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Engineered Materials: Bioinspired “Good Enough” versus Maximized Performance

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Utilizing various materials is fundamental for the production of physical objects. However, processing raw materials during production often leads to complex transformations that hinder the recyclability of modern high-performance materials. These materials possess increased durability and resilience, challenging their decomposition and limiting their potential for recycling and reuse. In contrast, living Nature manages material utilization without such complications. The emerging discipline of Engineered Living Materials (ELMs) shifts the focus to self-repairing, self-supporting growing materials, emphasizing overall sustainability. To effectively address the challenges associated with high-performance materials, the design process must incorporate considerations of recycling and decomposition from the outset. Environmental challenges associated with material utilization can be addressed by reevaluating material design and prioritizing recycling, decomposition, and embracing Nature’s “good enough” principle. The transition toward sustainable resource management requires substantial investment in scientific research that explores the mechanisms by which life sustains itself using solely local resources. Biomimetics and ELMs offer valuable insights, but a deeper understanding of how Nature efficiently utilizes resources is crucial. The integration of engineering advantages not identified in Nature, such as product sub-unit reuse, can complement these efforts. Paving the way toward a sustainable future requires a comprehensive approach rooted in biological evolution and innovative scientific research.

1. Introduction

The production of physical objects created by humanity relies on utilizing various engineering materials that have been categorized into four major groups: metals, polymers and elastomers, composites, and ceramics and glasses. Analysis of the vast history of the relative importance of these groups[1] show that the main trend is that metals increased in importance until about 1960 and then declined, but still remain the largest share (see **Figure 1**). The material flow analysis (MFA) of concentrated iron ore illustrates the complex material flow involved in its production (see **Figure 2**).[2]

The MFA of consumer products becomes even more complicated by combining the MFAs of all needed resources. In 2020, humanity’s total material extraction has surpassed 100 Gt per year, as indicated by the Circularity Gap Report (CGR)[4] (see Figure 1). To put this mass into perspective, it is equivalent to building a concrete wall measuring 1000 m high and 1 m thick that encircles planet Earth every year anew (**Figure 3**). Approximately 50 Gt, equivalent to half of the extracted material, is disposed of as waste each year. This waste is equivalent to dismantling half of the concrete wall. The following year’s wall, built adjacent to it, increases in thickness by 2.8 cm compared to the prior year. Based on current extraction rates, projections estimate annual mass extraction between 170 to 184 Gt by 2050.[4] By 2050, the equivalent annual wall will have a diameter of approximately 1.75 m if the current extraction rate persists. The CGR points out that only 7.2% of materials are recycled in 2023 (see **Figure 4**). This percentage is smaller than the percentages for 2018 and 2020.

The processing of raw materials during production involves significant transformations, which hinder the recyclability of complex materials. Modern high-performance materials exhibit fascinating designs across length scales, from the nanoscale (atomic arrangement) to the macroscale (composite materials). However, the increased durability and resilience of these materials make their decomposition more complex, limiting their recyclability and reuse potential.

Living Nature has no such problems, even though biological global net primary production is estimated to be 104.9 Gt of

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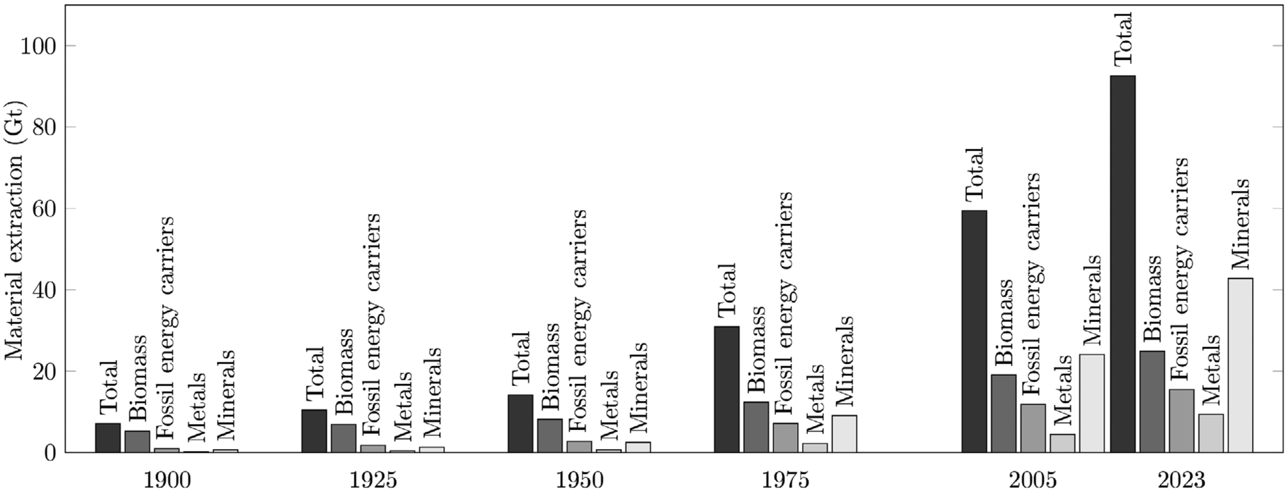

Figure 1. Global primary material extraction quantities from 1900 until 2023 exhibited increased growth. The extraction rates surpassed 100 Gt per year in 2020 and are projected to exceed 170 Gt by 2050.[3,4] The total annual extraction is graphically depicted using black diagram bars, representing the cumulative sum of biomass, fossil energy carriers, metals, and minerals. The rise in primary material extraction has implications for recycling rates, as a significant proportion is directed toward durable goods (see Figure 4).

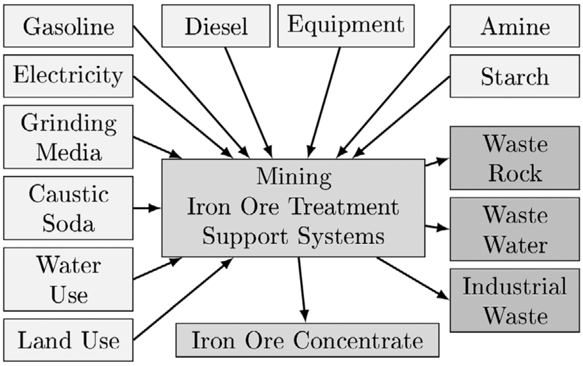

Figure 2. Material flow analysis on iron ore concentrate, excluding production, distribution, and delivery of resources for clarity.[2]

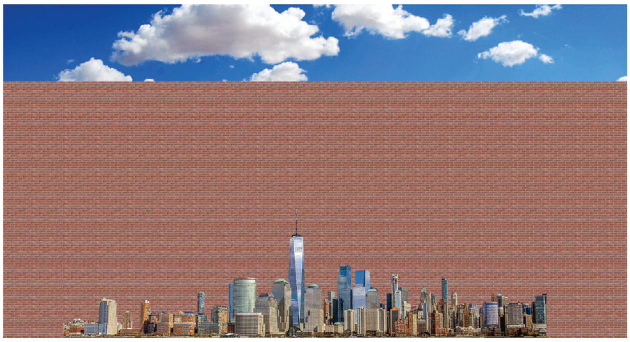

Figure 3. Annual global primary material extraction artistically imagined as a 1 km high wall around the world running through Manhattan. The currently 1 m thick wall increases in thickness by 2.8 cm every year.

carbon per year.[5] Converted to dry mass (approximately multiplying by 2[6]), this amounts to about 210 Gt a^{-1}. For instance, chitin is a basic material that is used widely by insects for various functions[7] with no waste problem at all.

"We try to really understand the principles of biological materials and make use of them. Once you extract those principles it doesn't mean in any way that you simply copy them, which is what people think. We know that evolution works on a 'just good enough principle', not an 'optimizing' or 'perfection' principle. So, you figure out the principles of these materials and then you look on the engineering side. If there is already something that does it better, you don't need to look to Nature. Nature is just another source of design ideas. But in some cases, they are spectacularly good!" (Robert Full in[8], p. 106). The classical Ashby diagram illustrates that biogenic materials have lower strength than composites, ceramics, and metals. Although the low density of biogenic materials can be significant, there are polymers and elastomers with higher strength than biogenic materials of comparable density. "Good enough" implies that the strength of biogenic materials is in the medium range and not maximized; **Figure 5**.

Nature often presents examples of materials that prioritize sufficient performance rather than maximum performance, adopting an engineering perspective of "good enough" and that those materials are fully recyclable ([8], p. 106). The required material performance is also reflected in the working conditions. Skeletal muscles operate at ambient temperatures and have a power output of around 200 W kg^{-1}, whereas aircraft engines operate at temperatures at which all biogenic materials disintegrate and have a power output of around 6000 W kg^{-1}[13], p. 158.

Biomimetics, an established and expanding scientific field, has demonstrated the successful transfer of natural principles to technical applications.[9–11] However, in most cases, the sustainability aspect is not explicitly addressed in biomimetic technology transfer. In contrast, the emerging field of Engineered Living Materials (ELMs) shifts the focus to self-repairing, self-supporting growing materials, and overall sustainability.[12] ELMs enclose a living component during the formation (engineering phase) or utilization of the material and can additionally encompass non-biogenic materials.

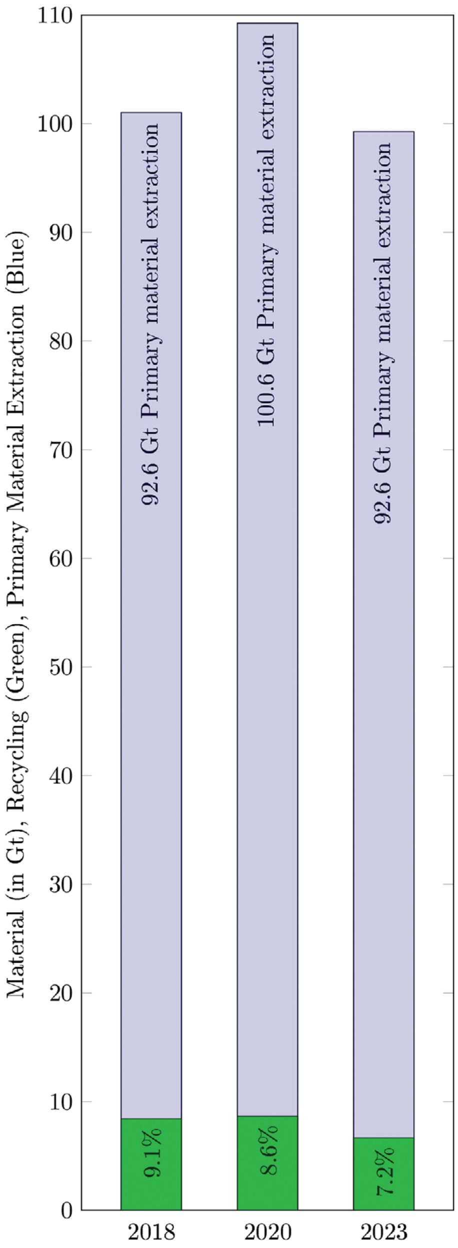

Figure 4. The percentage of recycled materials (secondary production) of the total global material extraction (for evaluating resource circularity). The decline in global circularity from 9.1% to 7.2% in 2023 can be attributed not only to a reduction in the absolute recycling quantity but also to a simultaneous increase in primary material extraction.[4] This decrease in global circularity is additionally attributed to the accumulation of material stocks in durable goods, such as infrastructure and building constructions.

Will science also be able to find solutions for reusing, recycling, and decomposing new high-performance materials after their introduction? To ensure the reuse, recycling, and decomposition of high-performance materials, we need to shift our focus and incorporate these considerations into the design process. Alternatively, a more radical change in perspective could involve embracing Nature's principle of "good enough." Such reflections on bioinspired materials "good enough" versus maximized performance of conventional engineered materials were the driving force to write this perspective paper.

Material utilization directly correlates with the consumption of material resources and energy. However, the generation of waste resulting from material utilization is often overlooked. For instance, the production of one cubic meter of concrete requires 2.8 MJ of energy, primarily derived from burning approximately 0.37 barrels of oil.[14] By reevaluating our industrial approach to material design, considering recycling and decomposition from the onset, we can address the environmental challenges associated with material utilization and promote sustainable resource management.

2. Standard Approach

In the following, the standard engineering approach is confronted with a potential new way of thinking about material utilization to tackle global challenges. Modern high-performance materials have various specific properties that make them superior to biogenic living materials, such as their high strength-to-weight ratio (see Figure 5). In engineering and construction, lightweight constructions can significantly improve efficiency and performance. Modern materials can be designed to be highly resistant to wear and corrosion, with low thermal expansion and degradation coefficients, making them ideal for use in harsh environments and high-stress applications. This historical transition is clearly visible in the classical Ashby diagram illustrating the relative importance of ceramics, glasses, polymers, and elastomers. In contrast, the importance of metals in their primary or alloy form decreases [[1], p. 1]. This observation aligns with the increased primary extraction quantities of minerals and metals compared to biomass as illustrated in Figure 1.

Biogenic materials, such as bones, represent another strategy for durability. They can self-repair and continuously replace organic and inorganic material components. However, they are generally weaker (see Figure 5) and less durable than man-made high-performance materials, rendering them, in principle, less suitable for high-performance applications (in their nonliving state). This is due—in general—to the fact that biological materials and structures are not optimised toward a single objective and often serve various functions; for example, wood provides mechanical stability but is also important for water transport.

Humanity has been using biogenic materials such as wood since our ancestors started using tools. The first use of biogenic tools is difficult to date, but it is safe to assume that it started concurrently with the use of first stone tools at least 3.3 million years ago.[15]

Recycling is generally understood as a separate step after material disposal, partly for historical reasons and partly because complex structured materials are tough to recycle. Historically, waste (largely consisting of biogenic materials) was just disposed of out of sight and smell. Only in the last centuries when substances contained in waste started to cause problems, the waste problem awareness arose (Figure 4). In Nature, recyclability is an integrative feature of the material. Organisms degrade and become nourishment for a multitude of organisms. The disposal of natural materials is unnecessary because they will be decomposed in place, and their basic components will be recycled by other organisms. Exceptions are ocean sediments, coal, or oil. These are

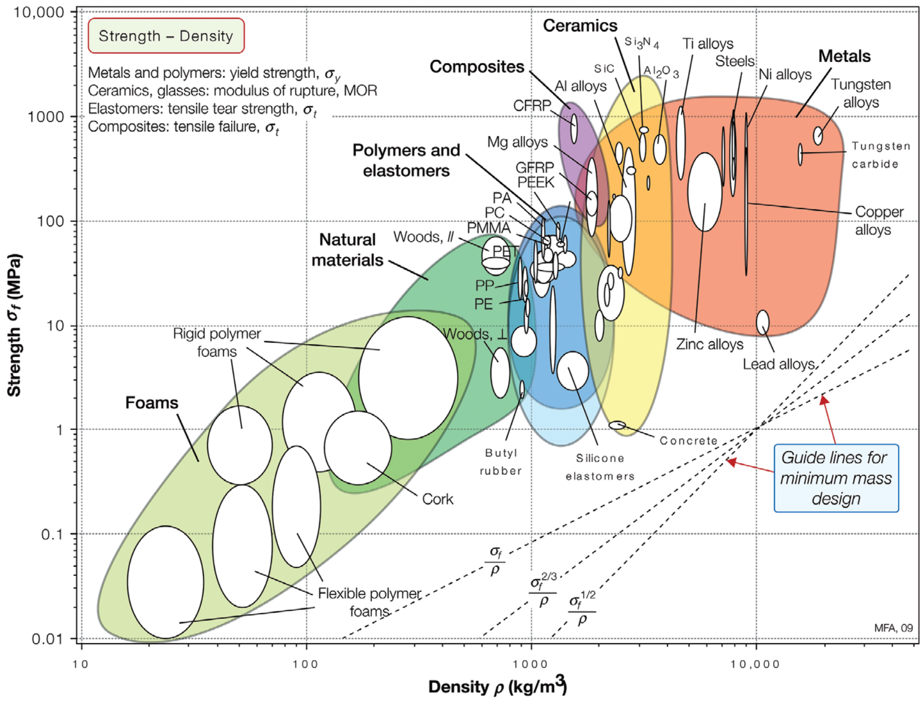

Figure 5. Strength plotted against density (permission requested).[1] This classical Ashby diagram illustrates that biogenic materials have lower strength than composites, ceramics and metals. Although the low density of biogenic materials can be significant, there are polymers and elastomers with higher strength than biogenic materials of comparable density. "Good enough" implies two directions through Ashby's diagram: first, how far down can the quested materials be, and how can science push biogenic composites (for example in ELMs) further up. Reproduced with permission.[1] 2011, Elsevier.

deposited and stored. In the context of the carbon cycle,[16] they are captured in sediments.

In contrast, for example, the composites used for modern windmill rotor blades must withstand extreme conditions without failure up to their end of life. Currently, wind parks are built worldwide at a never seen speed. Recycling these windmills at the end of their economic usefulness is not the focus of decision-makers. Science has still to develop ways for recycling such complex composite materials.

The composition of high-tech materials is well understood, this makes them calculable for constructing structures. In Nature, heterogeneous materials prevail that change their properties according to external necessities and stimuli that are so complex that they are hard to calculate with simple models (e.g., in bone; structural material is assembled at locations with high mechanical stresses and removed where the stresses are low). Materials adaptively grow in functional shapes so that they are uptaking and exerting forces during "construction." Adaptive growth results in nonhomogeneous hierarchical structures, such as bone or a tree trunk. Growth also needs continuous material transport, and Nature uses a wet environment for material transport, whereas high-tech materials are created mostly in dry environments.

As adaptive growth continues during the lifetime of the organism, the construction of functionalities such as rotational movement in parts of an organism (wheels or rotors) is challenging because it implies disconnecting two parts of the growing structure. However, Nature does not need such rotational movement, but uses contact, sliding, bending, pushing, and pulling instead. These constructions allow for gradually adapting the strength during growth.[13]

Growth is a slow process that happens locally. Modern technological approaches allow fast assembly of single components that are often produced in a distributed fashion. In some cases, Nature also shows distributed techniques mostly in organisms such as colony-forming cnidarians (corals).

Future efficiency in digital industrial applications requires materials that are no longer merely passive components of active devices but become operational as information carriers and processors. Biogenic materials intrinsically include these functional aspects over numerous length scales [[8], p. 72]. These future materials will need a new programming paradigm to cope with the complexity of controlling multiple massively parallel information processing levels.

3. New Approach

The first successes of ELM utilizations are based on mycelium, algae, bacteria, bacteria byproducts, or mold fungi.[17–19] Their material properties are still far from reaching the properties (especially regarding stiffness, toughness, and strength) that organic-based living materials can achieve (see Figure 5).

From the biologists' direction comes another aspect of ELMs science: the growth principles of organisms. By controlling an organism's growth, the mature organism's shape potentially can be altered by the designer. Historic example implementations of this technique are the tree bridges in India and Indonesia (see

Figure 6. a) Living root bridge (July 2015, Kanekes, Java, Indonesia). b) Growing furniture pieces by arborsculptors Alice and Gavin Munro.[20]

Figure 6a) and the growing furniture of Alice and Gavin Munro (see Figure 6b).[20]

Non-renewable resources, such as minerals and fossil fuels, will eventually deplete.[21] On the other hand, renewable resources, such as forests and fertile soil, can be sustained if they are managed responsibly and sustainably. Recycling can help extend the availability of resources, reduce the demand for new materials, and minimize the environmental impact of resource extraction, transport, and processing. However, it is crucial to understand that recycling alone is not enough to ensure resource availability and that a comprehensive approach by developing sustainable alternatives to non-renewable resources is necessary.[22,23]

ELMs are a rapidly evolving and interdisciplinary research area combining biology, engineering, and materials science. Researchers are exploring new ways to produce materials (such as bioplastics, biofuels, and other sustainable materials) using renewable resources (bio-based materials), such as plants and bacteria. Synthetic biology can be utilized to design ELMs bottom-up, by engineering new materials based on artificial cells (lipid vesicles enriched with functional proteins) to trigger metabolism to be part of or produce a material. In general, various techniques from the field of biologization of technology can be used to build ELMs[24]

Despite efforts at recycling, the current recycling rate is only 7.2%.[4] This failing effort indicates that a more profound and radical change is necessary to address our long-term challenges. We need to delve much deeper into mimicking Nature and its inherent processes to achieve this. The growth of multifunctional hierarchical materials derived from local resources holds immense potential in addressing various pressing issues such as climate change, waste management, and the transportation logistics crisis. By unraveling the intricacies of living growth through scientific research, we can harness this knowledge to pave the way for a sustainable future.

The increasing costs of high-tech materials have provoked a resurgence of interest in biogenic materials. Historically, the production of engineered materials was more cost-effective than the growing biogenic counterparts. However, the current trend has reversed, making biogenic materials a more economical choice.[25]

4. Evidence and Examples

In the following, selected evidence and examples for technical and biogenic materials are provided, comprising the topics of: material resources and recycling; information processing; the special case of metals; modes of fabrication, growth; functional structures; avoidance, repair, and death as well as the material selection process.

4.1. Material Resources and Recycling

In materials science, current research predominantly focuses on studying the properties of monolithic materials. Technical materials mainly consist of highly structured and processed raw materials that are sourced from various locations worldwide. This practice contributes to a cumulative carbon footprint associated with material production and transportation and creates a dependency on supply chains for delivery. Furthermore, the complex assembly of these composites poses challenges for effective recycling, as separating the different components due to their sheer variety becomes impractical. Numerous initiatives have emerged to address waste reduction and promote recycling processes, ranging from economically focused initiatives such as the “circular economy initiative”[8] to environmentally oriented approaches like “One Health.”[26] In contrast, Nature operates within the constraint of short ways for transportation and hence utilizing ubiquitously available resources (e.g., CO_2, H_2O) and locally available resources (e.g., Ca, Si) for producing constructions.[27] However, the restriction to local resources does not impede the potential volumetric or mass characteristics of organisms. The General Sherman Tree is a giant sequoia in California that provides a striking illustration, acknowledged as the largest documented living organism on the planet, with an approximate volume of 1500 m^3.[28]

Nature’s evolutionary history is characterized by an ongoing struggle between “inventions” and “counter-inventions.” Evolution favors herbivores that overcome the plant resistance against feeding, thus provoking plants to evolve ever-new resilience. This arms race between plants and herbivores (coevolution) has resulted in a wide array of resistance traits in terrestrial plants,[29–32] such as the production of biomineralized particles,[33] which thoroughly changes the material properties of the plant material. In this way, biogenic materials iteratively adapt to increasingly challenging conditions while using solely local and ubiquitous resources without recycling issues. This cycle continues again and again and demonstrates continuous innovation in Nature, such as more recent discoveries related to microbial polymer (plastics) degradation.[34]

An example of coevolution is the relationship between grasses and the dental composition of herbivores: Open woodlands and grasslands became abundant during the Tertiary Period. Grasses are particularly abrasive, compared to the ancestral diet of woodland plants, because of their high levels of endogenous silica bodies and the dust or grit on the surface of grass leaves. During the same period, herbivores evolved teeth that could endure high levels of wear, assumed to be adaptations for eating grasses.[35]

Thermal recycling, which uses waste as fuel, is comparable to a "natural" approach to recycling materials by decomposing them into their essential components. However, the presence of problematic additives in the material complicates the process significantly.

4.2. Information Processing

During their lifetime, living organisms exhibit a distributed system of information processing across multiple hierarchical levels. Accordingly, hierarchically structured materials can adapt autonomously and respond independently without direct communication with a central information processing entity. Swift reactions, such as spinal reflexes, bypass the brain entirely. The degree of distribution varies among different organisms, with some displaying a more pronounced distribution than others. For instance, the octopus possesses multiple sub-brains that work in harmony but independently.[36] On a material level, information processing can be more disguised. An example of this is a slime mold: It can explore and solve mazes by directed growth and processing sensory impulses.[37,38] This organism uses information processing during growth and operation. Also in the course of evolution, adaptation is often a process of changing information, for instance with respect to the hierarchical arrangement of components in structural biomaterials. Technical developments in contrast have made little use of information changes in problem solving [[39], p. 194].

Future digital industrial applications enforce materials that are operational as carriers of information. Such smart materials decrease the processing needed by central information systems. Biogenic materials, from molecules to tissues, organs, and whole organisms, store information and can operate autonomously to a certain degree. The many levels of control needed in such biogenic materials and systems are future challenges in hierarchically organized engineered materials [[8], p. 160].

4.3. Special Case: Metals

Metals present a unique scenario, as living organisms do not exploit the ductility and conductivity properties of metals. When subjected to stress, metals, being ductile by nature, undergo plastic deformation that blunts the tips of cracks. Consequently, critical crack lengths of metals are typically ten thousand to a million times longer than those of stiff nonmetals like glass.[40] The remarkable electrical conductivity of metals enables significantly faster conduction compared to biological materials. For instance, nerve impulses typically propagate at speeds around 120 m s^{-1}, whereas electrical wires transmit impulses approximately 5 million times faster.[13] The field of computing, especially concerning electrical circuits, relies on the extremely fast transmission of electrical pulses through metals and semiconductors. Nature tackles this challenge by employing massively parallel computing (such as in the brain), whereas our linear thinking hampers our ability to comprehend this extensive parallel processing. Current research in artificial intelligence is beginning to adopt this massively parallel computing approach, although a comprehensive understanding of the problems being solved remains elusive. Biological neural networks have the potential to bring biology also in the computation field[41]

4.4. Modes of Fabrication, Growth

In Nature, organisms follow an on-site construction method, whereby their constituent parts are assembled directly at or in the organism. In contrast, humanity practices typically distributed built systems, involving the separate manufacturing of components, often in disparate locations, followed by the subsequent assembly in later stages. For instance, in Nature, the growth and utilization of a thigh bone or a tree trunk occur continuously on-site. Specific components in Nature, such as certain plant leaves and butterfly wings, also undergo a prefabrication process, but notably grow on-site and unfold upon completion. Imagine the possibility of growing a modern bridge capable of progressively adapting to heavier loads. In such a scenario, the time scale for construction becomes relevant (growing takes time). The utilization of high-performance materials may allow loosely coordinated sub-tasks during production, with growth being a single integrated process that operates on a massively parallel scale. Gaining a deeper understanding of growth principles and the structural control exhibited by plants could aid in discovering novel strategies for constructing functional materials. The foundation for localized and sustainable production of various goods could be established by combining the in-function growth observed in plants with component-based production methods.

Biogenic materials typically exhibit limited long-term stability in their processed state after they cease to be alive. Proteins, basic components of any living system, are not known for their inherent stability, and their susceptibility to degradation or rotting is increased at higher temperatures. This process makes conservation measures or continuous maintenance necessary to mitigate the degradation effect, exhibiting specific modes of fabrication. The replacement rate or half-life, which refers to the time it takes to replace half of a specific type of material, provides valuable insights into an organism's resilience.[13] For example, the average half-life of tendon proteins ranges from 2 months to 200 years,[42] while the half-life of mouse liver gap-junction proteins is approximately 5 h.[43] This half-life characteristic underscores the importance of maintaining biogenic materials in a living state where continuous material replacement stays active if they are to be used in engineering.

4.5. Functional Structures

Biological materials commonly exhibit heterogeneity, and the same material (at times slightly chemically altered) can serve various functions dependent on structure. One widely used material is chitin,[44] which provides mechanical stability in insect exoskeletons, shrimp shells, arthropods, and certain fungi, whereas in butterfly wing scales it yields structural colors, hydrophobicity, and directed water run-off. The formation of significant functional structures in living organisms does not occur through bulk manufacturing but instead relies on the assembly of minuscule components. Research in bioinspired materials has already shown various possibilities to transfer Nature's solutions to technological solutions by following the ten basic principles from Nachtigall:[45] integrated instead of additive construction, optimization of the whole instead of maximization of a single element, multifunctionality instead of monofunctionality, fine-tuning toward the specific environment, energy saving instead of energy wasting, direct and indirect use of solar energy, time limitation instead of unnecessary durability, total recycling instead of waste accumulation, utilization of networks instead of linearity, and development via trial-and-error processes. These ten principles largely focus on the functional aspect of the material. Material science that follows the proposed new approach centers around the material sustainability aspects.

4.6. Avoidance, Repair, and Death

In Nature, a governing principle revolves around avoiding and repairing injuries. Trees are an example for the avoidance of injuries by adaptive growth yielding uniform stress distribution on the surface. When these preventative measures fail, the disposal and reuse of damaged parts are initiated. Death is an inherent part of the living process. Therefore, when incorporating living components into materials, it is essential to consider the fate of these living components once they die. The dead debris from living components will influence the material properties. Material management in Nature follows a cyclic process wherein a recycled molecule transitions through different organisms. Drawing from Chelsea Heveran's presentation titled "From Bones to Stones" at the MRS Spring Meeting 2023,[46] envisioning a scenario where the walls of one's home rebuild themselves by replacing one stone each day is indeed fascinating. Over the course of several years, the walls would be completely reconstructed. Several engineered self-healing materials have been developed in the field of material science.[47] However, these materials often lack the vital aspects of living systems. Most self-healing solutions incorporate a finite source of repairing material that cannot be replenished after the first rupture, such as concrete infused with encapsulated bacteria capable of healing cracks.[48] This limitation restricts their ability to sustainably repair and regenerate themselves over time.

However, there is a growing recognition that hierarchical decomposable materials (HDMs), which emulate the structure of natural materials, deserve more attention (Plenary Session of Kostya Novoselov at the 2023 MRS Spring Meeting[49]). Hierarchical materials are materials with different structural organizations across multiple length scales. HDMs are materials that can be broken down or decomposed into simpler components through natural or artificial processes.[50] These hierarchical materials call for reevaluating the material selection process and the associated requirements.

4.7. Material Selection Process

Traditional material selection utilities, such as Ashby diagrams[1] where technical materials often reside in the top right region (Figure 5), do not adequately represent the multidimensional properties of biogenic materials.[13] James E. Gordon has pointed out the disparity between human-built structures that emphasize adequate stiffness and natural structures that prioritize adequate strength.[51] For instance, consumer goods casings solely serving the purpose of encapsulating an object are not deemed useful in Nature. Although living organisms are constrained in their material "choices," skin, bark, or exoskeletons evolved with additional integral functions. By localizing the adaptation of material in various hierarchical layers, extreme property values can be circumvented, bringing the required properties closer to the range of natural materials, for example, the integration of printed circuit boards and batteries directly into the casing without extra compartmentalization. The effect is similar in a plant stem where the distinction between material and structure is not possible.[8] Furthermore, the flexibility and bending behavior of compliant structures hold greater significance in Nature compared to our classical designs, where it is often considered a nuisance. By exploring and integrating these principles from Nature, material scientists can potentially develop innovative approaches that enhance the performance and functionality of engineered materials.

5. Advantages of Technical Materials That Are not Identified in Nature

Technical manufactured materials have advantages (some examples listed below) over biogenic materials that should be addressed. Many technical advantages would only be possible with these technical materials. These technical advantages highlight the need for a sustainable and integrated approach between technical materials and biogenic materials.

Manufactured materials can be engineered to have exceptional durability and longevity. They can withstand harsh environmental conditions, wear, and degradation over extended periods. A photovoltaic cell can be used for years. In contrast, leaves are renewed constantly and their components (e.g., proteins) have an even higher turnover rate. They can be engineered with precise control and customized properties according to specific requirements. Manufactured materials can be manufactured with high consistency and reproducibility, ensuring uniformity and reliability in their performance. They can be seamlessly integrated with various technologies, such as electronics, sensors, and actuators. Due to their homogeneous structure, manufactured monolithic materials are generally more susceptible to decomposition than composite or heterogeneous materials. This characteristic can be advantageous for recycling, as manufactured monolithic materials are often more easily processed and recycled. In contrast to biological systems that are degraded to monomers before being reused by further organisms, technology allows for constructions where sub-units (consisting of various material parts) can be used in a further product if designed accordingly. High-performance materials may lead to hazardous waste problems, and it seems obvious to check for analogies in Nature. Very often the biogenic materials (e.g., fiber composites) are harmless, but other materials are not, for example, mussel adhesives rely on toxic catechols that may not comply with regulations [[52], p. 254].

Industrial processes allow for the production of materials on a large scale, enabling mass adoption and widespread availability. They are optimized for performance at the time of the next production step. The modular nature of component-based construction allows for the assembly and integration of standardized components, simplifying the design and construction process.

Engineers can easily change the material composition from one product generation to the next, for example, from wood to metal, but organisms cannot. Acantharea, single-celled organisms with a skeleton made of strontium sulfate cannot easily substitute this material by other materials, even though these might be more easily available or have a better performance.

6. Implications for Future Research

To effectively transition toward a sustainable future on a global scale, it is crucial to allocate substantial resources, including time, energy, power, and financial investments, toward scientific research focused on comprehending the mechanisms by which life sustains itself, even in the face of persistent challenges, utilizing solely local resources.

Nature has already provided us with numerous ingenious solutions, not only on the materials themselves but also on how materials are produced (including self-organization and self-assembly and biomineralization). With the increasing pursuit of biomimetics and the ongoing development of the emerging field of ELMs, more and more creative solutions of Nature are discovered and realized. However, to effectively address the major global challenges, it is imperative to understand how life utilizes solely local resources and adheres to the principle of “good enough.” How can we design products and produce and utilize materials so that the problems resulting from today’s engineering can be remedied?

Hence, materials research is required to reassess its approach. Incorporating (realistic) locality, recycling, and waste management considerations into its investigations is of paramount importance. It is recommended that research groups who develop new materials integrate reuse, recycling, and waste management into their endeavors. At the same time, advantages in engineering that are not identified in Nature (such as the reuse of product sub-units) have to complement the efforts.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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