciences. However, the prevalent model for new biomimetic materials is limited to biological designs reproduced with synthetic materials of known manufacturability. Materials reproducing those designs with the native components are few but have much deeper implications. Take the example Shrilk, a biomaterial reproducing the structure and composition of an insect's cuticle.[5] When the components of Shrilk (i.e., chitin, a polysaccharide; and fibroin, a protein) are merely mixed, even analogous to natural proportions, the resulting materials exhibit negligible mechanical properties. But if instead they are configured in the same way they are organized in nature, the result is a material of outstanding mechanical and functional properties way beyond those of its constituents. This result, also found in laboratory-made mollusks' nacre and spider's silk, offers a critical insight pertaining to the general utilization of biological components in engineering: biological molecules and the way they aggregate to form structures are inseparable aspects of biomaterials. Therefore, if we want to incorporate natural resources into industrial processes, it is not enough to use the right ingredients; we also need to reproduce the way they were designed and assembled. This offers a new paradigm for the development of sustainable materials—a bioinspired perspective based on the control and reproduction of the principles of biological materials using their own components (Figure 2).

Biomaterials and Additive Manufacturing as Necessary Pieces for Circular Economy

A property of plastics underpinning their dominance in current modes of industrial production is their ability to rapidly be manufactured into large quantities of objects using mass production methods such as injection molding. The emergence of additive manufacturing methods two decades ago introduced a fundamentally new

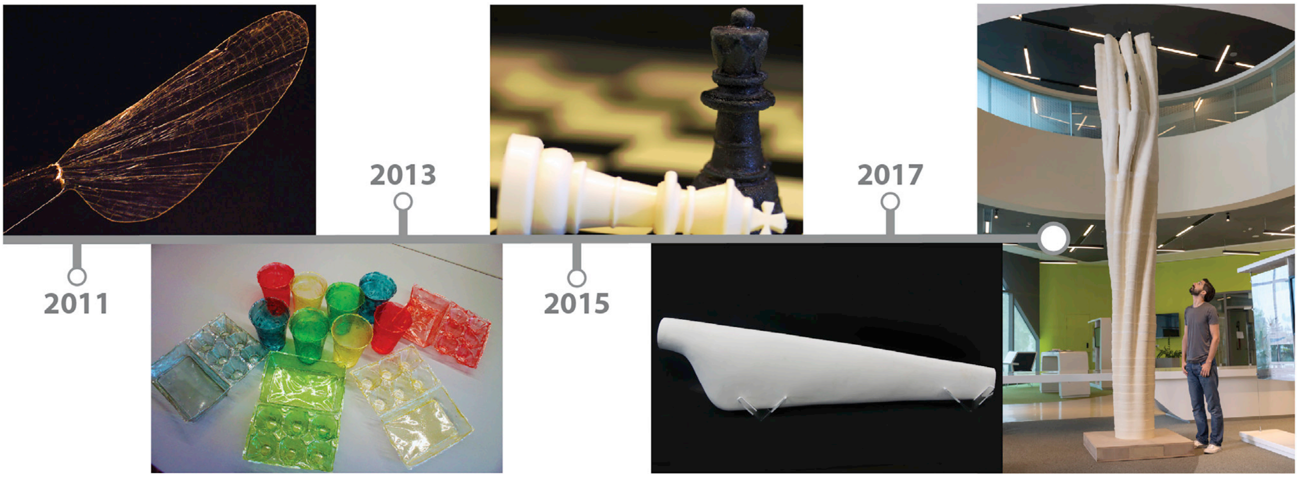

Figure 2. 10 Years of Evolution of Bioinspired Chitinous Manufacturing

Over 10 years, the bioinspired manufacture of chitinous composites developed from the first reproduction of the synergies of a structural bio-composite with the same components[5] to its use in the production of 3D objects,[8] the production of voluminous structures, the development of a biological freeform manufactured product,[6] and the production of the largest biological object ever printed and one of the largest 3D-printed objects in the world.[7]

way to fabricate objects, and coupled with an innate versatility for design, it allowed production to take place anywhere in the world. At a high level, three-dimensional (3D) printing is a process where objects are constructed by aggregating smaller material units in an organized and controlled manner. The process is conceptually similar to the formation of hierarchical biological structures from simpler components. Yet the most popular materials for 3D printing are currently thermoplastic and thermoset polymers, as the use of biological materials is mostly limited to the reproduction of organs and scaffolds for medical applications.

Recent research efforts in 3D printing aim to transform a technology popularized for rapid fabrication of low-cost, low-volume disposable plastic prototypes into an industrial method for the production of properly designed and engineered products. While great strides have taken place, additive manufacturing is still far from being competitive against conventional manufacturing techniques. Nevertheless, it is envisaged that 3D printing processes will eventually displace a substantial portion of currently used methods. This prospect motivates a unique opportunity to challenge the dominance of plastics in their stronghold of industrial production.

An indicative study of deploying natural biomaterials for large-scale production to offset the overuse of plastics is found in the development of the so-called fungus-like additive material (FLAM) 3D printing process.[6] FLAM is a reproduction with the same components and design of the cell wall of oomycetes. Oomycetes are a class of microorganisms very similar to fungi, but unlike fungi, they build their walls with cellulose and small amounts of another biopolymers, namely chitin. When this composition is reconstructed artificially, the results are materials of low density that cost similarly to the cheapest of plastics and have an extraordinary capacity to be printed into large 3D structures, matching many aspects of the current capabilities and economy of plastics use in industry.

A fascinating and often overlooked aspect of additive manufacturing is that it holds the potential to fully decentralize production of consumer goods; theoretically, all production could be sourced and manufactured from local resources. This is where biological materials offer a unique and powerful value proposition. The components of FLAM for example, cellulose and chitin, are the two most abundant and broadly distributed organic materials in the Earth's crust and, more importantly, are produced and degraded in large quantities in every ecosystem on Earth, readily sourced from even common waste in urban environments (Figure 3). These characteristics enable decentralized production models where materials are obtained, processed, and degraded within a closed and regional system without the need to transport components or develop synthesis and recovery systems that scale with their production.[7]

What Next

Manufacturing large-scale objects with bioinspired materials with costs and properties similar to those of plastics offers early evidence of the age of biomaterials, but it is still the beginning of what remains to come. Perhaps more important than the direct

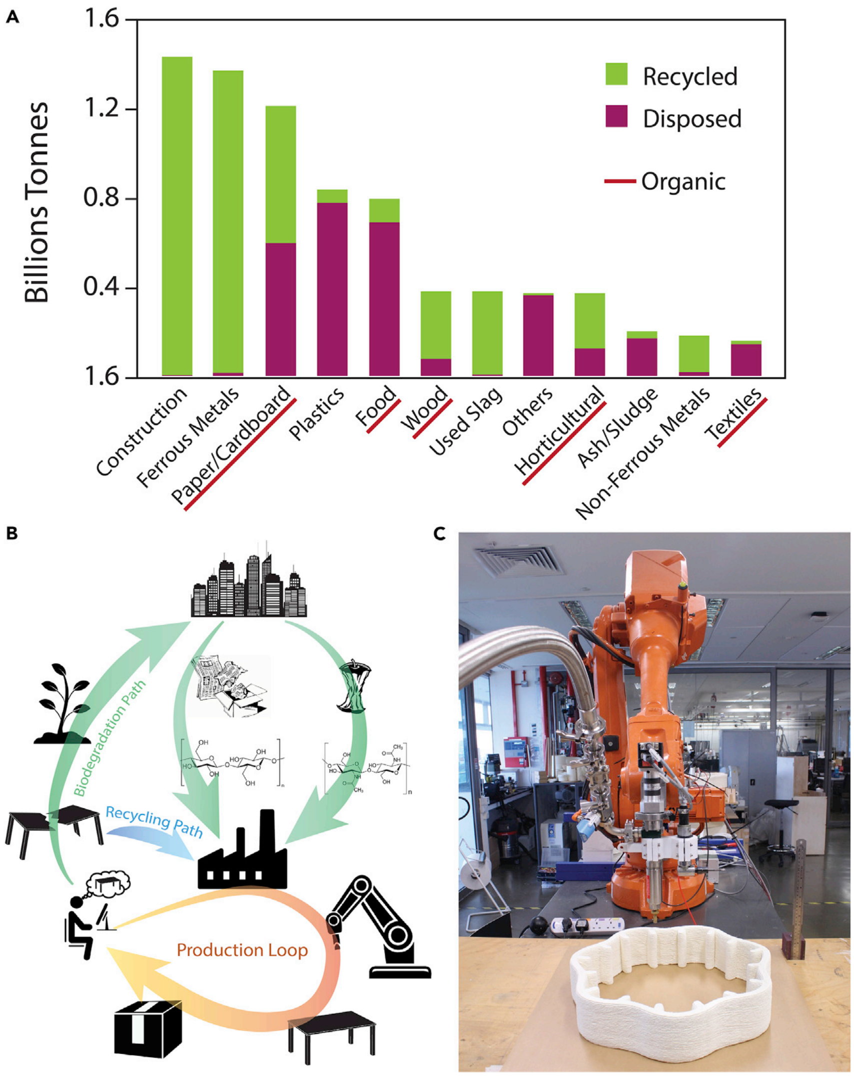

Figure 3. Urban Ecosystems, Biomaterials, and Circular Economy

(A) Waste production in a typical developed urban environment. Construction debris and ferrous metals are the main waste (by weight); they have recycling rates close to 99%. This contrasts with the next three waste streams (paper, plastics, and food), which have residual recycling rates, accounting for more than 70% of the total waste disposed.

(B) Example of a fully circular urban production model based on manufacturing with biological materials. The production loop represents a job production approach (in contrast with the usual flow and batch approach) where manufacturing occurs on demand in regional printing facilities.[7] The role of additive manufacturing, as a key piece for the freeform production of consumables, is highlighted.

(C) Large-scale biological printer, enabling the production of biological objects of several meters at a cost similar to commodity plastic and twenty times cheaper than the cheapest plastic-based printing filaments.[6]

technological repercussions associated with a paradigm shift toward biomaterials are their social and economic implications. Due to their ubiquity, the use of biological materials favors an economy based on local manufacturing centers and workforces that produce for a region that supplies and consumes primarily its own raw materials. This model also provides a favorable backdrop for developing legislative frameworks pertaining to the controlled use of materials originating outside the ecological cycles of a region, which in turn will significantly reduce the pressure from ever-increasing recovery systems as massive and economically unfeasible as those currently required.

Despite its youth and early stage of development regarding its potential, the latest achievements obtained by bioinspired manufacturing represent one of the first technologies that can compare with plastics in terms of the versatility of mechanical properties, cost, or manufacturing capacity. It is the first proof that the current age of plastics is far from being the technological peak of humanity, and we might be witnessing the birth of a new era: the biomaterial age, with profound technological, economic, and societal implications.

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