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Challenges and opportunities for innovation in bioinformed sustainable materials

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Nature provides a rich source of information for the design of novel materials; yet there remain significant challenges in the design and manufacture of materials that replicate the form, function, and sustainability of biological solutions. Here, we identify key challenges and promising approaches to the development of materials informed by biology. These challenges fall into two main areas; the first relates to harnessing biological information for materials innovation, including key differences between biological and synthetic materials, and the relationship between structure and function. We propose an approach to materials innovation that capitalizes on biodiversity, together with high-throughput characterization of biological material architectures and properties, linked to environmental and ecological context. The second area relates to the design and manufacture of bioinformed materials, including the physical scale of material architectures and manufacturing scale up. We suggest ways to address these challenges and promising prospects for a bioinformed approach to materials innovation.

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Life thrives in every environment on Earth, from the harshest deserts to the crushing pressure of the ocean's depths. Within the constraints of the material building blocks of life, hundreds of millions of years of evolution by natural selection have produced an extraordinary diversity of functional solutions. It is, therefore, no surprise that biology offers solutions to many of the problems we face today. The need to find sustainable solutions to existentially significant challenges, such as climate change, the energy crisis, plastic pollution, biodiversity declines, antimicrobial resistance, and food insecurity, has fueled rapid growth in biomimetic and bioinspired materials and technologies. These span many fields[1], such as advanced manufacturing[2,3]; photonics and electronics[4–6]; robotics[7], and biomedical and energy applications[8,9]. But despite this progress, we have yet to discover, fully understand and take advantage of nature's material design principles[10], and we are still far from achieving precision nanomanufacturing of even the simplest organisms, such as diatoms[11]. Current frontiers in materials innovation are concerned with many of the properties that are inherent to biological materials, such as sustainability, self-assembly, multifunctionality, responsiveness, self-repair, and replication[12]. Drawing from nature's designs has therefore become more than a trend - it is arguably an imperative.

There is now a large and growing literature on the principles and practice of bioinspired design[13–18], and numerous reviews of recent advances in types of bioinspired materials, e.g.,[2,7,12,19–27]. Here our goal is not to duplicate these efforts, but to identify key challenges to the effective design and development of bioinformed materials more generally, and ways to address those challenges. We begin by briefly outlining the overarching goal of bioinformed materials design in the context of sustainability. We then identify current challenges and promising approaches in three key areas: 1) accessing and harnessing biological information; 2) multifunctionality; and 3) designing and manufacturing bioinformed materials. We outline guiding principles for practitioners in the field, including researchers, designers, engineers and industry professionals, highlighting key examples to illustrate these principles.

From bioinspired to bioinformed. The natural functions and properties of biological materials can inform and even reimagine synthetic materials[23,28]. However, the perceived value of biomimetic and bioinspired approaches is often undermined by the prevalence of superficial biological analogy[29]. Previous studies have emphasized the importance of defining and differentiating between biomimetic and bioinspired approaches[30]. The terms distinguish respectively "between attempting to replicate a biological property or function versus applying a principle or process that underpins a biological system"[15]. In practice, there is a continuum in the degree of similarity to biological form or function; both approaches require us to understand and distil essential properties of complex biological systems. We argue that first and foremost, these approaches must be bioinformed. The term bioinformed describes a design approach that is informed by detailed and accurate information on biological systems or processes and makes a clear distinction from approaches that are based on superficial, figurative or one-dimensional analogy[15]. A bioinformed design approach considers multiple properties and functions of biological materials, which are also desirable in synthetic materials, to create a product that meets multiple design criteria. An approach that considers multiple properties and functions of biological materials, systems or processes has been repeatedly advocated in the literature on biomimetic and bioinspired design[31–34], but has not been conceptually differentiated. We therefore adopt the term bioinformed to make clear this conceptual distinction and argue for the utility of such an approach to materials innovation.

Sustainable materials for a circular economy. Sustainability is a growing imperative for future materials, and an area with significant potential to draw on biological solutions. However, sustainability is a broad concept that has different meanings from human and ecological perspectives. From a human perspective, sustainability, or more specifically sustainable development, has been defined by the United Nations Brundtland Commission as "meeting the needs of the present without compromising the ability of future generations to meet their own needs"[35], and is operationalized in the United Nations' 17 Sustainability Goals[36]. From an ecological perspective, sustainability describes the ability of biological systems to remain healthy, diverse, and productive over time. Thus, sustainability is a concept that applies to higher levels of biological organization, such as ecosystems, rather than to individual species.

In ecosystems, species perform different functional roles; for example, primary producers such as plants use solar energy to synthesize organic compounds, which are then consumed by herbivores; and detritivores consume and breakdown waste material from consumers, which then provides nutrients for primary producers. In a similar way, the sustainability of materials should ideally encompass the entire cycle of an engineered material in a systems context (Fig. 1). This is a core requirement of a circular economy[37], defined by the World Economic Forum as "an industrial system that is restorative or regenerative by intention and design"[38]. Under a circular economy model, materials and products are designed for durability, reuse, remanufacturing, and recycling in contrast to the current linear take-make-consume-discard industrial system. There are clear analogies between ecosystems and a sustainable, circular economy industrial system, with substantial scope for bioinformed enhancement of materials at different stages of the materials life cycle, from raw materials to manufacture and end-of-life management (Fig. 1). For example, there are extensive efforts to develop sustainable and biodegradable biopolymers to replace petrochemical polymers and to design for disassembly through the use of enzymes[39,40]. Embedding a holistic, entire lifecycle view into materials design represents one of the greatest challenges for the future of bioinformed materials, beyond the commercial requirements that such materials are economical at the required scale and lend themselves to mass manufacturing.

Accessing biological information. At first glance, design practitioners have access to a vast biological literature that seems to provide unlimited possibilities to draw from. In practice, however, translating these biological concepts to other disciplines is challenging[17,41]. Practitioners are often overwhelmed when confronting the knowledge gap required to understand a different field and translate it into their disciplinary context[15,42]. This has spurred the development of databases, such as Ask Nature[43] and calls to expand such databases to generate a Biological Information System[44]. While these databases are undoubtedly valuable, they can help to perpetuate the use of limited model biological systems and an overly simplistic understanding of structure-function relationships. They often ignore the myriad variations on a theme that enable organisms to adapt to diverse and specific biotic and abiotic environments, and the multiple competing functions that these adaptations accommodate[45]. For example,

Fig. 1 Materials and surfaces in nature are adaptive, biodegradable, multifunctional, self-assembling, self-cleaning, and self-repairing. The five images within the bioinformed cycle show examples of materials/surfaces exhibiting these features (self-repairing not shown) and describe bioinspired materials and technologies with these properties. Bioinformed materials should ideally exist within a circular bioinformed material lifecycle to achieve sustainability. Such materials can be designed and manufactured to be biodegradable using recycled materials, they can then be distributed using methods which reduce environmental waste, and finally at the end of life, materials can be recycled or reused. All images from unsplash.com.

the tokay gecko (*Gecko gecko*) completely dominates the literature as a model for gecko-like adhesives[15], yet this unusually large species is only one of over 1000 species of gecko, each of which provides a unique evolutionary solution to surface attachment in the context of their own environmental niche[46]. Use of this single-species model therefore restricts our ability to develop bioinformed adhesive materials across a broad range of applications and contexts.

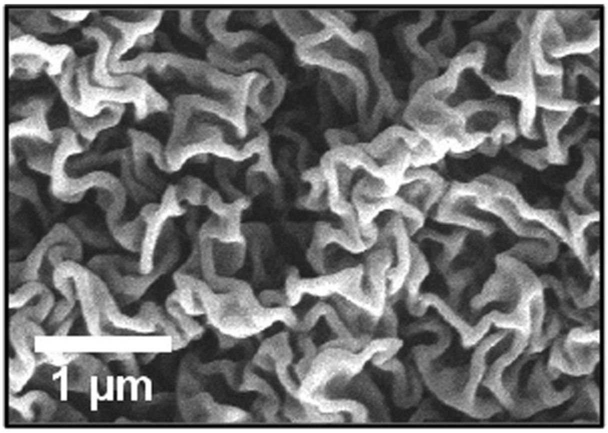
An alternative source of biological information is publicly available curated databases that aim to systematically document aspects of biological diversity. For example, Yan et al.[47] reported the construction of a large nanomaterial database containing annotated nanostructures for 705 unique nanomaterials covering 11 material types (http://www.pubvinas.com/). Such databases provide important insight into the evolutionary diversity of a desired material; for instance, Arakawa et al.[48] provide a silkomics database documenting the genetic diversity of spider silks in over 1000 species. In addition, natural history collections have become increasingly digitized and provide a rich source of information on georeferenced biological specimens. These collections implicitly contain environmental information through georeferencing. To connect structures to the environment in which they occur, structural, material, or trait information, could be integrated into georeferenced natural history collections. This is already occurring in an ad-hoc fashion (e.g. publicly available computed tomography (CT) and micro-CT scans linked to specimens)[49,50], and there are growing efforts towards many forms of high-throughput trait characterization[51–53]. We envisage that such efforts could be systematically extended to include imaging at different length scales, and other forms of material characterization. Equally, existing information, which is often stored haphazardly, needs to be collated and curated within centralized, publicly accessible repositories.

Leveraging biological diversity. While curated, annotated and georeferenced databases can improve access to accurate biological information and link it to specific environments, we must also consider how this information is integrated into the design process. Conventional bioinspired materials design focuses on a particular biological example or material property as the basis for narrow optimization of a specific property or function. We emphasize that this conventional approach should be broadened to more effectively leverage biodiversity[54]. This could be approached in several ways. First, properties or functions of biological materials could be investigated across multiple organisms to reveal how these characteristics vary in different environments (Box 1) and to identify fundamental design principles shared by many organisms. Comparison of closely related species with shared evolutionary, developmental, and material constraints can reveal the specific modifications required to achieve different functional solutions in different environments[55]. For example, major ampullate (MA) silks from Argiope spiders, commonly found in tropical grasslands, appear to be more resistant to temperature and humidity stress than those spun by *Leucauge* species from tropical forests[56]. Conversely, comparison of distantly related species can reveal general underlying principles or convergent solutions to a problem. For example, the eggs of the leaf insect (*Phyllium philippinicum*) and the seeds of the ivy gourd (*Coccinia grandis*) have different adhesive structures, but these share certain design features[57]. The presence of adhesive fibrillar structures in both these models suggests that fiber reinforcement is an effective solution to surface attachment across different biological and ecological contexts[58].

Second, properties or functions in different taxa can be combined to produce hybrid multifunctional materials; for example, the development of spider silk and bacterial cellulose hybrid 'smart' switches and pores for multiple applications. Third, different biological models or sources of biological information can inform multiple stages of the material life cycle. For instance, the design of self-cleaning materials can be informed by hydrophobic surfaces found in nature, whilst the packaging of such products can be informed by other solutions featuring high degrees of biodegradability. This diversity-driven approach is more challenging than the conventional approach but will be necessary to design bioinformed materials for a circular economy.

Box 1 | Diversity and multifunctionality – drag and fouling resistant coatings

The strong market need to develop low-cost, sustainable, scalable methods to fabricate drag and fouling resistant coatings[98,99] has driven the investigation of antifouling strategies inspired from diverse biological sources[100]. For example, natural antifoulants have been isolated from various marine invertebrates such as soft corals, mussels, and sponges[101,102]. In addition, recent developments in nanocomposite coatings also appear promising as they are relatively cheap to produce, environmentally friendly, and easy to apply to irregular surfaces[100,103,104]. Rapidly increasing developments in nanotechnology may also reduce perceived risk of initial investment by the marine coating industry. Additionally, there is now consensus that an ideal solution to drag and fouling resistance requires multifunctional coatings, which incorporate multiple synergistic solutions to target various antifouling organisms at different scales[99,105]. Indeed, marine organisms usually employ multiple mechanisms to achieve an antifouling effect[100,106], therefore synergy between different strategies is likely required to achieve a broad-spectrum (targeting various marine organisms) and long-term (durable and self-cleaning) solution to the problem. Whilst the scaling of these materials to large-scale production remains a current challenge, the clear demand for such a solution in the market continues to rapidly drive research in this field, which is increasingly harnessing biological solutions and drawing on biological diversity.



Box 1 Figure: Bio-inspired fine structure such as these polymer wrinkles has been used to induce slippery materials that are able to reduce marine fouling and hydrodynamic drag on surfaces immersed in water[107,108]. The fine structure can be used to either trap microscale pockets of air or of an oil to induce this anti-adhesive effect. Image by Chris Vega-Sanchez and Chiara Neto.

Multifunctionality. Understanding the structure-function relationship in biology is essential to bioinformed design and one of the most significant challenges faced by biologists and materials scientists alike. Multifunctionality is a hallmark of biological materials, which commonly achieve diverse functional solutions through variation in structure rather than through variation in material composition[22,24]. To achieve a diversity of functions, biological structures are often highly complex, composite or modular, and hierarchical (i.e., with different properties at different length scales; Fig. 2)[24]. Additionally, there is rarely a one-to-one correspondence between structure and function in biology. One domain of a hierarchical structure can serve many functions, and organisms have evolved a remarkable diversity of solutions to similar functional problems (Fig. 3). For example, each of the close to 100,000 species of marine diatoms has developed its own unique hierarchically nanostructured silica shell as an elegant solution to solve its mechanical, molecular transport and optical problems[59,60]. This is achieved under physiologically compatible and environmentally benign conditions using minimal energy and producing minimal waste. Even in well studied taxa like birds, each of the approximately 10,000 species has its own unique combination of feather coloration and detailed feather arrangement to meet the organism's aerodynamic, thermal, sensory and communication needs[61]. As with diatoms, this reflects the need for organisms to simultaneously optimize multiple functional requirements, together with specific combinations of ecological and evolutionary processes that generate diversity in biological systems. Importantly, the observed variation within a taxonomic group (e.g., diatoms) is limited by evolutionary and developmental constraints, and these design constraints are very different from those for synthetic materials. Yet efforts to characterize biological materials often focus on single characteristics (e.g., optical, thermal, or mechanical properties), in single species, with little knowledge of such constraints or adaptive value within their environment.

An additional complication is that structure-function relationships in biology may not always be obvious even when analyzed at the nanoscale, especially as the function of a material is often the result of many structural and chemical characteristics contributing synergistically at multiple length scales[62,63]. For example, the photonic nanostructures that produce vivid blue coloration in *Morpho* butterflies have inspired >50 articles on bioinspired materials[15] and the optical properties of biophotonic crystals based on the Gyroid structure of some green butterflies is well understood (Fig. 2); yet we have limited experimental data on their biological function. Similarly, a twisted-ply (Bouligand) structure observed in insect cuticles has been found to improve the fracture toughness but its superiority compared with a simpler cross-ply structure – and hence its adaptive value – remains debatable[64]. In part, this is because structural characterizations are commonly based on specimens from museums, or purchased on the internet, with limited understanding of how these structures are used or their adaptive value in their natural environments. Determining function through behavioral and ecological investigation is often possible, but such investigations are invariably longer in duration than determining material structure. False assumptions about the biology of the model and discrepancy between biological function and the desired properties of the synthetic materials have been

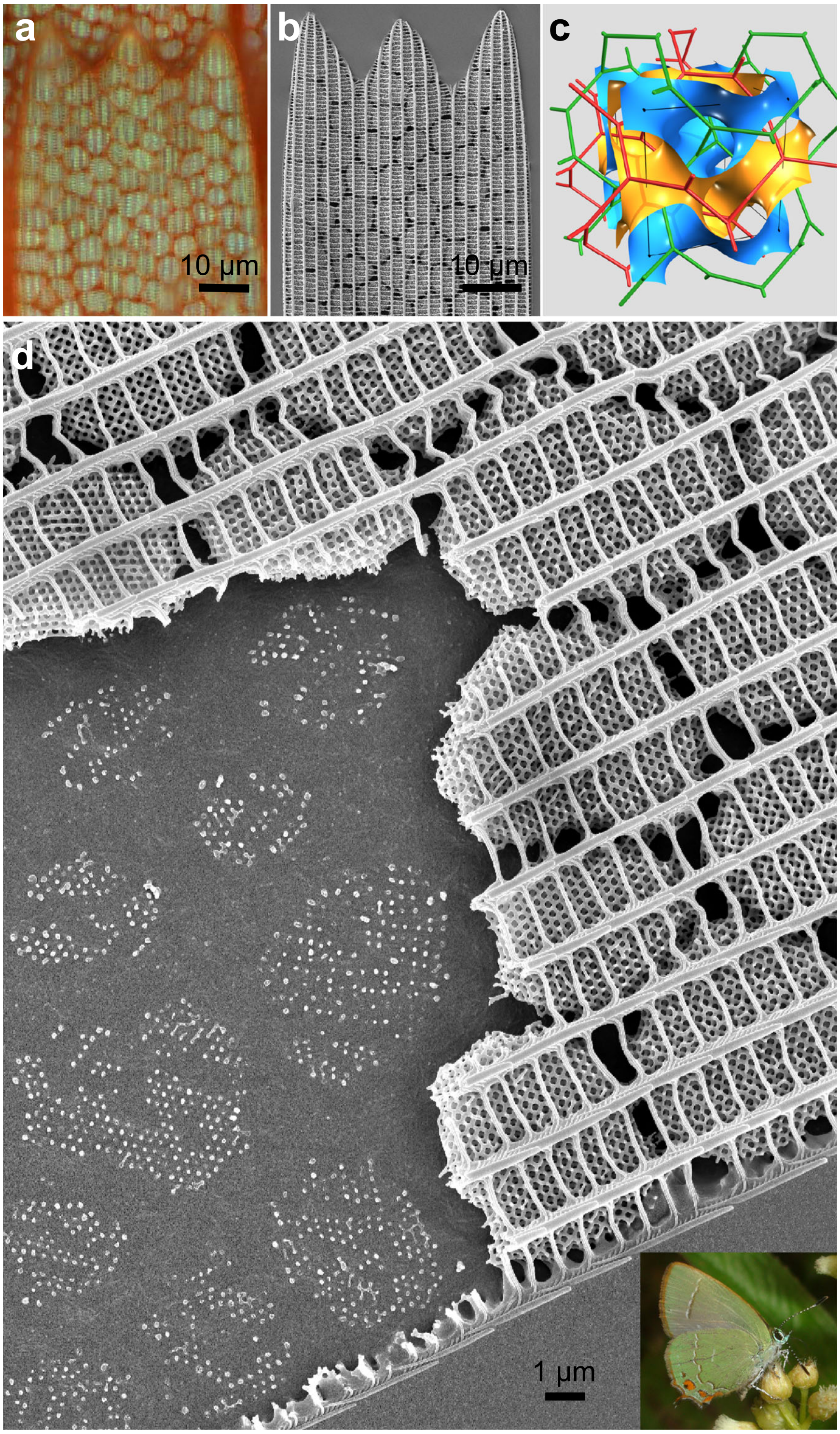


Fig. 2 Structures producing green coloration in some butterflies - an example of complex, modular, and hierarchical biological structures. a High magnification image of a green wing scale from the butterfly *Thecla opisena* (image by B. Wilts adapted from ref. [93]). Green coloration is produced by discrete chitin domains. **b** Scanning electron micrograph (SEM) of the wing scale showing the structure of the domains. Each domain comprises a porous network-like structure that closely resembles the single gyroid (a highly ordered 3D photonic nanostructure). **c** A simulated unit cell of the gyroid showing the two intertwined channels (blue and yellow surfaces) and the two 'srs' nets (a type of 3D network structure) embedded within each channel (red and green graphs). In the butterfly, one of these channels is filled with chitin allowing the nanostructure to operate as photonic crystals. **d** A magnified SEM micrograph of the wing scale with the upper lamina partially removed showing a closer view of the gyroid domains and their attachment locations on the lower lamina. The inset is a photograph of a male *Thecla opisena* (image by K. Garwood adapted with permission from butterflycatalogs.com).

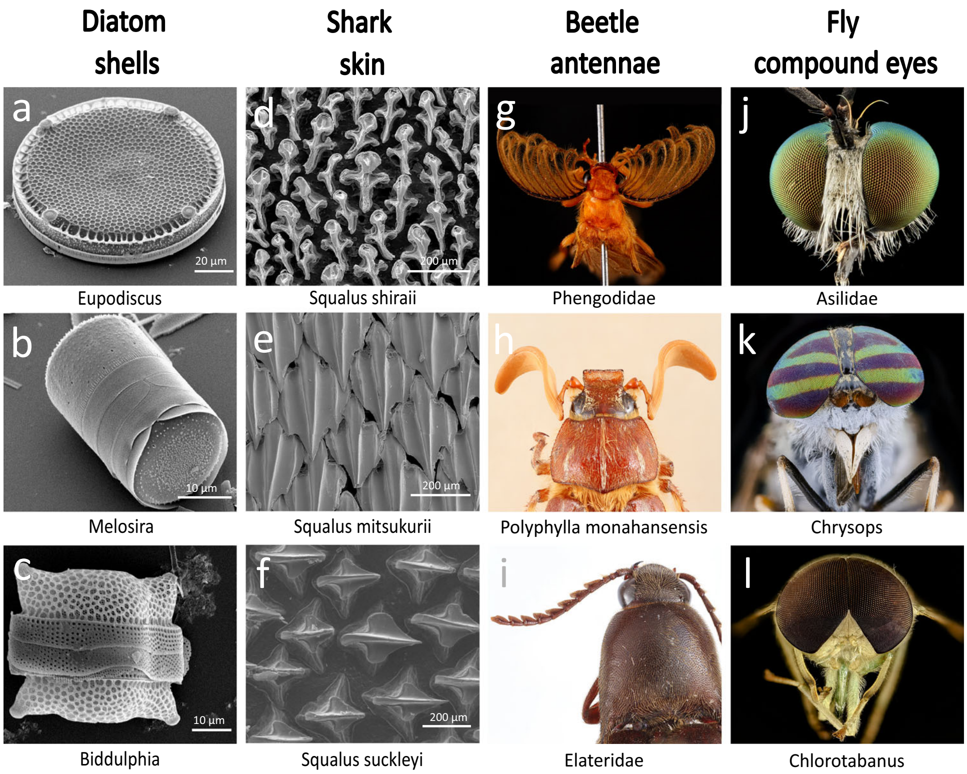


Fig. 3 Examples of structural diversity found in nature. Biological materials and structure such as diatom shells (**a, b, c**), shark skin (**d, e, f**), moth antennae (**g, h, i**), and compound eyes (**j, k, l**) often vary in structure across species depending on ecological context. Diatom shell images adapted from ref. [94], CC BY 4.0. Shark skin images adapted from ref. [95], CC BY 4.0. Beetle antennae images are in the public domain from flickr.com by T. Olson produced as part of the Insects Unlocked Project at the University of Texas at Austin. Fly compound eye images are in the public domain from flickr.com by Sam Droege produced as part of the USGS Native Bee Inventory and Monitoring Program at the Eastern Ecological Science Center.

identified as two of the key obstacles to the successful development of bioinformed products[45,65].

Linking structure to function and environment through multi-disciplinary collaboration. To improve our ability to develop multifunctional bioinformed materials, there needs to be a concerted collaborative effort to link biological structures to the environments in which they occur, and ideally, to the multiple functions they serve[45]. As an example, such efforts have allowed us to explore the outstanding mechanical performance of highly mineralized biological materials such as bone and nacre in hydrated environments[66], and the loss of this functionality upon desiccation[67]. Importantly, collaborative efforts to integrate materials science and biology provide reciprocal benefits[68]: materials scientists/engineers can greatly streamline the design process by understanding a biological material within its environmental context, and such collaborations can lead to "engineering-enabled biology" where a biological system or process can be examined from an engineering perspective to test novel functional hypotheses[69].

We acknowledge the non-trivial barriers to such multi-disciplinary collaborations. For example, the goals of biologists and materials engineers/designers seldom align, and the answers to questions posed by biologists are often not easily transferable to the problems engineers face[69]. Nevertheless, there are significant efforts to bridge the gap between biological and engineering approaches, including the communication and development of shared research objectives which inform the interests of both biologists and materials engineers/designers alike[70]. Although collaboration across fields can be challenging, it has clear benefits for innovation, and is increasingly becoming a strategic research priority.

Design and manufacture of bioinformed materials

Design approaches. Innovations are typically characterized as emanating from either technology push or market pull[54,71]. In the case of bioinformed materials, most efforts are technology pushed, meaning that the efforts focus on improving some new seemingly interesting technology and expecting to find a market for it once its usefulness is proven (Box 2). The market pull type technologies, on the other hand, build on a need identified in the market. This need triggers or guides technology development. Both are valid approaches but from the design point of view, a market need is essential for ultimate success[72,73]. One potential we identify here is the efficiency of natural systems optimized for performance in a specific environment, rather than a direct one-to-one mapping between function and form. In engineering this is called an integral system (as opposed to a modular system). These performance efficiencies are desired but they also complicate the design process due to the numerous interdependencies between the sub-systems[74]. There are systems engineering methods that engineers use to support this process[75], however they are rarely applied to biological systems. In materials design, a common approach to achieve non-one-to-one mapping with function and material properties is to use composites. They generally outperform other materials due to their engineered properties, but often suffer from poor recyclability at the end of the material's life[76].

The challenges of scale and material composition. An important challenge for bioinformed materials design is the frequent mismatch between the scale of the biological model and the synthetic material (Fig. 4)[37]. The function of a material derives from its forms, processes, forces, and behaviour, which often change with physical scale. For instance, a microliter drop of

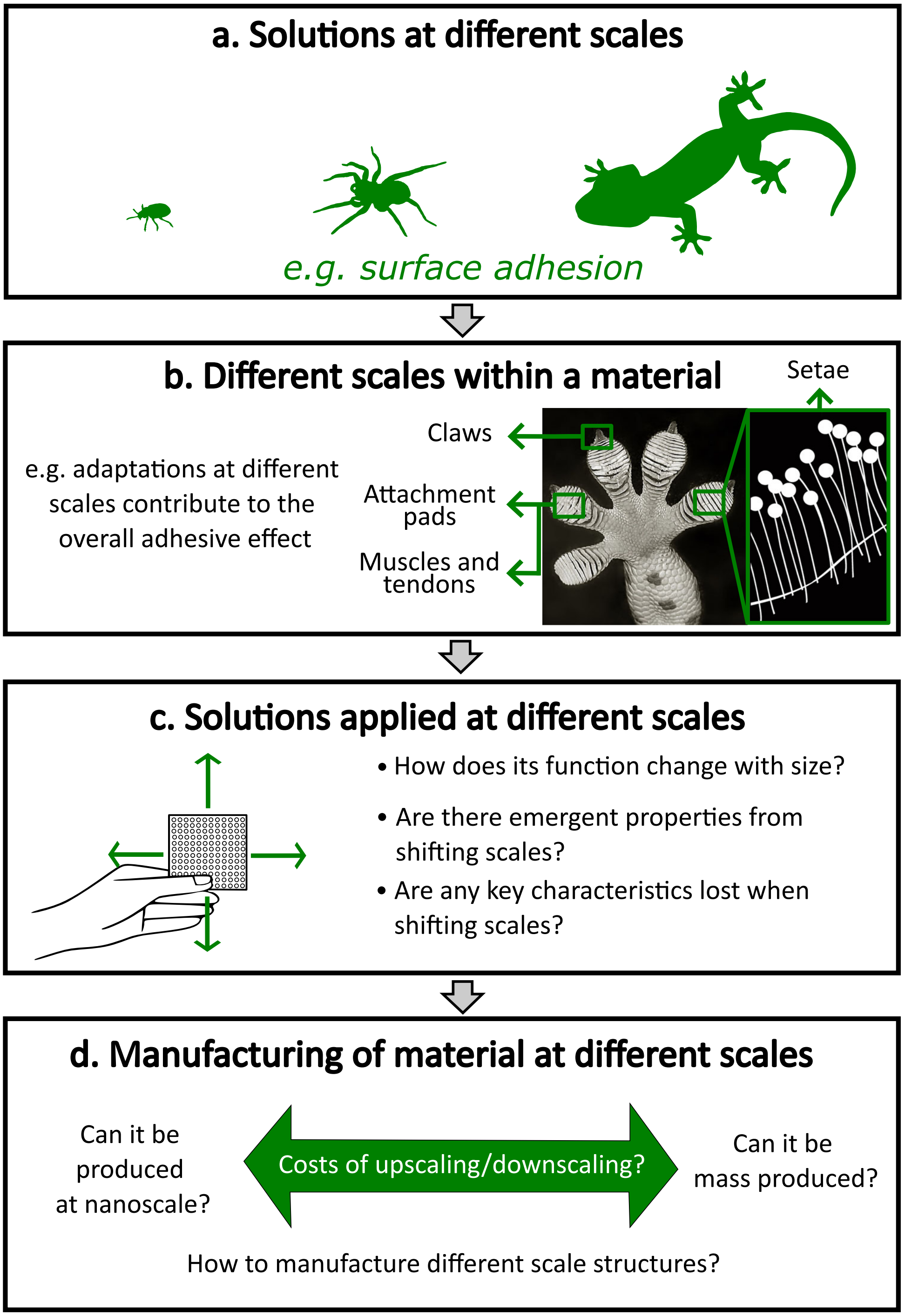


Fig. 4 Different considerations of scale during the design and manufacture of a bioinformed material. a Different species can exhibit different solutions to a similar functional need. For example, adaptations for surface adhesion can be observed in small invertebrates such as beetles and spiders, as well as larger vertebrates such as geckos. Differences in individual adhesion strategies can reflect differences in scale as different forces dominate at each scale. **b** Biological materials are often complex and hierarchical and can comprise multiple adaptations at different scales. For example, not only are the microscopic setae on each toepad important for adhesion, but the muscles, tendons, and digit orientation have a significant effect on overall surface attachment[96,97]. **c** Biologically informed solutions can be applied at different scales depending on the desired performance of the material. It is important to evaluate how a shift in scale may change the effectiveness of a biological solution applied to materials. **d** The manufacture of a material can also present challenges depending on its scale; for example, not every nanoscale structure can be easily mass produced. Image of gecko foot is in the public domain from Wikipedia Commons by David Clements. Silhouette images from unsplash.com.

water will bounce off a surface, whereas a basket-ball sized volume of water will splash because the surface tension acting on it is insufficient to hold the increased mass of liquid. Different forces dominate at different length scales, with molecular interactions at the nanoscale, interactions with light at the nanoscale and microscale, capillary/interfacial effects at the micrometer and millimeter scale, and gravity dominating at larger length scales. In other words, geometric similarity almost

Box 2 | Social and economic considerations - mycelium for replacement building products

Mycelium-based products exhibit many of the characteristics of an ideal bioinspired material (Fig. 1). They are adaptable, multifunctional, biodegradable, and unlike most manufactured materials, self-assembling. Mycelium is the fast-growing vegetative body of a mushroom or fungus and can grow to fill any shape or mold required. Its network structure consisting of branching tubular filaments called hyphae are mainly composed of chitin, β-glucans, and proteins[109]. It has been developed as a sustainable alternative to packaging material and synthetic polymers for a limited range of building products[110,111]. With changes to its feedstock mycelium mimics the functionality of products as diverse as polystyrene, particle board and leather. Moreover, it is a detrivore, consuming carbon waste from agriculture and timber manufacturing. In theory it should be a low cost to maintain and produce, and is completely biodegradable[112].

Despite all the advantages of mycelium-based products, there are several obstacles preventing the widespread uptake of mycelium materials in the building industry, including a psychological and aesthetic barrier to the uptake of biological products such as mycelium[73,112]. Early prototypes for the building industry focused on direct replacement of building insulation and cabinetry particle board. However, market failures led to the development of mycelium-based products for alternate markets to improve its reputation as a sustainable multifunctional material[73]. For example, mycelium technology companies have successfully partnered with businesses in the fashion and packaging industries where product cycles are short, and perishability is highly valued[73,112,113]. Nevertheless, collaborative multidisciplinary research into viable materials for the building industry is ongoing. Materials scientists have focused on developing mycelium-based biocomposites to seek improvements in durability[114], whilst biologists investigate and characterize the morphology and performance of mycelium strains to improve its mechanical properties[109,115]. With ongoing exposure and education of mycelium products to the general public, the psychological and aesthetic barriers towards such products are likely to decrease, especially with the ever-increasing demand for zero-emission sustainable products. That is, with the improving reliability, functionality, and growing mainstream appeal of mycelium-based products, technology-push is steadily being matched by market-pull. It is therefore becoming less risky for businesses to invest into mycelium-based solutions. Overall, it is clear that the current barriers against product uptake are wide-ranging and present over the entire product cycle. Consequently, the goal of replacing building materials with mycelium-based alternatives represents an interdisciplinary effort to solve each of these technical, social, and economic challenges.

never corresponds to dynamic or functional similarity[77]. We must therefore ask: how does function change with physical scale? If we attempt to scale up a structure or material, does it lose the key characteristics? There are also hierarchical properties of scale, and emergent properties when shifting from one scale to another, making it frequently difficult to predict the effects of scaling up materials[62]. To address these many problems in scaling and material composition, we can observe how these problems are solved in natural models. For example, adhesive pad area appears to increase with body mass, although maintaining a pad size proportional to body size requires drastic morphological changes[78]. To compensate, some animals such as tree frogs appear to increase the efficiency of their adhesive pads with increasing body mass[78], therefore such insights provide an important basis for designing adhesive attachment systems at larger size scales. These biological principles can then be represented as a digital model or virtual simulation to enable physical and mathematical analyses at scales of interest[79].

Another major challenge is material composition. The extraordinary diversity of life's designs is achieved using a few abundant organic and inorganic materials such as silks, chitin, keratin, cellulose, calcium carbonate and silica. The use of biopolymers such as chitosan and cellulose for materials innovation is gaining substantial momentum because they are (bio)degradable, among other advantages (Box 2)[80–82]; however, they are often less durable than synthetic materials. In general, a circular economy encourages minimal material use while also requiring materials to be as durable as possible due to the energy inputs into production and distribution. Further, materials should ultimately be reusable and recyclable, for which composite materials may be difficult to break down into constituents for reuse[76,83]. However, composites of biodegradable materials may offer new and so far, poorly explored opportunities for high performance materials (Box 2)[24,27,84].

To some extent, considerations of scale and material composition can be addressed through careful material selection and performance evaluation against key criteria, including function and physical properties at different length scales. Increasingly, material selection criteria also include sustainability indicators such as carbon footprint, embodied energy (direct and indirect energy inputs from cradle-to-gate or cradle-to-grave), recycled content, material recyclability and other environmental indicators (e.g. biodegradability, water use, material longevity)[85]. Indeed, sustainability is a key focus of the materials selection framework developed by Ashby and colleagues[86,87], with sustainability criteria incorporated into the associated material selection tool (Eco-Selector Tool in the Granta Ansys Materials Selector software[88]). The use of clearly defined material selection and performance evaluation criteria can help to refine the list of candidate materials appropriate for design and development of novel bioinformed materials.

Manufacture and cost. Many of the most promising functions of biological materials are achieved through elegant architectures at the nanometer and micron scale, and there are significant challenges around scaling up nanoscale structures to large surface areas or volumes[22]. Considerations include the expense of testing as well as cost of manufacture (current cost, as well as the likelihood that costs may come down), reliability (will the material have a long life?) and feasibility. Cost is a key consideration for all material production, but particularly for synthetic materials that replicate complex, composite or modular, and hierarchical features of biological materials because these features may increase the number of processing steps, the time taken to process, and so require more costly processing approaches.

Nevertheless, in some cases, certain nanoscale features can be replicated at scale relatively easily and cheaply. For example, self-cleaning surface coatings with superhydrophobic properties require the fabrication of micro- and nanoscale features that are robust over large surface areas, and these can be achieved with intrinsically scalable methods such as spraying or large-scale printing[89]. Many other features, however, would require a significant nanofabrication effort, even at a small scale. For example, the nanopattern of one layer of the multi-layered silica frustules of diatoms can be replicated using cost-effective replica molding, but manufacturing the multi-layered structure is pushing the current limits of nanofabrication, be it via top-down or bottom-up approaches[90]. Industry has cost-effectively harnessed these nanostructures in a very different way: mining diatom fossils (diatomaceous Earth) for a range of applications.

Synthetic materials rely on industrial manufacturing systems to produce objects at scale and with speed. Techniques most widely used include extruding, casting, rolling, and assembling. These allow for some variety, but not the kind of dynamic, fractal changeability that biological material systems exhibit. Additive manufacturing offers some potential to achieve more diverse structures, but to date it suffers from slower speeds compared with mass manufacturing methods, which results in more costly items[91,92]. Arguably, cost is one of the greatest obstacles for translating knowledge about biological materials into materials that can replace synthetics. While new manufacturing systems, like digital printing and robotics, have the capacity to integrate morphological variety, the system scale change required to replace existing systems is expensive and a carbon intensive process. Additionally, we note that all of the typical barriers to industry uptake of research apply to bioinformed materials, from regulatory requirements to lack of incentives to reduce energy consumption. Ultimately, scaling up requires integration of multiple disciplines from the earliest stages of the design process, including researchers, manufacturers, approval bodies, and end users.

Conclusions and guiding principles for future bioinformed innovation. Bioinformed design approaches hold enormous promise for innovation to meet the challenges of a circular economy and sustainable world. Perhaps unsurprisingly, the best design is one that resembles the process and outcome of biological evolution, insofar as the design process is adaptive and designs are refined to optimize multiple functions simultaneously (that is, designed in a holistic way). We have outlined key challenges in harnessing biological knowledge for bioinformed materials innovation and for the design, manufacture, and uptake of such materials. Addressing these challenges will require more effective multidisciplinary integration from the earliest stages of the design process, including researchers, product designers, manufacturers, approval bodies, and end users. Based on deliberations from a multidisciplinary workshop, we suggest guiding principles for future bioinformed innovation.

1. A bioinformed approach to materials innovation and sustainability extends beyond inspiration from single species to incorporate insights from higher levels of biological organization, such as ecosystems, and should inform all stages of materials production. Like biological systems, it is imperative to take a holistic view of the properties we desire in materials, over their full lifecycle, rather than narrowly optimizing for a single, specific function. Ultimately, materials must be designed for a circular economy and assessed against sustainability indicators. Bioinformed enhancements to improve both functionality and sustainability should be considered at multiple stages of the material lifecycle.
2. We suggest that biological information used for bioinformed design should be explicitly linked to the environmental context of the organism. We advocate high through-put characterization of material architectures and properties at different length scales, with information made publicly available and linked to environmental context through curated, annotated, and georeferenced databases. These repositories should be augmented by libraries of packages for analyzing and coalescing data.
3. We urge an approach to materials innovation that capitalizes on the defining feature of the natural world: diversity, produced via evolution by natural selection. This approach may entail examining material properties in multiple related species to understand how they vary in relation to the environment, given similar material, evolutionary and developmental constraints. Alternatively, it may entail examining functional solutions to similar problems in unrelated species to uncover general principles. Such a diversity-driven approach enables materials design to capitalize on multiple types of biological information, in multiple ways. We acknowledge that a diversity-driven approach is more difficult and may require development of biomaterials databases, approaches to processing large quantities of complex data such as machine learning, and world-wide collaborations (e.g., citizen science, crowd sources).
4. A bioinformed approach ultimately entails a shift away from one-to-one mapping between form and function or material property. This ideally needs to be achieved through material structure (e.g., hierarchical or layered), rather than through composition (composites), to maximize our ability to reuse and recycle materials. Innovation in structural properties is arguably where a bioinformed approach to materials design holds most promise.
5. The ability to manufacture bioinformed materials cost-effectively and at scale remain significant obstacles. These may be overcome with continued developments in nanofabrication and additive manufacturing techniques. Cost and manufacture should be considered from the earliest stages of bioinformed materials design, to gauge whether features can be replicated at scale using currently scalable techniques or require more complex, costly or novel manufacturing approaches.
6. Market need, in addition to the socio-cultural and economic context are essential factors to consider in the design of bioinformed sustainable materials. These factors ultimately determine the success or failure of materials at market and underscore the imperative for multidisciplinary integration in materials innovation.

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References

1. Zhao, N. et al. Bioinspired Materials: from Low to High Dimensional Structure. *Adv. Mater.* **26**, 6994–7017 (2014).
2. Zhang, C., McAdams Ii, D. A. & Grunlan, J. C. Nano/Micro-Manufacturing of Bioinspired Materials: a Review of Methods to Mimic Natural Structures. *Adv. Mater.* **28**, 6292–6321 (2016).
3. Ding, Z., Zreiqat, H. & Mirkhalaf, M. Rationally-designed self-shaped ceramics through heterogeneous green body compositions. *Mater. Horiz.* **9**, 2762–2772 (2022).
4. Greanya, V. *Bioinspired Photonics: Optical Structures and Systems Inspired by Nature*. 1–416 (CRC Press, 2015).
5. Jung, Y. H., Park, B., Kim, J. U. & Kim, T. I. Bioinspired Electronics for Artificial Sensory Systems. *Adv. Mater.* **31**, e1803637 (2019).
6. Yang, X. et al. Bioinspired neuron-like electronics. *Nat. Mater.* **18**, 510–517 (2019).
7. Palagi, S. & Fischer, P. Bioinspired microrobots. *Nat. Rev. Mater.* **3**, 113–124 (2018).
8. Bhattacharya, P., Du, D. & Lin, Y. Bioinspired nanoscale materials for biomedical and energy applications. *J. R. Soc. Interface* **11**, 20131067 (2014).
9. Proppe, A. H. et al. Bioinspiration in light harvesting and catalysis. *Nat. Rev. Mater.* **5**, 828–846 (2020).
10. Ortiz, C. & Boyce, M. C. Bioinspired structural materials. *Science* **319**, 1053–1054 (2008).
11. Losic, D., Mitchell, J. G. & Voelcker, N. H. Diatomaceous Lessons in Nanotechnology and Advanced Materials. *Adv. Mater.* **21**, 2947–2958 (2009).
12. Nguyen, P. Q., Courchesne, N. D., Duraj-Thatte, A., Praveschotinunt, P. & Joshi, N. S. Engineered Living Materials: Prospects and Challenges for Using Biological Systems to Direct the Assembly of Smart Materials. *Adv. Mater.* **30**, e1704847 (2018).
13. Cohen, Y. H. & Reich, Y. The biomimicry discipline: Boundaries, definitions, drivers, promises and limits. In *Biomimetic Design Method for Innovation and*

Sustainability (eds Cohen Y. H. & Reich Y.). Ch. 1, 3–17 (Springer Cham, 2016).
14. Whitesides, G. M. Bioinspiration: something for everyone. *Interf. Focus* **5**, 20150031 (2015).
15. Ng, L., Elgar, M. A. & Stuart-Fox, D. From Bioinspired to Bioinformed: Benefits of Greater Engagement From Biologists. *Front. Ecol. Environ.* **9**, 1–9 (2021).
16. Cutkosky, M. R. Climbing with adhesion: from bioinspiration to biounderstanding. *Interface Focus* **5**, 20150015 (2015).
17. Adriaens, D., Lakhtakia, A., Martín-Palma, R. J. & Knez, M. Evomimetics: The biomimetic design thinking 2.0. In *Proceedings of SPIE 10965: SPIE Smart Structures + Nondestructive Evaluation*. (eds R. K. Martín-Palma, M. Knez, & A. Lakhtakia). 41–53 (CO: SPIE, 2019).
18. Ilieva, L., Ursano, I., Traista, L., Hoffmann, B. & Dahy, H. Biomimicry as a Sustainable Design Methodology - Introducing the 'Biomimicry for Sustainability' Framework. *Biomimetics* **7**, 37 (2022).
19. Dou, S. et al. Bioinspired Microstructured Materials for Optical and Thermal Regulation. *Adv. Mater.* **33**, e2000697 (2021).
20. Wang, Y., Naleway, S. E. & Wang, B. Biological and bioinspired materials: Structure leading to functional and mechanical performance. *Bioact. Mater.* **5**, 745–757 (2020).
21. Ghazlan, A. et al. Inspiration from Nature's body armours – A review of biological and bioinspired composites. *Compos. B. Eng.* **205**, 108513 (2021).
22. Wegst, U. G. K., Bai, H., Saiz, E., Tomsia, A. P. & Ritchie, R. O. Bioinspired structural materials. *Nat. Mater.* **14**, 23–36 (2015).
23. Pena-Francesch, A., Jung, H. H., Demirel, M. C. & Sitti, M. Biosynthetic self-healing materials for soft machines. *Nat. Mater.* **19**, 1230–1235 (2020).
24. Eder, M., Amini, S. & Fratzl, P. Biological composites-complex structures for functional diversity. *Science* **362**, 543–547 (2018).
25. Naik, R. R. & Singamaneni, S. Introduction: Bioinspired and Biomimetic Materials. *Chem. Rev.* **117**, 12581–12583 (2017).
26. Yu, Z.-L. et al. Bioinspired polymeric woods. *Sci. Adv.* **4**, eaat7223 (2018).
27. Nepal, D. et al. Hierarchically structured bioinspired nanocomposites. *Nat. Mater.* **22**, 18–35 (2023).
28. Barthelat, F., Yin, Z. & Buehler, M. J. Structure and mechanics of interfaces in biological materials. *Nat. Rev. Mater.* **1**, 16007 (2016).
29. Fu, K., Moreno, D., Yang, M. & Wood, K. L. Bio-Inspired Design: An Overview Investigating Open Questions From the Broader Field of Design-by-Analogy. *J. Mech. Des.* **136**, 111102 (2014).
30. ISO/TC 266. *Biomimetics — Terminology, concepts and methodology. 25 (International Organization for Standardization*, Beuth Verlag, Berlin, Germany, 2015).
31. Chen, P.-Y., McKittrick, J. & Meyers, M. A. Biological materials: Functional adaptations and bioinspired designs. *Prog. Mater. Sci.* **57**, 1492–1704 (2012).
32. Vijayan, P. P. & Puglia, D. Biomimetic multifunctional materials: a review. *Emerg. Mater.* **2**, 391–415 (2019).
33. Shu, L. H., Ueda, K., Chiu, I. & Cheong, H. Biologically inspired design. *CIRP Ann.* **60**, 673–693 (2011).
34. Goel, A. K., McAdams, D. A. & Stone, R. B. *Biologically inspired design*. 1 edn, 1–333 (Springer-Verlag, 2014).
35. UN. *Report of the World Commission on Environment and Development: Our common future*. (United Nations, 1987).
36. UN. *Transforming our world: the 2030 Agenda for Sustainable Development*. (United Nations, 2015).
37. Perricone, V., Langella, C. & Santulli, C. Sustainable Biomimetics: A Discussion on Differences in Scale, Complexity, and Organization Between the Natural and Artificial World. In *Bionics and Sustainable Design* (eds Palombini F. L. & Muthu S. S.). Ch. 7, 171–193 (Springer Singapore, 2022).
38. MacArthur, E. Towards the circular economy. *J. Ind. Ecol.* **2**, 23–44 (2013).
39. Rahman, M. Z. et al. Advanced biopolymers for automobile and aviation engineering applications. *J. Polym. Res.* **30**, 106 (2023).
40. Sohn, Y. J. et al. Recent Advances in Sustainable Plastic Upcycling and Biopolymers. *Biotechnology Journal* **15**, 1900489 (2020).
41. Nagel, J. K. S. A Thesaurus for Bioinspired Engineering Design. In *Biologically Inspired Design* (eds Goel A. K., McAdams D. A., & Stone R. B.). Ch. 4, 63–94 (Springer, 2014).
42. Nagel, J. K. S., Nagel, R. L. & Eggermont, M. Teaching Biomimicry With an Engineering-to-Biology Thesaurus. In *International design engineering technical conferences and computers and information in engineering conference*. 1–10 (IDETC/CIE, 2013).
43. Deldin, J.-M. & Schuknecht, M. The AskNature Database: Enabling Solutions in Biomimetic Design. In *Biologically Inspired Design: Computational Methods and Tools* (eds Goel A. K., McAdams D. A., & Stone R. B.). Ch. 2, 17–27 (Springer London, 2014).
44. Küntzer, J. et al. BN++ – A Biological Information System. *J. Integr. Bioinform.* **3**, 148–161 (2006).
45. Wolff, J. O., Wells, D., Reid, C. R. & Blamires, S. J. Clarity of objectives and working principles enhances the success of biomimetic programs. *Bioinspir. Biomim.* **12**, 051001 (2017).
46. Niewiarowski, P. H., Stark, A. Y. & Dhinojwala, A. Sticking to the story: outstanding challenges in gecko-inspired adhesives. *J. Exp. Biol.* **219**, 912–919 (2016).
47. Yan, X., Sedykh, A., Wang, W., Yan, B. & Zhu, H. Construction of a web-based nanomaterial database by big data curation and modeling friendly nanostructure annotations. *Nat. Commun.* **11**, 2519 (2020).
48. Arakawa, K. et al. 1000 spider silkomes: Linking sequences to silk physical properties. *Sci. Adv.* **8**, eabo6043 (2022).
49. DigiMorph. *A voxel-based digital library of morphology*, http://digimorph.org/aboutdigimorph.phtml (2022).
50. Boyer, D. M., Gunnell, G. F., Kaufman, S. & McGeary, T. M. Morphosource: Archiving and sharing 3-D digital specimen data. *Pap. Palaeontol.* **22**, 157–181 (2016).
51. Chan, W.-P. et al. A high-throughput multispectral imaging system for museum specimens. *Communications Biology* **5**, 1318 (2022).
52. Shirey, V. et al. LepTraits 1.0 A globally comprehensive dataset of butterfly traits. *Sci. Data* **9**, 382 (2022).
53. Nelson, G. & Ellis, S. The history and impact of digitization and digital data mobilization on biodiversity research. *Philos. Trans. Royal Soc. B* **374**, 20170391 (2019).
54. Broeckhoven, C. & du Plessis, A. Escaping the Labyrinth of Bioinspiration: Biodiversity as Key to Successful Product Innovation. *Adv. Funct. Mater.* **32**, 2110235 (2022).
55. Mitchell, J. G. et al. The Role of Diatom Nanostructures in Biasing Diffusion to Improve Uptake in a Patchy Nutrient Environment. *PLoS One* **8**, e59548 (2013).
56. Blamires, S. J., Wu, C.-L., Blackledge, T. A. & Tso, I.-M. Environmentally induced post-spin property changes in spider silks: influences of web type, spidroin composition and ecology. *Biol. J. Linn.* **106**, 580–588 (2012).
57. Büscher, T. H., Bank, S., Cumming, R. T., Gorb, S. N. & Bradler, S. Leaves that walk and eggs that stick: comparative functional morphology and evolution of the adhesive system of leaf insect eggs (Phasmatodea: Phylliidae). *BMC Ecol. Evol.* **23**, 17 (2023).
58. Büscher, T. H. & Gorb, S. N. Convergent Evolution of Adhesive Properties in Leaf Insect Eggs and Plant Seeds: Cross-Kingdom Bioinspiration. *Biomimetics* **7**, 173 (2022).
59. De Tommasi, E., Gielis, J. & Rogato, A. Diatom Frustule Morphogenesis and Function: a Multidisciplinary Survey. *Mar. Genom.* **35**, 1–18 (2017).
60. Hamm, C. E. The evolution of advanced mechanical defenses and potential technological applications of diatom shells. *J. Nanosci. Nanotechnol.* **5**, 108–119 (2005).
61. Ng, C. S. & Li, W.-H. Genetic and Molecular Basis of Feather Diversity in Birds. *Genome Biol. Evol.* **10**, 2572–2586 (2018).
62. Craig, H. C. et al. Nanovoid formation induces property variation within and across individual silkworm silk threads. *J. Mater. Chem. B.* **10**, 5561–5570 (2022).
63. Patek, S. N. Biomimetics and evolution. *Science* **345**, 1448–1449 (2014).
64. Pro, J. W. & Barthelat, F. Is the Bouligand architecture tougher than regular cross-ply laminates? A discrete element method study. *Extreme Mech. Lett.* **41**, 101042 (2020).
65. Tan, E. J., Elgar, M. A., Bian, X. & Peters, R. A. Interpreting animal behaviors – A cautionary note about swaying in phasmids. *Front. Ecol. Environ*. **11**, 1065789 (2023).
66. Mirkhalaf, M. & Zreiqat, H. Fabrication and Mechanics of Bioinspired Materials with Dense Architectures: Current Status and Future Perspectives. *JOM* **72**, 1458–1476 (2020).
67. Jackson, A. P., Vincent, J. F. V., Turner, R. M. & Alexander, R. M. The mechanical design of nacre. *Proc. Royal Soc. B* **234**, 415–440 (1988).
68. Hashemi Farzaneh, H. Bio-inspired design: the impact of collaboration between engineers and biologists on analogical transfer and ideation. *Res. Eng. Des.* **31**, 299–322 (2020).
69. Barley, W. C., Ruge-Jones, L., Wissa, A., Suarez, A. V. & Alleyne, M. Addressing Diverse Motivations to Enable Bioinspired Design. *Integrat. Comparat. Biol.* **5**, 1–10 (2022).
70. Blamires, S. J., Spicer, P. T. & Flanagan, P. J. Spider Silk Biomimetics Programs to Inform the Development of New Wearable Technologies. *Front. Mater. Sci.* **7**, 29 (2020).
71. Speck, O., Speck, D., Horn, R., Gantner, J. & Sedlbauer, K. P. Biomimetic bio-inspired biomorph sustainable? An attempt to classify and clarify biology-derived technical developments. *Bioinspir. Biomim.* **12**, 011004 (2017).
72. Lin, R.-J., Tan, K.-H. & Geng, Y. Market demand, green product innovation, and firm performance: evidence from Vietnam motorcycle industry. *J. Clean. Prod.* **40**, 101–107 (2013).

73. McGaw, J., Andrianopoulos, A. & Liuti, A. Tangled Tales of Mycelium and Architecture: Learning From Failure. *Front. Built Environ.* **8**, 1–8 (2022).
74. Hölttä-Otto, K. & de Weck, O. Degree of modularity in engineering systems and products with technical and business constraints. *Concurr. Eng.* **15**, 113–126 (2007).
75. Hölttä, K., Suh, E. S. & de Weck, O. Tradeoff between modularity and performance for engineered systems and products. In *DS 35: Proceedings ICED 05, the 15th international conference on engineering design*. 449–450 (ICED, 2005).
76. Yang, Y. et al. Recycling of composite materials. *Chem. Eng. Process.* **51**, 53–68 (2012).
77. Miller, B. D. & Clark, J. E. Dynamic similarity and scaling for the design of dynamical legged robots. In *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 5719–5726 (IEEE, 2015).
78. Labonte, D. et al. Extreme positive allometry of animal adhesive pads and the size limits of adhesion-based climbing. *PNAS* **113**, 1297–1302 (2016).
79. Perricone, V., Grun, T. B., Marmo, F., Langella, C. & Candia Carnevali, M. D. Constructional design of echinoid endoskeleton: main structural components and their potential for biomimetic applications. *Bioinspir. Biomim.* **16**, 011001 (2020).
80. Kalirajan, C., Dukle, A., Nathanael, A. J., Oh, T. H. & Manivasagam, G. A Critical Review on Polymeric Biomaterials for Biomedical Applications. *Polymers (Basel)* **13**, 3015 (2021).
81. Gumrah Dumanli, A. Nanocellulose and its composites for biomedical applications. *Curr. Med. Chem.* **24**, 512–528 (2017).
82. Hou, J., Aydemir, B. E. & Dumanli, A. G. Understanding the structural diversity of chitins as a versatile biomaterial. *Philos. Trans. Royal Soc. A* **379**, 20200331 (2021).
83. Ramamoorthy, S. K., Skrifvars, M. & Persson, A. A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers. *Polym. Rev.* **55**, 107–162 (2015).
84. Rodrigo-Navarro, A., Sankaran, S., Dalby, M. J., del Campo, A. & Salmeron-Sanchez, M. Engineered living biomaterials. *Nat. Rev. Mater.* **6**, 1175–1190 (2021).
85. Lenzen, M. et al. Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. *Nat. Sustainab.* **5**, 157–166 (2022).
86. Ashby, M. F. *Materials and sustainable development* (Butterworth-Heinemann, 2022).
87. Ashby, M. F. *Materials and the environment: eco-informed material choice* (Elsevier, 2012).
88. *Ansys GRANTA selector software* (Cambridge, UK, 2023).
89. Scarratt, L. R. J., Steiner, U. & Neto, C. A review on the mechanical and thermodynamic robustness of superhydrophobic surfaces. *Adv. Colloid Interface Sci.* **246**, 133–152 (2017).
90. Losic, D., Pillar, R. J., Dilger, T., Mitchell, J. G. & Voelcker, N. H. Atomic force microscopy (AFM) characterisation of the porous silica nanostructure of two centric diatoms. *J. Porous Mater.* **14**, 61–69 (2007).
91. Studart, A. R. Additive manufacturing of biologically-inspired materials. *Chem. Soc. Rev.* **45**, 359–376 (2016).
92. Hasanov, S. et al. Review on Additive Manufacturing of Multi-Material Parts: Progress and Challenges. *J. Manuf. Mater. Process.* **6**, 1–32 (2021).
93. Wilts, B. D. et al. Butterfly gyroid nanostructures as a time-frozen glimpse of intracellular membrane development. *Sci. Adv.* **3**, e1603119 (2017).
94. Bradbury, J. Nature's Nanotechnologists: Unveiling the Secrets of Diatoms. *PLOS Biol.* **2**, e306 (2004).
95. Viana, S. T. F. L. & de Carvalho, M. R. *Squalus shiraii* sp. nov. (Squaliformes, Squalidae), a new species of dogfish shark from Japan with regional nominal species revisited. *Zoosyst. Evol.* **96**, 275–311 (2020).
96. King, D. R., Bartlett, M. D., Gilman, C. A., Irschick, D. J. & Crosby, A. J. Creating gecko-like adhesives for "real world" surfaces. *Adv. Mater.* **26**, 4345–4351 (2014).
97. Imburgia, M. J., Kuo, C.-Y., Briggs, D. R., Irschick, D. J. & Crosby, A. J. Effects of Digit Orientation on Gecko Adhesive Force Capacity: Synthetic and Behavioral Studies. *Integr. Comp. Biol.* **59**, 182–192 (2019).
98. Nwuzor, I. C., Idumah, C. I., Nwanonenyi, S. C. & Ezeani, O. E. Emerging trends in self-polishing anti-fouling coatings for marine environment. *Saf. Extreme. Environ.* **3**, 9–25 (2021).
99. Maan, A. M. C., Hofman, A. H., Vos, W. M. & Kamperman, M. Recent Developments and Practical Feasibility of Polymer-Based Antifouling Coatings. *Adv. Funct. Mater.* **30**, 2000936 (2020).
100. Jin, H., Tian, L., Bing, W., Zhao, J. & Ren, L. Bioinspired marine antifouling coatings: Status, prospects, and future. *Prog. Mater. Sci.* **124**, 100889 (2022).
101. Almeida, J. R. & Vasconcelos, V. Natural antifouling compounds: Effectiveness in preventing invertebrate settlement and adhesion. *Biotechnol. Adv.* **33**, 343–357 (2015).
102. Tsoukatou, M., Hellio, C., Vagias, C., Harvala, C. & Roussis, V. Chemical Defense and Antifouling Activity of Three Mediterranean Sponges of the Genus Ircinia. *Z. Naturforsch C. J. Biosci.* **57**, 161–171 (2002).
103. Bhoj, Y., Tharmavaram, M. & Rawtani, D. A comprehensive approach to antifouling strategies in desalination, marine environment, and wastewater treatment. *Chem. Phys.* **2**, 100008 (2021).
104. Sousa-Cardoso, F., Teixeira-Santos, R. & Mergulhão, F. J. M. Antifouling Performance of Carbon-Based Coatings for Marine Applications: A Systematic Review. *Antibiotics* **11**, 1102 (2022).
105. Kumar, S., Ye, F., Dobretsov, S. & Dutta, J. Nanocoating Is a New Way for Biofouling Prevention. *Front. Nanosci.* **3**, 771098 (2021).
106. Tian, L. et al. Novel Anti-fouling Strategies of Live and Dead Soft Corals (*Sarcophyton trocheliophorum*): Combined Physical and Chemical Mechanisms. *J. Bionic. Eng.* **17**, 677–685 (2020).
107. Vega-Sánchez, C., Peppou-Chapman, S., Zhu, L. & Neto, C. Nanobubbles explain the large slip observed on lubricant-infused surfaces. *Nature Comm.* **13**, 351 (2022).
108. Ware, C. S. et al. Marine Antifouling Behavior of Lubricant-Infused Nanowrinkled Polymeric Surfaces. *ACS Appl. Mater. Interfaces* **10**, 4173–4182 (2018).
109. Islam, M. R., Tudryn, G., Bucinell, R., Schadler, L. & Picu, R. C. Morphology and mechanics of fungal mycelium. *Sci. Rep.* **7**, 13070 (2017).
110. Dias, P. P., Jayasinghe, L. B. & Waldmann, D. Investigation of Mycelium-Miscanthus composites as building insulation material. *Res. Mat.* **10**, 100189 (2021).
111. Javadian, A., Le Ferrand, H., Hebel, D. E. & Saeidi, N. Application of Mycelium-Bound Composite Materials in Construction Industry: A Short Review. *Mater. Sci. Eng.* **7**, 1–9 (2020).
112. Abhijith, R., Ashok, A. & Rejeesh, C. R. Sustainable packaging applications from mycelium to substitute polystyrene: a review. *Mater. Today* **5**, 2139–2145 (2018).
113. Silverman, J., Cao, H. & Cobb, K. Development of Mushroom Mycelium Composites for Footwear Products. *Cloth. Text. Res. J.* **38**, 119–133 (2020).
114. Jones, M., Mautner, A., Luenco, S., Bismarck, A. & John, S. Engineered mycelium composite construction materials from fungal biorefineries: A critical review. *Mater. Des.* **187**, 108397 (2020).
115. Tacer-Caba, Z., Varis, J. J., Lankinen, P. & Mikkonen, K. S. Comparison of novel fungal mycelia strains and sustainable growth substrates to produce humidity-resistant biocomposites. *Mater. Des.* **192**, 108728 (2020).

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Author contributions

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Competing interests

The authors declare no competing interests.

Additional information

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