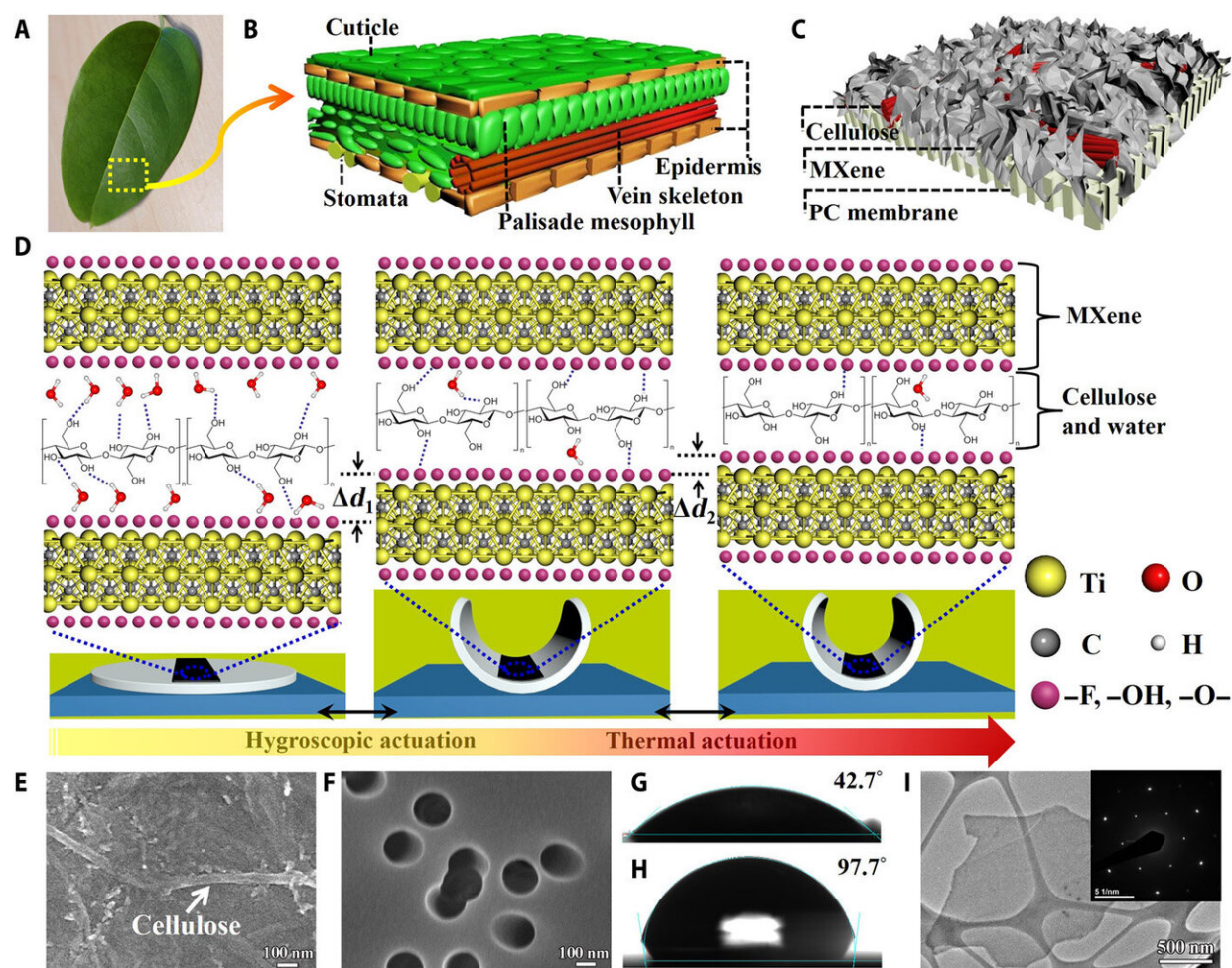


# Bioinspired MXene-based actuators for programmable smart devices

July 18 2019, by Thamarasee Jeewandara



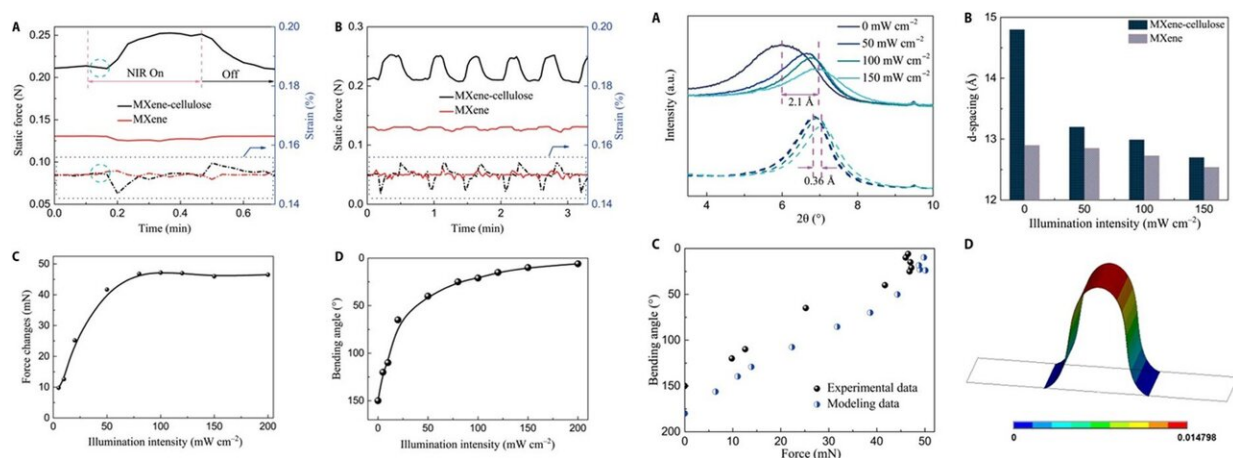
The elaborate structure, components, and actuation mechanism of the MXene-cellulose-based actuator. (A) Photograph of a natural leaf. (B) Schematic diagram of a leaf structure. (C) Schematic diagram of the MXCC/PC bilayer-structured actuator, which is composed of MXCC and a PC filter membrane. (D) Actuation mechanism of the MXCC/PC bilayer-structured actuator.

Macroscopic and microcosmic (involving H bonds) structure changes of the MXCC/PC bilayer-structured actuator in response to hygroscopic and thermal stimuli simultaneously (both hygroscopic and thermal actuation processes are controlled by electrical and NIR light actuation). Scanning electron microscopy images of the MXCC (E) and the PC filter membrane (F). Contact angle measurement of the MXCC (G) and PC filter membrane (H). (I) Transmission electron microscopy image of the 2D MXene nanosheet (inset: SAED pattern). Credit: Science Advances, doi: 10.1126/sciadv.aaw7956

During photosynthesis, natural leaves with elaborate architectures and functional components can harvest and convert solar energy into chemical fuels that are converted into energy. The biological energy production has provided [materials scientists](#) a new bioinspired paradigm to produce many autonomous systems, including light-triggered motion. In a recent report, Guofo Cai and co-workers at the departments of Materials Science and Engineering, Astronautic Science and Mechanics, and Chemical Engineering, developed an unprecedented bilayered actuator base on [MXene](#) ( $\text{Ti}_3\text{C}_2\text{T}_x$ )-cellulose composites (MXCC) and polycarbonate (PC) membranes.

The device mimicked the sophisticated architecture of a leaf and showed energy-harvesting and conversion capabilities similar to [photosynthesis](#). The bilayered actuator contained highly desirable features including; multi-responsiveness, low-power actuation, fast actuation speed, large-shape deformation, robust stability and programmable adaptability—well suited for modern soft [actuator](#)-based smart systems. Cai et al. believe these adaptive soft systems will be attractive as revolutionary technologies to build soft robots, smart switches, for information encryption, infrared dynamic display, camouflage and temperature regulation. They envision additional uses of the technology to develop human-machine interfaces such as [haptics](#). The study is now published in *Science Advances*.

Materials scientists have studied materials and devices that dynamically change shape, size and electrical/[mechanical properties](#) in response to external stimuli for a variety of applications. Such devices have [important functions as actuators](#), artificial muscles, in robotics, as energy generators, sensors and smart curtains. Scientists have devoted substantial efforts to develop smart actuators based on a variety of active materials such as [carbon nanotubes and graphene](#), [shape memory polymers](#), gels, conjugated polymers and [liquid crystal elastomers](#) as well as [ceramics](#) and [alloys](#).



LEFT: Mechanical performance and motions of the MXCC/PC bilayer-structured actuator caused by NIR light. (A) Typical static force and strain changes of the MXCC- and cellulose-based actuators during one actuation cycle when NIR light illumination was turned on and off (50 mW cm<sup>-2</sup>). (B) Plot of the static force and strain of the MXCC- and cellulose-based actuators as a function of time for five consecutive NIR light on and off cycles, indicating the reversible, stable, and rapid actuation process. (C) Static force changes of the MXCC-based actuator under different NIR illumination intensities (from 5 to 200 mW cm<sup>-2</sup>). (D) Bending angle of the MXCC-based actuator under different NIR illumination intensities (from 5 to 200 mW cm<sup>-2</sup>). RIGHT: Structure change under different NIR illumination intensities and mechanical modeling. (A) XRD patterns of MXCC- and MXene-based actuators under different NIR light illumination intensities (solid lines, MXCC-based actuator; dashed lines,

MXene-based actuator). (B) Corresponding d-spacing of the MXCC- and MXene-based actuators under different NIR light illumination intensities. (C) Simulated and experimental results of the MXCC-based actuator. (D) Simulated results of the MXCC-based actuator under NIR light illumination. Credit: Science Advances, doi: 10.1126/sciadv.aaw7956

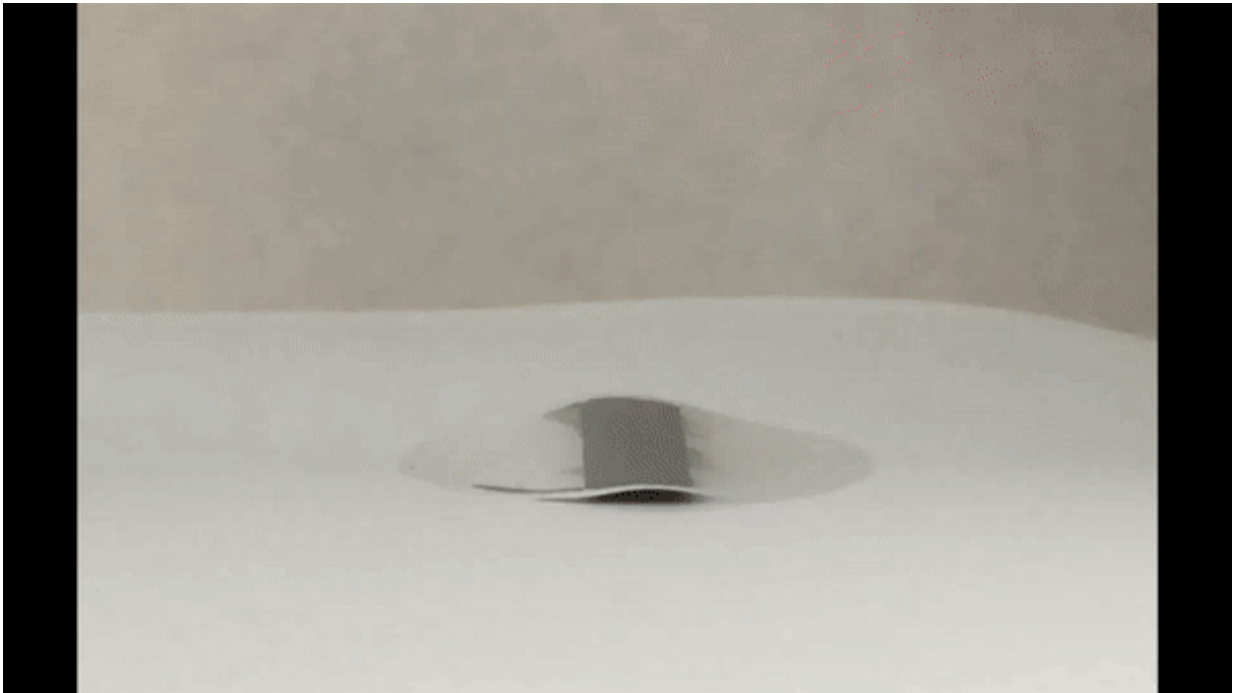
A variety of environmental stimuli such as [humidity](#), [temperature](#), [electricity](#), [light](#) and [pH](#) can trigger physical alterations of these materials. But it is presently difficult to enhance the speed of actuation and scale-up shape changes due to poor [mechanical](#) and [thermal](#) instability that restrict their capabilities. Building a smart actuator that responds to diverse stimuli such as humidity, electricity, heat or light with fast actuation, large-shape deformation, programmable adaptability and robust stability is therefore highly desirable. To build new and improved material properties, the [materials scientists](#) must therefore explore previously unidentified [combinatorial materials](#) and rationally design device configurations to invent high-performance actuators.

MXene ( $\text{Ti}_3\text{C}_2\text{T}_x$ ) used in the present work belongs to a new family of liquid-crystalline, [two-dimensional \(2-D\) metal carbides](#) with excellent [electrical conductivity](#), [thermal conductivity](#) and [photothermal conversion](#) to form multiresponsive and potentially high performance actuators. Only a single example currently exists of the [use of MXene as an electrochemical actuator](#). In the present work, therefore, Cai et al. aimed at using MXene as a multiresponsive soft actuator to explore leaf-inspired, sophisticated architecture for simple actuation, coupled with synergistic functional components.

Inspired by the biological architecture and [photosynthetic mechanism of a natural leaf](#), Cai et al. designed an asymmetric, bilayered soft actuator using single-crystal, 2-D MXene nanosheets to harvest electric or light



energy for conversion into thermal energy. For this, they used biocompatible, cellulose nanofibers to form the vein skeleton for rapid leaf-like shape changes alongside polycarbonate (PC) filter membranes to form the [stomata](#) and epidermis for water insertion and extraction to or from the MXene-cellulose composites (MXCC). The scientists confirmed the increased absorption of water in MXCC due to the presence of cellulose using [Fourier Transform Infrared](#) (FTIR) spectra. Using [selected area electron diffraction](#) (SAED) patterns, they detected the presence of MXene as a hexagonal structure and single crystallinity without defects at the nanometer scale.

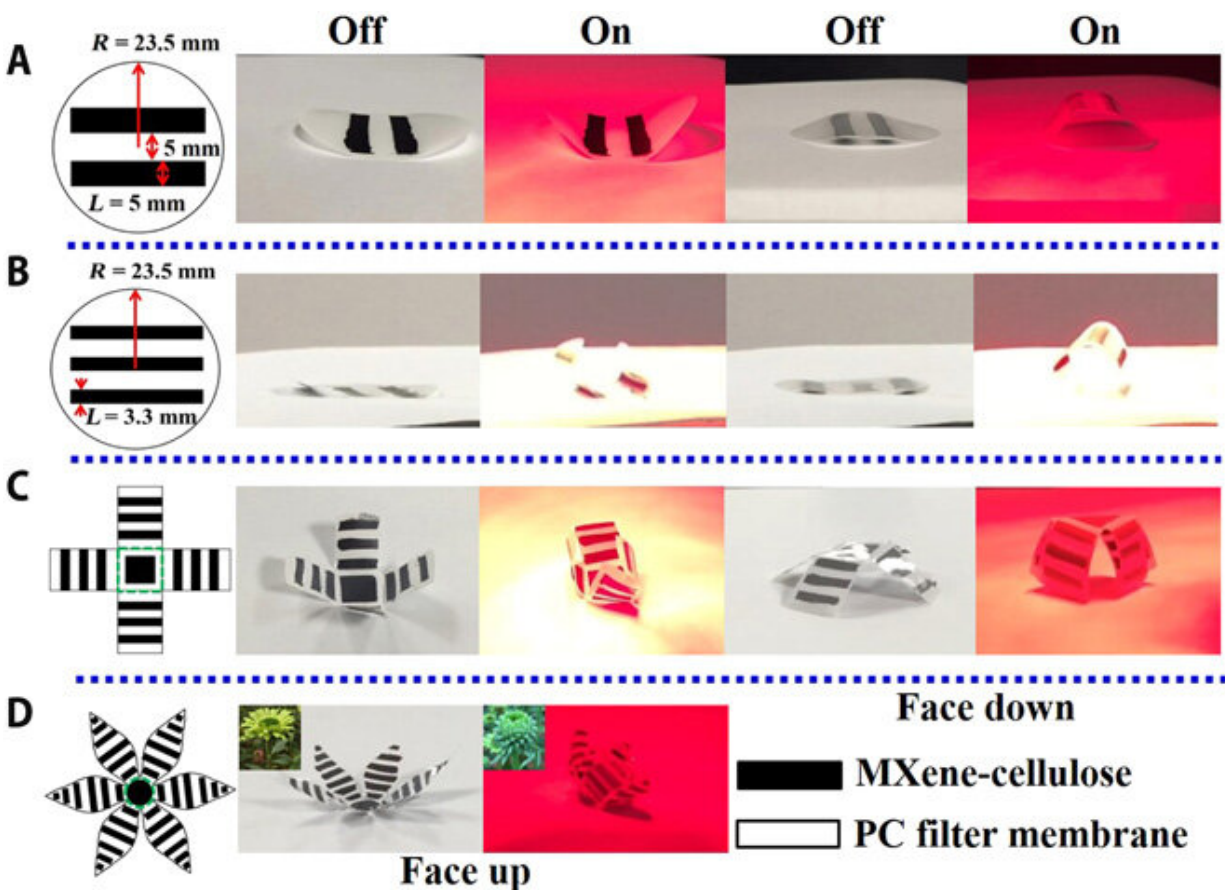


A real-time digital camera video of the MXCC/PC bilayer-structured actuator upon sequential on/off NIR light irradiation. Credit: Science Advances, doi: 10.1126/sciadv.aaw7956

The soft actuator maintained a flat and unwrinkled form under ambient conditions with relative humidity, while bending in response to increasing/decreasing humidity in the environment, which Cai et al. quantitatively analyzed. They noted excellent actuator performance and controllable bending angles in a variety of humidity levels. The scientists next investigated the electrical actuation of the device by connecting an MXene-cellulose strip to two copper wires. The bending angle almost linearly decreased with increasing electrical power, while the soft actuator only required a low voltage to achieve extreme actuation. Compared to humidity-based actuation, the scientists achieved larger bending angles with electrothermal actuation.

The scientists also recorded temperature variation and binding angles of soft actuators using near infrared (NIR) light irradiation. They observed remarkable synergistic actuation motion of the MXene/cellulose composite material, in contrast to poor actuation performance of the individual components. Based on the observed optical absorption, photothermal conversion and electrochemical actuation, Cai et al anticipate the use of these composite smart soft actuators in photo-responsive functions.

Cai et al. further investigated the photoinduced mechanical forces of the material under NIR light irradiation on a mechanical analyzer. The actuation process of MXCC/PC was rapid and reversible. The scientists studied the structural changes of the MXCC/PC and MXene/PC actuators under different intensities of illumination using [X-ray diffraction](#) (XRD) measurements to show amorphous character of cellulose and PC membrane. They investigated the mechanical behavior using [finite element modelling methods](#) (FEM) to further understand the actuation process of the composite material. The modeling results agreed with the experimental outcomes in the study.



Representative programmable motions for the MXCC/PC bilayer-structured actuator. (A) Double folding U-shape actuator. (B) Trefoil arch-shaped actuator. (C) Self-folding box. (D) Self-blooming flower. Green dashed lines in (C) and (D) (left diagram drawing) are the slight creases created on the bottom of the box and flower to make the self-folding box and self-blooming flower work well under NIR irradiation. (Photo credit: Guofa Cai, Nanyang Technological University.) Credit: Science Advances, doi: 10.1126/sciadv.aaw7956

To demonstrate programmable actuation behavior, the scientists developed a series of sophisticated configurations. Including a double folding U-shaped actuator, trefoil arch-shaped actuator and self-blooming flower where the petals opened and bloomed before NIR irradiation to close rapidly on exposure to NIR. Additionally, the

scientists explored a variety of smart devices such as worm-like robots, smart switches, an encryption device as well as IR dynamic display and camouflage to extend the primary concept. Furthermore, Cai et al. constructed a smart switch by patterning cross-shaped MXCC on the PC membrane, which they controlled using wireless NIR light. Based on the principles, the scientists also formed an open electrical circuit to switch on/off a smart watch using NIR light.

For data encryption, based on the programmable MXene-cellulose ink, Cai et al. engineered a desired pattern and conveyed the information by local heating using NIR light or electricity. The information was only readable using IR and invisible to the human eye, providing better suited information encryption beyond machine readable barcodes and QR codes. The ability to integrate diverse functionalities into one system to achieve camouflage, display and [actuation](#) is important and useful in multiple disciplines. These devices confirmed the possibility of using MXCC/PC membranes to serve multiple functions in smart soft systems including information encryption, camouflage and thermo-responsive behavior.





A real-time digital camera video of smart switch upon sequential on/off NIR light irradiation. Credit: Science Advances, doi: 10.1126/sciadv.aaw7956

The new composite materials, rational design and low-cost fabrication introduced in the study, alongside synthetic strategies implemented by the scientists, will make the MXCC/PC membrane systems accessible for broad scientific and engineering fields. In this way, Guofa Cai and co-workers developed and established a new class of multiresponsive materials and devices with unprecedented integration of multiple properties inspired by multifunctional biological structures.

The MXCC/PC membrane systems mimicked crucial features of a natural leaf from the microstructure to photosynthetic capabilities, which included energy-harvesting and conversion. The bilayer actuators showed strong features, similar to state-of-the-art multiresponsive actuators. The explored materials and advanced systems can be further developed to

establish novel possibilities for revolutionary technologies in the fields of soft robotics, information encryption and IR dynamic display.

**More information:** Guofa Cai et al. Leaf-inspired multiresponsive MXene-based actuator for programmable smart devices, *Science Advances* (2019). [DOI: 10.1126/sciadv.aaw7956](https://doi.org/10.1126/sciadv.aaw7956)

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