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News & Highlights

Biology Inspires Innovative Materials Science

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From the club-like limbs of the mantis shrimp to the texture of a cicada's wing, recently reported studies of the structures found in living creatures are fostering innovations in synthetic materials. The work shows how biological research can underpin the development of novel materials that adopt key attributes or functions of natural substances with the goal of applying them in improved, often high-technology products [1].

Over the past two decades, such bio-inspired materials have started to shift from the lab into commercial use [2]. Take the surface of a lotus leaf, for instance, which is covered in microscopic waxy dimples that force water to bead into droplets and roll off. This superhydrophobic structure has been mimicked in products such as Lotusan paint (Sto Corp., Atlanta, GA, USA), which can give buildings a self-cleaning facade—as the water runs off the surface, it carries fine particles of dirt with it [3]. Other bio-inspired materials can respond to their environment, display durable colors, stick to smooth surfaces, or absorb shocks [4].

"Bio-inspired designs are increasingly moving toward real-world applications, particularly in armor, impact mitigation, and wear-resistant coatings," said Horacio Espinosa, professor of mechanical and biomedical engineering and director of the Theoretical and Applied Mechanics Program at the McCormick School of Engineering at Northwestern University (Evanston, IL, USA).

A range of factors are accelerating this work, according to Anna Sandak, head of materials science at Slovenia's InnoRenew Center of Excellence and professor at the University of Primorska. Analytical techniques such as electron microscopy and atomic force microscopy, which are used to investigate the structure of biological materials, have become much more affordable, she said. So too have the computer-processing power and machine-learning systems that can tease useful results from reams of data. And one of the most significant factors is a trend towards forming multidisciplinary teams that include not only materials scientists and engineers, but biologists as well. "We are really at the intersection of biotechnology, advanced materials, and engineering," Sandak said.

Illustrating the approach, in January 2025, attendees of the annual meeting of the Society for Integrative and Comparative Biology (SICB) in Atlanta, GA, USA, heard about new work to mimic cicada wings. The insect's wings are covered in tiny nanopillars made of proteins and a tough polysaccharide called chitin [5]. The tiny spikes are roughly 150 nm wide and 300 nm high [6] and have long been known to have an antibacterial action [7].

Various researchers have attempted to figure out how the nanopillars work—some have suggested that the pillars puncture bacteria like a pin bursting a balloon, or that contact with the pillars induces oxidative stress in the microbes [8]. At the SICB meeting, Marianne Alleyne, an assistant professor of entomology at the University of Illinois Urbana–Champaign (USA), and her graduate student Yutao Chen, revealed they had used synthetic analogs of the nanopillars to investigate the antibacterial mechanism [9].

The researchers started with a piece of aluminum that carried an array of minuscule wells on its surface. Then they filled the wells with polystyrene and dissolved the aluminum, leaving a bristling surface of polystyrene pillars that were similar in size to the pillars on cicada wings (Fig. 1). When bacteria settled on these tips, the nanopillars bent and pulled at the microbes' membranes, tearing them open. "The shearing force just kind of rips them apart," said Alleyne.

Chen has already found that her polystyrene nanopillars can stop bacteria from colonizing a surface. The research suggests that a layer of these pillars on catheters or other medical equipment

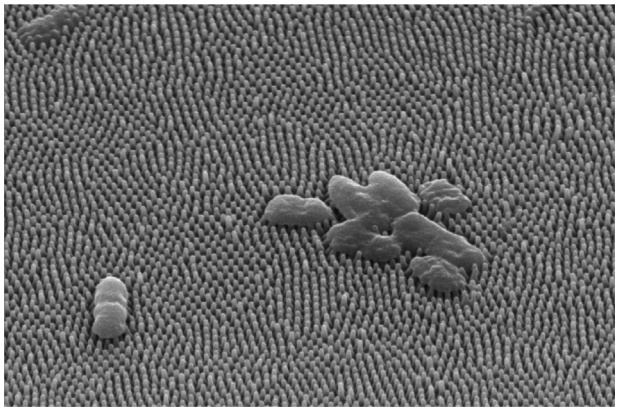

Fig. 1. Cicada wings are covered in nanopillars that have an antibacterial effect. To understand the mechanism, researchers created an array of polystyrene nanopillars to mimic the structures. In this electron microscopy image, bacteria (each ~1 μm long) placed onto the synthetic nanopillars were torn open by shearing force. Such nanopillars could potentially be used as antibacterial coatings in medical equipment. Credit: Yutao Chen; Beckman Institute/University of Illinois Urbana–Champaign (with permission).

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could serve as an alternative to coatings with conventional chemical disinfectants.

As reported in a paper published in February 2025 [10], a similar approach to prevent bacteria from colonizing food cutting-boards was taken by a research team led by Sebastiampillai Raymond at Callaghan Innovation, a government research center in Lower Hutt, New Zealand. The group used a laser to etch metals with nanoscale patterns like those on cicada wings or shark skin. Their results suggested that the water-repelling effect of these patterns made it difficult for bacteria to stick to the surface. Raymond said that the laser texturing process could be used to produce antibacterial cutting boards without chemical coatings that might leach into foods [11].

In another example presented at the January 2025 SICB meeting, Alleyne described the work that her graduate student Elizabeth Bello has conducted on water-repelling structures found in tiny insects called leafhoppers [12]. These creatures coat themselves with hollow, spherical nanoparticles known as brochosomes (Fig. 2) that are superhydrophobic and anti-reflective, perhaps offering a form of camouflage [13]. The hollow balls are excreted by the equivalent of the insect's kidney and come in a variety of shapes and sizes. Bello has begun studying how the brochosomes stick to the insects' exoskeleton, and how durable they are, research that could lead to synthetic versions for waterproof coatings.

Insects are just one source for bio-inspired materials. In a February 2025 issue of the journal *Science*, Espinosa and colleagues revealed the biological structures that allow a mantis shrimp to deliver a knockout blow to its prey without damaging itself [14].

The peacock mantis shrimp uniquely has two specialized limbs, known as dactyl clubs (Fig. 3), which can deliver a hammer blow of more than 700 N, enough to smash mollusc shells or stun fish [15]. Yet despite the immense force of this impact, the club itself remains unscathed. "The mantis shrimp's dactyl club is exceptionally resistant to damage," said Espinosa, who led the research team.

Researchers have previously shown that the club's outer surface has a hard coating of hydroxyapatite, a calcium phosphate mineral like those found in teeth and bone [15]. This coating lies atop a region containing a mix of hydroxyapatite and chitin. The mineralized chitin fibers form a herringbone pattern roughly 500 μm thick, an arrangement that helps to diffuse and deflect cracks to stop them spreading through the material.

Beneath that region, bundles of twisted fibers are arranged in a series of layers—called a Bouligand structure—in which the orientation of each layer is slightly offset compared to its neighbors. Espinosa's team used a method called pump-probe laser ultrasonics to demonstrate how this pattern filters out high-frequency vibrations as they pass through the club, preventing them from damaging the rest of the shrimp's limb [14,16]. "Together, these mechanisms enable the dactyl club to endure repeated, extremely intense impacts without significant structural damage," Espinosa said.

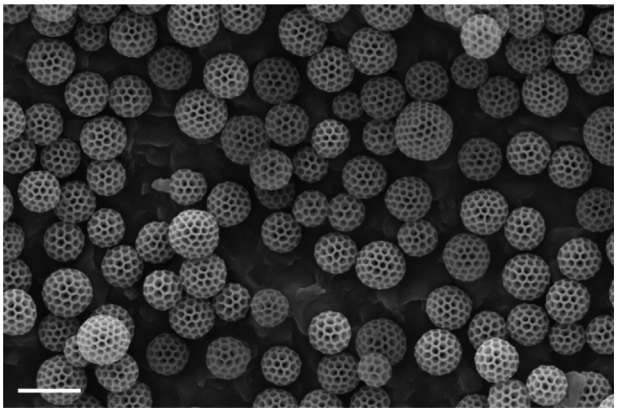

Fig. 2. This electron microscopy image shows hollow spheres called brochosomes found on leafhopper insects (scale bar = 1 μm). Researchers are studying the water-repelling properties of these nanoforms, which might prove useful as a basis for synthetic coatings. Credit: Elizabeth Bello (with permission).

Fig. 3. The peacock mantis shrimp has two reddish–white dactyl clubs that it uses to smash its prey with great force. Researchers have studied how the structure of these clubs prevents impacts from damaging them, which could help to design materials that absorb shocks or dampen unwanted vibrations. Credit: Cédric Péneau/Wikimedia (CC BY-SA 4.0).

Many biological materials depend on these sorts of hierarchical structures, in which different components contribute different properties at different scales [17]. Espinosa said that advanced techniques such as pump-probe laser ultrasonic analysis have become crucial tools for studying the mechanical properties of these materials in detail, at multiple size scales.

Structures like those in the dactyl club could eventually be used as shock absorbers in applications including protective coatings, armor systems, or even sports equipment, Espinosa said. Such materials might also be used to damp down vibrations that could interfere with sensitive equipment, such as precision optics.

Turning fundamental biological discoveries into advanced synthetic materials, however, depends on businesses playing a greater role in their development, said Alleyne. "The next step is having a little bit more buy-in from private companies, to come up with better frameworks of how to translate studies on these kinds of things into products," she said.

Simply replicating a biological structure is rarely enough for successful bio-inspired design, Alleyne said. Biological materials evolved in response to a wide range of selection pressures—cicada wings need to enable flight, as well as conferring antimicrobial benefits, for example—which may not be required for other applications. "We need to get better at iteration, going back to nature to figure out which organism is the best inspiration," Alleyne said.

Sandak pointed out that some materials researchers are moving beyond bio-inspiration, and instead using sustainable biological materials directly in products, or even incorporating living cells into materials.

In Delft, the Netherlands, for example, a company called Green Basilisk uses bacteria to make self-healing concrete [18]. Conventional concrete tends to accumulate tiny cracks that allow water to creep inside, weakening its structure. The company's solution is to add bacterial spores and calcium lactate to the concrete mix before it sets. The bacteria remain dormant until cracks allow water to reach them, which activates them to feed on lactate and excrete CO_2. The CO_2 combines with calcium ions to form solid calcium carbonate, which can fill cracks up to 1 mm wide and halt the damage [19].

Sandak herself leads a project called "Bioinspired Living Skin for Architecture," or ARCHI-SKIN, which is developing a protective coating for buildings based on a living biofilm of fungi [20]. Architectural coatings applied to extend a building's service life usually include biocides to kill microorganisms, but this can create problems during demolition and disposal because the substances may be toxic. Instead, as reported in 2024 [21], Sandak's team coats wood with a colony of "good" fungi that ensures damaging fungi cannot take hold. In addition, the living coating can even repair itself over time and provide additional functionalities such as ultraviolet (UV) protection.

Sandak said her work demonstrates that the most powerful aspects of bio-inspired design are often about autonomy: self-growing, self-assembling, and self-repairing. In some circumstances, she said, it makes more sense to co-opt those abilities by putting living organisms to work, rather than reinventing them—or some aspect of them—using synthetic materials. "Those are fantastic phenomena that are hard to imitate with conventional materials."

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