Tailoring Flexible Arrays for Artificial Cilia Actuators

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Artificial cilia actuators are described as responsive and actutable cilia-structured arrays that are mainly made of flexible polymers. Over the past few decades, researchers have investigated the features and functions of cilia in nature, and have developed a vast number of bio-mimicked cilia based on these findings. Nowadays, great progresses are accomplished, including the optimization of the fabrication methods, the increase in the actuation approaches, and the promotion of the application fields. Artificial cilia are tailored to react to magnetics, electrics, light, acoustics, heat, or even multi-stimulus, and are endowed with abilities of moving, sensing, carrying cargos, transporting, etc. These achievements create a great leap for artificial cilia actuators being applied in a huge scope of forefront fields, such as digital microfluidics, organ-on-chip systems, precision medicine, wearable electro-devices, minimal robots, artificial intelligence, and so on.

1. Introduction

Soft actuators refer to active devices made of flexible or compliant materials which can respond to and be motivated by external triggers such as magnetic fields, electric fields, acoustic waves, light fields, chemical reagents, and so on.[13–17] Recent years have witnessed the rapid development of soft actuators. Thanks to the great endeavors ever paid to this field, a large variety of smart soft actuators with multiple actuation mechanisms and diverse structures, including film-shaped, tube-shaped, cilia-shaped, etc., have been designed and fabricated,[4–7] playing an increasingly important role in electronics,[8] robotics engineering,[9] artificial intelligence,[10] fluid manipulation,[11] biomedicine,[12] and life science.[13] Among these intriguing soft actuators, the artificial cilia actuator, which is composed of a cilia-like array, is a representative example. Such artificial cilia can be fabricated through numerous strategies, from top-down approaches such as FES and template replication[14–17] to bottom-up ones such as self-assembly.[18–20] These fabricated artificial cilia not only exhibit high flexibility, sensitivity, tailorability, and controllability but also can be simultaneously imparted with various functions after specific modification.

To better tailor the artificial cilia and to further improve their performances in complicated and changeable environments, researchers seek inspirations from nature. Cilia are ubiquitous in nature and can be found in a wide range of species including microbiome, plant stems, fish skins, legs of insects, and airways of mammals.[21–23] These natural cilia have been reported to exhibit the functions of guiding movements, sensing ambient environments, clearing foreign matters, etc. By mimicking and recapitulating the natural cilia, scientists have developed swimming cilia robots, multi-legged cilia carpets, micropillar sensors, slippery cilia surfaces, and other artificial cilia actuators.[24–26] In addition, to achieve the intelligent manipulation and remote control, different single-factor or multi-factor actuation methods of the artificial cilia have also been investigated.[27–29] To date, these artificial cilia have found applications in a wide spectrum of fields, including microfluidics, droplet manipulation, flexible electronics, and soft robots.[30–32]

In this review, we present the recent progress on the tailoring and applications of the artificial cilia actuators. Different from existing reviews in this field which only involve artificial cilia in some sections, this review provides a profound, comprehensive, and exclusive summary of artificial cilia actuators for the first time. We first introduce some typical examples of natural cilia, their properties and functions, as well as the bionic cilia derived from them. We then summarize the actuation mechanisms of the artificial cilia, and emphasize the magnetically actuated artificial cilia and multi-responsive artificial cilia in particular. In the following section, we discuss the applications of artificial cilia in fluid and droplet manipulation, including droplet transport, wettability regulation, and microfluidic chip constructions. Their roles as sensors or robots for detection, diagnosis, disease treatment, and engineering are also covered. Finally, we present a general summary and some critical thinking about the current challenges and future trends in the artificial cilia actuators.

2. Cilia: From Nature to Artificiality

Cilia are generally regarded as hair-like or rod-like projections on cells or organisms with sizes ranging from nanometers to...
millimeters.\textsuperscript{[21]} Motile cilia, such as human airway epithelial cilia, reef coral cilia, and \textit{Paramecium} flagella, can regularly beat in various patterns, enabling the removal of foreign bodies, feeding, self-propulsion, and so on.\textsuperscript{[22,23,31]} As for nonmotile cilia, they play an important part in chemical sensation, environment adaptation, and signal transduction by functioning as sensory organs to constantly monitor the ambience.\textsuperscript{[34]} Typical examples of nonmotile cilia include the cilia on the legs of spiders, those at the fish lateral lines, etc. Due to their marvelous features and functions, researchers have been trying to introduce the structures and properties of the natural cilia to people’s production and life. Thus, a series of artificial cilia have been fabricated by template-based or template-free methods for transporting, sensing, and moving.\textsuperscript{[35–37]}

2.1. Cilia for Transport

The metachronal beating of natural cilia can generate vigorous flows, thus offering the driving force and effectively facilitating mass transport.\textsuperscript{[18]} Shapiro and co-workers have studied the ciliary flows created by reef corals and their abilities on cargo transport.\textsuperscript{[19]} With the help of flow-field imaging together with mathematical simulation, it was found that the intense flows produced by the rhythmical asymmetric beating of coral cilia could stir a 2-mm deep water layer adjacent to the coral surface. Such vortical flows allowed corals to actively transport cargos such as oxygen and nutrients rather than passively relying on environmental streams. In addition, a large number of cilia are located on the lumen of the respiratory tract, which swing in a coordinating and orientational manner to push respiratory secretions and foreign particulate matters toward the oropharynx, thus removing the inhaled dust and bacteria.\textsuperscript{[40]}

By mimicking the structures and movement patterns of natural cilia, researchers have generated various kinds of artificial cilia with mass transport abilities and have applied them in anti-biofouling, self-cleaning, droplet management, etc.\textsuperscript{[41,42]} For example, bionic human pulmonary cilia composed of cobalt magnetic particles and polydimethylsiloxane (PDMS) has been prepared by a template replication method recently, as shown in Figure 1a.\textsuperscript{[40]} Due to the magnetic cobalt magnetic particles and the flexible PDMS, such artificial cilia could rapidly respond to external magnetic fields and rhythmically bend like pulmonary cilia under a periodic alternating field. It was demonstrated that these artificial cilia could directionally and continuously transport silica microspheres underwater. In addition, by changing the beating frequency, the separation distance, and the height of the cilia, the transport speed of the microsphere could be precisely adjusted. These results indicated that the bionic human pulmonary cilia could arouse inspirations in building a general and efficient micromanipulation system.

2.2. Cilia for Sensing

Another important function of natural cilia is sensing, which enables organisms to quickly react to environmental changes, hunt for food, and defend against the predators and thus help them survive in the cruel natural selection. Sensory cilia are ubiquitous in nature and can be found from cricket cerci, spider tarsi, and fish lateral line systems to bat hearing systems and even human respiratory tracts.\textsuperscript{[43]} Take spider tarsi as an example.\textsuperscript{[44]} The air flow or external vibration first causes the mechanical bending of the sensory cilia (Figure 1b). Such mechanical signals will then be translated to electrical impulses across the cells located at the cilium base and finally be acquired by spiders. In addition, it has been found that some of the respiratory epithelium cilia can act as chemosensors.\textsuperscript{[45]} Specifically, bitter compounds can be recognized by the bitter taste receptors, and thus lead to the increase in the intracellular Ca\textsuperscript{2+} concentration and high-frequency cilial beat.

The sensing principle of artificial cilia sensors is similar to that of natural sensory cilia. A typical cilia sensor is mainly composed of two parts: the sensitive cilia part and the signal conversion part.\textsuperscript{[46]} The cilia part will deform or bend against touching, air flow, or water flow stimuli; while the signal conversion part, containing sensing materials such as silver nanowires, carbon nanotubes, can transform the mechanical signals of the cilia into electrical signals based on piezoresistive effects, piezoelectric effects, and so on. For instance, Pei and co-workers used a 3D printing and casting method to fabricate tactile sensors with flexible PDMS as the material of the cilia part and graphene nanoplatelets as the piezoresistive sensing material of the signal conversion part, as shown in Figure 1c.\textsuperscript{[47]} These sensors were found to be very sensitive to both tactile and flow stimuli, showing a detection limit as low as 12 \(\mu\)m in detecting oscillating tactility and 58 mm s\(^{-1}\) in detecting oscillatory flow in water.

2.3. Cilia for Movement

Beating cilia can also provide propulsion forces to facilitate the locomotion of various species, including Chlamydomonas, paramecia, placozoa, sponge larvae, starfish larvae, ctenophore, and so on.\textsuperscript{[48–50]} To investigate the propelling mechanisms of natural cilia, both quantitative experiments and modeling have been used and the complex vortex patterns produced by the cilia could be visualized (Figure 1d).\textsuperscript{[51]} In addition, it is suggested to use noisy, nonlinear oscillation models under chemical, mechanical, and hydrodynamical factors to simulate beating dynamics of single cilium.\textsuperscript{[52]} Meanwhile, by establishing coupled oscillator models, the transient synchronization and desynchronization of a group of cilia could be well studied. Research results have revealed that the spatial distribution of beating cilia on organisms could be dense tufts, curved bands, amorphous sheets, or closed surfaces. It has also been found that the synchronous locomotion mode of cilia might be indispensable in swimming and navigation of micro-organisms. In addition, some larger organisms such as insects have cilia carpets, which are composed of densely arranged cilia and can promote crawling or walking movements.

These cilia-driven organisms shed light on the invention of smart moving robots. The key point in this area is how to highly mimic the locomotion modes of natural cilia so as to effectively actuate the robots. To achieve this goal, Palagi et al. prepared a self-propelled microrobot that relied on embedded electroactive materials rather than external stimuli for actuation.\textsuperscript{[53]} It was also demonstrated that these microrobots could generate metachronal wave, similar to the natural cilia of paramecia. In another study, Sitti and co-workers utilized a shape-programming method and realized the automatic generation of required magnetization
profiles and actuating fields for every small-scale soft matter. Based on this technique, they further fabricated artificial cilia with time-varying shapes and satisfactory beating rhythms (Figure 1e). The researchers further presented jellyfish-like swimming robots as well as spermatozoid-like undulating moving robots based on their new producing and actuating stratagem.

2.4. Fabrication Methods for Artificial Cilia

2.4.1. Template-Based Fabrication

In general, a template-based fabrication method contains the following steps. First, a cilia-like master structure is prepared via 3D printing, etching, ablation, and other micromachining techniques, which is then used to fabricate the template. By casting moldable polymers or elastomers over the master structure and detaching them after molding, the template with complementary structures to the master structure can be obtained. Finally, the polymer of the cilia material is filled into the template through centrifugation or vacuum treatment, and the desired artificial cilia can be peeled off after solidification. Notably, it will be difficult to demold the artificial cilia if they are extremely long and thin. In this case, the template will be sacrificed by approaches such as corroding and dissolving during the demolding process.

2.4.2. Template-Free Fabrication

Template-free approaches and template-based approaches have their own merits and drawbacks. In comparison to template-based
methods, template-free methods are unrestricted and flexible, with simplified procedures and easier operations; while their uniformity is less satisfactory than template-based ones. Field effect spinning (FES) is a recently proposed strategy for template-free artificial cilia fabrication.[57] To be specific, the FES unit contained two parts: a brass substrate at the bottom and an array of nickel needles at the top, which faced each other. A thin layer of prepolymer was coated on the brass substrate. At the initial state, the tips of nickel needles just contacted with the prepolymer layer. Then as the needles vertically moved up, an electric field was applied between the needles and the substrate. The needles stopped after a certain distance, which determined the heights of the cilia. The electric field was continuously applied until solvent vaporization and artificial cilia solidification.

Magnetic field-guided assembly is another common template-free approach, which is specifically applicable to magnetically responsive artificial cilia. For example, Shen and co-workers evenly distributed the mixture of PDMS, hexane, and magnetic nanoparticles on a plate via spin coating.[26] A strong magnet was then placed beneath the plate. Influenced by the magnetic field, the magnetic particles would assemble and form cilia-shaped structures on the mixture film. In addition to magnetic nanoparticles, micro-sized magnetic particles can also form cilia under the guidance of magnetic fields. For example, den Toonder et al. assembled 2.7 μm magnetic beads into chains in the presence of external magnetic fields, and used polymer shells to stabilize the magnetic beads and anchored them to the substrate.[74]

3. Actuating Strategies for Artificial Cilia

Magnetic actuation is one of the most common approaches to control the movement of cilia.[57,58] The outstanding advantages of magnetic actuation include remote manipulation, precise control, and relative facile operation. In addition, there are a number of methods for fabricating magnetically responsive cilia (e.g., template replication, magnetically induced molding, magnetic self-assembly, etc.) and numerous magnetic materials to choose from (e.g., magnetic nanoparticles, ferromagnetic microparticles, etc.). To further diversify the artificial cilia and broaden their applications, many other actuation approaches are also developed, such as electric stimulation,[59] light,[60] acoustic actuation,[61] temperature control,[62] pH,[63] and so on.[64,65] Moreover, artificial cilia that can be simultaneously driven by more than one stimuli have emerged in recent years, which makes these cilia more functional and able to perform more complicated tasks.[66] A selective summary of different actuation strategies, their mechanisms, and corresponding applications are given in Table 1.

3.1. Magnetic Actuation

In general, magnetic cilia contain two important components.[67] The first is magnetic particles, which impart the cilia with the capacity to respond to magnetic fields. Pure iron, ferric oxide, ferroferric oxide, nickel, cobalt, etc., are all satisfactory candidates for magnetic particles. The other is the matrix material, which should be both flexible enough to be easily deformed and tenacious enough to keep integrity. Commonly-used matrix materials include PDMS, polyurethane (PU), polystyrene (PS), polymethyl methacrylate (PMMA), epoxy, and so on. To date, researchers have not only developed magnetic cilia that can swing in high frequency[68] or produce metachronal waves[69] but also realized the specific programming of magnetic orientations of each cilium and formed special patterned cilia arrays.[27] In addition, by assembling magnetic colloidal particles, reversible magnetic cilia can also be generated.[70]

Table 1. Actuation strategies for artificial cilia.

| Strategy       | Mechanism                        | Material                      | Application                                                                 | Ref               |
|----------------|----------------------------------|-------------------------------|-----------------------------------------------------------------------------|-------------------|
| Magnetism      | Magnetic field-induced attraction and repulsion | Elastomer/hydrogel and magnetic particles | Transporting, moving, sensing                                               | [55,56,71-74]    |
| Electricity    | Electric field-induced polarization of dielectric particles | Elastomers and electroresponsive dielectric particles | Transporting, moving, sensing                                               | [75,76]          |
| Light          | Light-induced trans-isomerization of molecules | LCE                            | Flow creating and mixing, lab-on-a-chip applications, microrobots           | [77-80]          |
| Acoustics      | Acoustic pulse-induced driving force in liquid environments | Flexible polymer              | Biological or chemical analysis, engineering                                | [61]             |
| Temperature    | Heat-induced phase transition     | SMP                            | Tunable wettability, liquid/droplet manipulation, chemical engineering     | [62]             |
| pH             | pH-induced volume-phase transition | Hydrogels composed of weakly ionizing monomers and acrylamide | Microfluidics, environmental sensing                                      | [63]             |
| Gas            | Pneumatically-induced pressure difference | Silicone rubber              | Fluid manipulation, microfluidics                                           | [64]             |
| Capillary Force| Capillarity-induced self-assembly | Silicon composite gel         | Material fabrication, optical devices                                       | [65]             |
and species of the embedded magnetic particles, the sizes and materials of the cilia, etc. Thus, by altering these parameters, the speed as well as the amplitude of the movements can be flexibly adjusted.

3.1.2. Metachronal Motion

Metachronal motion is a usual beating pattern of natural cilia, which results from the phase differences among neighboring beating cilia and appears as propagating waves. It has been found that compared to synchronous motion, metachronal motion increases the propulsion rate and can create unidirectional pumping in an energy-efficient way. To generate such metachronal motion, Alexeev and co-workers fabricated an array of magnetic cilia with different lengths and made use of a uniform rotating magnetic field, as shown in Figure 2a. Results showed that the magnetic numbers of the cilia could be affected by the cilia lengths. As a result, magnetic cilia with varying lengths had different beating cycles under the uniform magnetic field and would produce metachronal waves. It was further known that cilia thicknesses also influenced the magnetic numbers, and thus it was anticipated that an array of cilia with a thickness gradient could also yield a similar metachronal locomotion.

3.1.3. Magnetic Programming

A general programming strategy for designing magnetic orientation patterns of cilia arrays is selectively and step-by-step curing specific cilia under different magnetic directions. For example, a heterogeneous cilia array was prepared via a photomask-guided template-casting approach. In this case, poly(urethane acrylate) (PUA) was set as the matrix material and silica-coated iron oxide nanoparticles (Fe₃O₄@SiO₂) were the embedded magnetic particles. To fabricate this cilia array, PUA/Fe₃O₄@SiO₂ pre-solution was first filled into the cavities of a silicon template and then placed under a vertical magnetic field gradient.
Due to their high-aspect-ratio structure, magnetic cilia are prone to be contaminated, and therefore must be fabricated in a clean environment. In addition, traditional template-casting approach involves repeated template replication, which consumes a lot of time and may break the viminaline cilia. To solve these problems, the approach based on self-assembly of superparamagnetic colloid particles has been put forward. Previous report showed that superparamagnetic colloid particles would self-assemble into lines and form the backbone of magnetic cilia in the presence of proper magnetic fields, as shown in Figure 2e. Meanwhile, polymer particles in the same solution would bond to the surface of the backbone via electrostatic interaction, linking the superparamagnetic colloid particles, forming the outer shell of magnetic cilia, and anchoring to the substrate. These resultant magnetic cilia were demonstrated to perform a net flow rate of 3 mm/s when the actuation frequency was 5 Hz.

3.2. Other Actuation Factors

3.2.1. Electric Stimulation

Electric stimulation is another approach to remotely and precisely control artificial cilia. For example, artificial cilia composed of dielectric elastomer has been presented, which could deform when exposed to an alternating-current (AC) electric field. The matrix material of such cilia was PDMS and electro-sensitive barium titanate (BaTiO₃) nanoparticles were embedded inside. The mechanism of electric actuation of these cilia was proposed to be dielectrophoretic effects, as shown in Figure 3a. To be specific, the applied AC electric field could polarize BaTiO₃ nanoparticles and enforce them to closely align along the electric field direction. As a result, the mutual interaction between the nanoparticles were strengthened, leading to the electro-responsive deformation of the artificial cilia. In addition to the electric-actuated movement, electric-responsive cilia may also serve as sensors by turning external signals into electrical impulses based on piezoelectric effects, triboelectric effects, and so on.

3.2.2. Light

Liquid crystal elastomers (LCEs) are generally defined as mesogenic-unite-containing cross-linked polymer networks that exhibit both the self-organization property of mesogenic unites and the flexibility and elasticity of polymer networks. Nowadays, LCEs have become common candidates for fabricating photo-responsive artificial cilia. UV light-actuated artificial cilia have already been prepared in recent years. LCE cilia functionalized with photosensitive molecules such as diarylethene, azobenzene, and so on, have the ability to bend toward the incident UV light, and thus they can be used to carry objects in a light-controlled manner or act as soft robots. Remarkably, artificial cilia that can respond to diverse wavelengths varying from UV to visible light with multiple response modes have also been developed. The basic design idea is to integrate LCE-containing photosensitive molecules with different absorption peaks for the trans state together. For example, van Oosten et al. chose two azobenzene dyes, A3MA (absorption peak: 358 nm) and DR1A (absorption peak: 490 nm), and connected A3MA LCE and DR1A LCE to form the artificial cilia. Without light, the artificial cilia relaxed and stayed in the initial state (Figure 3b,c). However, when the visible light turned on, the red DR1A LCE part bent toward the light source. With only the UV irradiation, the yellow A3MA LCE part deformed correspondingly. In addition, by applying the visible light and the UV light simultaneously, the whole part of the cilia bent into the light, indicating a complete and strong response.

3.2.3. Acoustic Actuation

Acousto-actuated artificial cilia can be integrated with microfluidic systems. The advantages of acoustic actuation include low cost, handy procedures, and simplified setups. In a typical example, a cilia array was polymerized in situ inside a microfluidic channel with one end fixed to the glass channel substrate and the other end free. A simple piezo transducer was used to generate acoustic fields for actuating these cilia. Under these acoustic pulses, the artificial cilia would swing dramatically and perform a waveform within the microchannel that was strong enough to mix two different solutions. It was found that by using acoustic pulses with 20 to 140 VPP amplitude and a 4.6 kHz frequency, these artificial cilia displayed an oscillatory motion and their maximal deflection magnitude was about 55 μm.

3.2.4. Temperature

Based on shape-memory polymers (SMP), researchers have presented thermo responsive artificial cilia whose shapes will change at different temperatures. For instance, Yong and co-workers used a laser ablation method to fabricate thermo responsive micropillar arrays from epoxy-based SMP films. The glass transition temperature of such SMP films was found to be around 55 °C, meaning that they would become soft and easily deformed under the temperature higher than 55 °C.
Taking advantage of this property, the micropillar array was first bent and deformed by applying an external force at the temperature of 80 °C; this twisted shape was memorized and maintained after the micropillar array cooled down. Notably, once heated up again, the micropillar array would restore to its original shape. Thus, by switching between 55 and 80 °C, the micropillar array could constantly bend and recover, making possible droplet transportation and other applications.

3.2.5. pH

It has been reported that hydrogels composed of weakly ionizing monomers (e.g., acrylic acid (AAC), vinlypyridine, and maleic acid) and acrylamide (AA) are sensitive to the ambient pH[63]. Take the poly(AAC-co-AAm) hydrogel as an example. The hydrogel swells at pH > 4.25, because the ionized AAC brings about the increased osmotic pressure and causes the water to infiltrate into
the hydrogel (Figure 3d). Comparatively, at pH < 4.25, AAc is protonated, decreasing the osmotic pressure, expelling the water inside the hydrogel, and ultimately contracting the hydrogel. By using this pH-responsive poly(AAc-co-AAm) hydrogel as the “muscle”, epoxy artificial cilia, the “skeleton”, can be actuated in response to pH changes. Specifically, in an acidic environment, the poly(AAc-co-AAm) hydrogel contracts, which strains the cilia and drags them to bend; while, in an alkaline environment, the cilia recover to their original straight configuration as the swollen hydrogel eliminates the high strain.

3.2.6. Gas

Gas actuation is commonly used in large-sized mechanical equipment due to its convenient operation and low cost. To miniaturize the pneumatically actuated devices and apply them to artificial cilia, Gorissen et al. designed a hollow structured cilia system. These pneumatically actuated artificial cilia have an asymmetric cavity with one end sealed.[84] Due to such a structure, the pressure from the gas inlet causes the flexible cilia to deform asymmetrically and bend down. The most outstanding attribute of such pneumatically actuated cilia is that each cilium can be controlled undisturbedly and independently, which enables more complicated manipulation forms. In addition, these artificial cilia can be applied to flow direction control, fluid pumping, mixing, and many other applications when they are introduced into a microfluidic system.

3.2.7. Capillary Force

Capillary force during solvent evaporation can lead to the self-assembly behavior of adjacent artificial cilia, providing a facile strategy to fabricate chiral structures. For this purpose, Hu et al. first printed the micropillar array with specific geometry and spatial location via a laser printing approach and immersed it in liquid (Figure 3e).[85] As the liquid gradually evaporated, a meniscus was formed between the liquid and the micropillar, and capillary force was generated to deform the micropillars. It was found that cylinder-shaped micropillars in a square array would finally assemble into a symmetric pattern and prism-shaped ones would form a chiral assembly. Notably, by changing the amount of micropillars in the array, different types of assemblies, such as the 6-pillar and 12-pillar chiral assemblies, could be facilely fabricated.

3.3. Multi-Responsive Artificial Cilia

Biological organisms depend on sensitive, rapid, synchronous responses to multiple stimuli in the environment to ensure their survival in the fierce natural competition. Similarly, the ability to respond to various stimuli imparts the artificial cilia with richer locomotion patterns, more universal application places, and more advanced functions.[86] Therefore, the development of multi-responsive artificial cilia has been attracting increasing attention. For example, Mendes and co-workers have fabricated pH/magneto/electro-triple-responsive artificial cilia, which consisted of magnetic nanoparticles and electro-responsive gel matrix that could swell or shrink at different pH environments.[82] One application of these triple-actuated cilia was to detect the local pH, as their response time would change when the pH values were different. In addition, these cilia were also promising in creating new-generation bio-mimicking moving robots.

Most recently, a magneto/photo-double-responsive artificial cilia array was fabricated.[29] Made from PDMS and CrO2 particles, these cilia could not only swing in a large area under the guidance of a magnetic field, but also be locally actuated by a targeted laser light illumination. There were basically three locomotion modes of the cilia. The flexibility of PDMS and the magnetism of CrO2 particles made all the cilia bend in the same direction when an external magnetic field was applied, which was the first locomotion mode. The second mode was the slight deformation of the local cilia exposed directly to the laser light because of the high light-absorption capacity of CrO2 particles and the satisfactory thermal expansion of PDMS. The third mode was the local, large displacement using the combination of magnetic fields and laser light, which could be explained by the demagnetization of CrO2-doped cilia resulting from the high temperature.

4. Artificial Cilia for Particle and Fluid Manipulation

Droplet plus fluid manipulation is playing a significant role in a large variety of fields, including material processing, chemical analysis, biomedical applications, and environmental science. Attributed to their flexibility, controllability, as well as the ability for further modification, artificial cilia are regarded as the ideal candidate for droplet/fluid manipulation.[83] To improve the droplet/fluid manipulation capacity, these cilia often undergo the hydrophobic or hydrophilic treatment, or are imparted with specially designed structures.[84,85] Nowadays, artificial cilia have been reported to directionally and controllably transport water droplets, oil droplets, and even viscous or polymer particles.[86–88] In addition, those swinging cilia can also be integrated into microfluidic systems,[89] thus generating flows of different forms in the microfluidic channels for pumping,[90,91] fluid mixing,[92] and even the establishment of organs-on-chips.[93]

4.1. Single Droplet/Particle Manipulation

4.1.1. Water Droplets

To realize successful manipulation of water droplet via artificial cilia, plenty of strategies have been put forward, such as attaching silicon scales to the top of the cilia,[85] shifting the water adhesion through the mechanical property transition of the cilia,[86] etc. The usage of slippery liquid-infused porous surfaces is also an emerging strategy raised in recent years. For example, PDMS containing carbonyl iron particles was made into the artificial cilia, which then underwent oxygen plasma and nanoparticle deposition treatment to form a hierarchical nanostructure.[94] Finally, lubricant was applied to cover the surface of the cilia and some would infiltrate into the nanostructures. It was observed that under an upward magnetic field, these cilia would
vertically orient and only allow water droplets to touch the hydrophobic tips, thus behaving in a superhydrophobic way. In contrast, when the magnetic field was tilted, these cilia would lay down to generate a slippery lubricant-infused surface so that water droplets could easily slip down. Through this approach, the pinning and removal of water droplets could be facilely realized (Figure 4a). In the same year, Jiang and co-workers also presented slippery lubricant-infused cilia for smart water-droplet transportation.[95] They found that with the tilt angle of cilia within a certain scope, water droplets were pinned along the cilia tilt direction but could quickly slide down in the opposite direction. Notably, such a phenomenon was most striking when the tilt angle was around 60°. Thus, by changing the magnetic direction to tune the tilt direction of the cilia, omnidirectional and controllable water droplet delivery was achieved (Figure 4b).

In general, a uniform field is used to actuate the artificial cilia for water-droplet manipulation. However, a double-magnet-composed junction has been used recently to transport a single water droplet or multiple droplets together along the predesigned complicated anisotropic orbits, as shown in Figure 4c.[96] The magnet junction provided a moving unidirectional wave during its movement, driving the carried water droplet to move in the same direction. The water droplet was found to move forth and back along a straight orbit or a circular arc orbit under the guidance of the magnet junction (Figure 4d). In addition, two nearby droplets could be transported in parallel without touching each other and different droplets on the same orbit could merge, indicating the precise control. It was noted that the presented cilia could stably transport the droplet along a horizontal trajectory on an inclined surface with the inclination angle as large as 10°, demonstrating the anti-gravity active water-droplet transport capacity of these cilia.

4.1.2. Oil Droplets

In addition to water-droplet manipulation, efficient control of oil droplets in air or under water is attracting wide attention due to

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**Figure 4.** Artificial cilia for water droplet manipulation. a) Pinning and sliding of water droplets on switchable lubricant-infused nanostructured magnetic cilia. Reproduced with permission.[94] Copyright 2016, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. b) Water transport along eight different directions by slippery lubricant-infused cilia. Reproduced with permission.[95] Copyright 2017, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. c) Scheme and optical image of artificial cilia actuated via a double-magnet-composed junction. d) Different locomotion modes of water droplets: (i) reciprocating of a single droplet; (ii) parallel moving of two adjacent droplets; (iii) merging of droplets on the same orbit; (iv) moving along an arc orbit; (v) horizontal moving on an inclined surface. Reproduced with permission.[96] Copyright 2020, American Chemical Society.
its significance in environmental protection, energy resource engineering, chemical production, and many other fields. Similar to manipulating water droplets, there are basically two approaches for oil-droplet manipulation via artificial cilia. One is to adjust the wettability by switching cilia between the erect state and the bent state. The other is to propel droplets based on the continually moving local deformation of the cilia array. For instance, Zhang and co-workers made use of the first approach and fabricated a magnetically responsive mushroom-headed cilia array.[97] It was found that oil droplets could freely slide on the mushroom-like heads of upright cilia, while would be pinned to the surface made by magnetic-field-induced curved cilia (Figure 5a). In addition, by stretching and relaxing such cilia arrays to change the contact points with oil droplets, researchers could capture an oil droplet, transfer it, and release it on another substrate, as shown in Figure 5b. In addition, Jiang and co-workers used the second approach and realized both the rolling and the pinning of oil droplets on superhydrophobic modified magnetic cilia (Figure 5c).[87]

4.1.3. Viscous/Polymer Particles

The propulsion of viscous or polymer particles rely on the swinging of artificial cilia. Specifically speaking, the rhythmic wave form vibration makes the particle subject to a forward net force, thus driving the particle to move continually and directionally along a predetermined track.[98] Recently, Onck and co-workers actuated artificial cilia with a rotating magnet system to transport polylactic acid (PLA) particles in multiple designated directions. [88] As shown in Figure 5d, during this transport process, the PLA particle would first move with the tips of the bent cilia. This locomotion resulted from the coaction of the pulling forces provided by the anterior cilia and the pushing forces brought by the posterior ones. As the cilia further deformed, the contact area of the PLA particle and the anterior cilia increased and the net force separated the particle from the posterior cilia. The cilia then rotated under the guidance of magnetic fields, making the particle deviate from its original track and twisting themselves in the meanwhile. Eventually, the cilia recovered to their original alignment, which led to a small net forward movement of the particle. By repeating such cycles, the PLA particle could transfer from cilia to cilia along a straight line, a zigzag, or other shaped paths (Figure 5e,f).

4.2. Fluid Manipulation

The swinging motion of cilia can disturb fluids and generate flows, and such locomotion patterns are highly changeable under different external stimuli.[99-101] Due to these features, scientists have introduced cilia-mimicked structures into microfluidic systems for the development of novel microfluidic platforms with enhanced functions to better manipulate the fluids. In general, cilia in such platforms have one end fixed to a certain region of the microfluidic channel and the other end free.[102] To further improve these platforms, fundamental investigations on the parameters that will influence the motion of cilia in microchannels are of necessity. For this purpose, Wang et al. created magnetic artificial cilia directly in the channel of a closed-loop microfluidic device using a technique named magnetic fiber drawing.[103] It was found that the density of the cilia, the frequency of the external actuation, as well as the viscosity of the media were critical factors that determined the flow velocity generated by the cilia. In addition, Liu and co-workers established simulation models to systematically analyze the forces exerted on the cilia, the resultant movements, and produced flow waves.[104] In addition, Superfine and co-workers combined the experimental results and the mathematic models, which not only successfully illustrated the flow types of their cilia arrays but also explained the velocity flow profiles of embryonic nodes.[105]

Although much progress has been made, there is still room for improvement in the fabrication and control of the cilia-integrated microfluidic systems. For example, because of the softness of the cilia, the high interfacial energy in air, and the surface tension, the high-aspect-ratio cilia array tend to collapse during the fabrication process or the period when solutions are added to the microchannels. To solve this problem, an underwater fabrication strategy has been put forward, which takes advantage of the lower interfacial energy in water to avoid the collapse.[106] In addition, the maximum velocity of flows generated by cilia can never be increased too much. Aiming at this goal, den Toonder and co-workers utilized a rod-like-magnet-composed array where the magnetic dipole orientations of adjacent magnets were opposite to actuate magnetic cilia.[107] Under such a magnet field, the cilia performed a whip-like movement and induced a net velocity of about 3000 μm s⁻¹ in water, which outperformed all former reported congeners. Furthermore, the concept of fingertip drawing control has also been presented for smarter and more convenient cilia actuation and fluid manipulation.[108] During the actuation process, the data-processing unit serves to identify the gestures, translate them into specific instructions, build communications with the actuation system, and finally actuate the cilia accordingly.

As mentioned earlier, due to the flexible actuation and flow generation ability, the cilia are satisfactory candidates for micropumps.[109] Important applications include in vitro cell culture and construction of organ-on-chips, where these cilia micropumps can well promote the fluid circulation and substance exchange among different microchambers. In addition, artificial cilia can act as micromixers in microfluidic systems. One example is electrically actuated cilia provided by den Toonder et al.[109] The provided Y-shaped microfluidic channel contained 16 cilia segments, each of which was composed of a 20 × 5 cilia array, as shown in Figure 6a. When these cilia segments were arranged in a “A-B-A-B...” layout, violent transverse vortices would be generated and two differently colored silicone oils were found to homogeneously merged within 1.5 s (Figure 6b). Another example is magnetic cilia dispersed in the shared outlet channel of a Y-shaped microfluidic chip (Figure 6c).[110] By switching on or off the magnetic field, the mixing and separation of two solutions could be conducted in 0.5 s.

5. Artificial Cilia as Sensors and Robots

Artificial cilia are featured by large specific surface areas, small sizes, tendency to be deformed, wide choices of materials, and
convenience in combining with other devices, which make them suitable for a new generation of flexible wearable sensors. To date, a variety of cilia sensors have come into the public attention, such as magneto-resistive cilia sensors, piezoelectric cilia sensors, piezo-resistive cilia sensors, and so on. In addition, artificial cilia can serve as “feet” to imitate the locomotion of insects and some other animals, walking, crawling, turning, overcoming obstacles, and carrying objects based on synergistic movements. These smart cilia robots are promising to find applications in untethered manipulation in hard-to-reach

Figure 5. Artificial cilia for oil droplet and particle manipulation. a) Sliding (i) and pinning (ii) of oil droplets on mushroom-headed cilia. Reproduced with permission. Copyright 2019, American Chemical Society. b) Capturing and releasing oil droplets by stretching and relaxing the mushroom-headed cilia array. Reproduced with permission. Copyright 2019, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. c) Rolling and pinning of oil droplets on a superhydrophobic artificial cilia array based on the local deformation. Scale bars: 5 mm. Reproduced with permission. Copyright 2019, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. d–f) Simulation results and snapshot images of PLA particles transported on rotating-magnet-actuated cilia: (d) simulations (i,ii) and experiments (iii) of the transport process; (e) simulations (i) and experiments (ii) of the straight line path; (f) simulations (i) and experiments (ii) of the zigzag path. Reproduced with permission. Copyright 2020, American Chemical Society.
places, movable detecting, in vivo medical diagnosis and drug delivery, etc.

5.1. Flexible Sensors

5.1.1. Impedance Sensors

Giant magneto-impedance (GMI) sensors can sense the surrounding magnetic fields with high sensitivity and convert the change of the magnetic field to the change of their own impedance. Coupling GMI sensors and magnetic artificial cilia, Alfadhel and Kosel developed a magneto-resistive cilia tactile sensor based on a template-guided curing method.[115,116] When deformed by external forces such as touch, vibration, flow, etc., the cilia would generate a different stray magnetic field, which could be sensed by the attached GMI sensors (Figure 7a). Notably, such tactile sensors have shown their practical values in measuring blood pressure waves and detecting water flow with an ultrahigh resolution of less than 16 Pa. In follow-up work of the same group, the high temperature tolerance of the magneto-resistive cilia tactile sensor was evaluated.[117] By utilizing PDMS-containing single-crystalline iron nanowires as the cilia material, the tactile sensor could provide reliable information at up to 140 °C. In addition, these tactile sensors could also perform well in reading Braille, as they can identify the tiny changes in the surface texture by detecting vertical and shear touches.[118]

Artificial cilia can also act as part of piezoresistive sensors.[119] For example, such cilia sensors could contain a top sensing layer of graphene-coated magnetic cilia and a bottom electrode layer of graphite electrodes.[120] Without external pressure, the cilia hardly contacted the bottom electrode layer; while the cilia were deflected and touched the electrode layer under applied pressure, leading to a change in resistance. In addition, the contact area would increase along with the increase in the pressure, thus showing a more remarkable resistance change. It was found that the cilia sensors were highly sensitive, with a sensitivity of 0.025% Pa to the pressure range of 100–1000 Pa and 12.08 T to the contactless magnetic field. It was also demonstrated that this cilia sensor could accurately monitor wrist blood pulse and could be applied as wearable healthcare devices.

5.1.2. Capacitive Sensors

Capacitive-type sensors are generally composed of two parallel conductive plates and a dielectric layer sandwiched between them.
For improving their performance, the dielectric layer has been designed into various structures, such as irregular protuberances, domes, pyramids, cilia, and so on. Among them, cilia-shaped dielectric layers have received wide attention as they can provide voids between two conductive plates to optimize the storage and release of energy, improve the sensitivity and accuracy, and reduce viscoelasticity related problems. For example, Zhou et al. prepared cilia pressure sensors with Ag-nanowire-dispersed PDMS films as the conductive plates and carbonyl-iron-particle-loaded PDMS cilia arrays as the dielectric layer (Figure 7b). It was noted that such cilia pressure sensors have been applied as wearable sensors for movement monitoring (bending, stretching, walking, jumping, standing, etc.), voice vibration recognizing, and wrist pulse recording, as shown in Figure 7c.

Figure 7. Artificial cilia for sensing. a) Mechanism of a cilia GMI sensor (i) and the relationship between the impedance change and the external pressure. Reproduced with permission.[115] Copyright 2015, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. b) Scheme of the composition of a cilia capacitive sensor. c) Potential applications of the cilia capacitive sensor in monitoring elbow bending and relaxing, recognizing voice vibration, recording real-time wrist pulse, monitoring finger bending and relaxing, as well as monitoring movements (walking, jumping, standing). Reproduced with permission.[122] Copyright 2019, The Royal Society of Chemistry. d) Working principle of a cilia triboelectric sensor (i,ii) and the corresponding charge potential distribution (iii). Reproduced with permission.[123] Copyright 2019, Elsevier Ltd.
5.1.3. Triboelectric Sensors

The sensing principle of triboelectric sensors is triboelectric effects. To be specific, under vibration or touching, the relative positions of the two electrodes change, leading to charge transfer between the electrodes and thus forming an electric potential difference, which can be detected and recorded. Inspired by the ampulla of fish lateral line, artificial cilia have been introduced into triboelectric vibration sensors and placed on one of the electrodes. When vibration wave approaches, the electrode immobilized with cilia would vibrate accordingly, making the cilia twist to generate opposite electric charges at the interface between the cilia and the other electrode layer (Figure 7d). Following, when the cilia recover to original state, the cilia-immobilized-electrode are also charged because of electrostatic induction effects, and an electrical current is generated until the electric equilibrium is obtained. Such cilia triboelectric sensors greatly facilitate human–machine interface and could be attached to ordinary surfaces such as walls, doors, and computers to establish multifunctional interactive interfaces.

5.2. Microrobots

In nature, many arthropods and reptiles such as millipedes and caterpillars move relying on their cilia-like feet. This phenomenon inspires the development of microrobots using cilia as their moving media. To prepare such moving microrobots, some demands need to be satisfied at first. On the one hand, the cilia feet must be dense and strong enough to support and drive the microrobot. On the other hand, a remote and flexible trigger strategy should be adopted to actuate the cilia feet. Considering these requirements, Shen and co-workers used a magnet-induced cilia growth method to generate PDMS cilia feet with the foot-to-foot spacing of about 600 μm on a film robot. In addition, to better control the robots and expand their locomotion modes, both the magnetic torque and the pulling force were utilized as the driving sources. The resultant moving robots were demonstrated to have the ability to crawl on a wet surface with liquid film, carry a heavy cargo while moving, climb over a steep obstacle, and move on a human hand back and a stomach model (Figure 8a).

Figure 8. Artificial cilia as moving feet. a) Moving conditions of a film robot with magneto-responsive PDMS feet: (i) crawling on a wet surface with liquid film; (ii) carrying a heavy cargo while moving; (iii) climbing over obstacles; (iv) moving on a human hand back; (v) transporting a capsule on a stomach model. Reproduced with permission. Copyright 2018, Springer Nature. b) Magnetization of an encoded cilia carpet. c) The encoded cilia carpet crawling on a surface. d) The encoded cilia carpet rolling forward. Reproduced with permission. Copyright 2020, Springer Nature. e) Composition and functions of a multifunctional sensing robot: (i) scheme of the three modules and the appearance of the robot; (ii) sensing and communicating functions of the robot; (iii) voltage responses of the robot under stretching, pressing, bending, and twisting. Reproduced with permission. Copyright 2020, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.
In a recent study, an encoded cilia carpet was presented by a mold replicating and anisotropic magnetization approach. There were more than 200 cilia structures on the carpet, which were made from a stretchable, magnetizable composite material. By wrapping the cilia carpet around a 3D template and magnetizing it via a magnetizer, a variety of magnetization patterns could be encoded in the cilia, as shown in Figure 8b. Due to these complicated magnetization patterns, the cilia would perform metachronal waves depending only on these patterns when exposed to a dynamic external magnetic field. Thus, such encoded cilia carpets could not only crawl like other counterparts but also curl up and roll forward (Figure 8c,d).

5.3. Sensing Robots

The moving cilia robots can receive remote trigger signals, carry heavy cargos, and move in a confined space or on complex terrains. These attributes make these cilia robots suitable as a sensor carrier. Therefore, on the basis of their previously developed cilia–foot film robots, Shen and co-workers integrated sensing and self-power together with moving to design a multifunctional sensing robot. Such robots are constructed by three modules: a wireless communication module, a piezoelectric generator module, and a cilia leg module, as shown in Figure 8e. These sensing robots could detect temperature and surface morphology, communicate remotely and wirelessly, and power itself based on the piezoelectric effects. In addition, it was found that the sensing robots had practical values in bio-detecting, medical monitoring, in vivo therapy, etc.

6. Conclusion

The past few years have seen great efforts on investigating artificial cilia actuators. Getting inspirations from brilliant and smart natural cilia, a large variety of artificial cilia devices have been fabricated and more progress has been made. To better imitate the behaviors of natural cilia and further improve the functions, the actuation principles and strategies of artificial cilia are widely studied and the materials and fabrication approaches are optimized. In addition, applications of these cilia actuators in different types of fields are also explored. Nowadays, artificial cilia have been endowed with the capacity to transport, sense, communicate, and move. Multiple stimuli have been used to actuate such artificial cilia, including magnetism, light, electrics, heat, acoustics, gas, chemical reagents, capillary forces, and combination of these factors. Attributed to these features, artificial cilia have found applications in wettability regulation, slippery surface construction, oil manipulation, microfluidic platform establishment, real-time health monitoring, in vivo medical therapy, micro-robot design, etc. Herein, we provide a review focusing on the current developments of artificial cilia, their breakthroughs, remaining challenges, and future trends. We also laid special emphasis on the practical applications of these artificial cilia actuators in frontier areas.

Compared with other types of actuators such as thin-film actuators and tubular actuators, artificial cilia actuators are featured by three main advantages. The first is higher flexibility. Each cilium that constitutes the actuator can not only be controlled independently but also collaborate to play their role as a whole. Benefitting from this feature, artificial cilia actuators can be operated flexibly and diversely. The second is more complicated and broader functions. The diversified locomotion modes and multifarious configuration patterns of artificial cilia imparted them with the abilities to conduct a wide variety of functions. The third is improved sensitivity. Attributed to the cilia-like structure, the artificial cilia actuator has a large specific surface area. Thus, they are very sensitive to external stimuli such as forces and vibrations, and can capture targets with great ease.

Although many advancements and exciting accomplishments have been made, there remain several challenges waiting to be overcome in artificial cilia fields. To begin with, current techniques enable the efficient fabrication of artificial cilia actuators with small sizes. However, their fabrication on an industrial, large scale is still a problem. In addition, in spite of the accurate control of the entire artificial cilia, the independent and heterogeneous manipulation of single cilium is far from perfect. Furthermore, there is still large space for improvements in the integration of artificial cilia and other devices. Only artificial cilia in microfluidic chips for fluid mixing and pumping have been reported. Also the prepared artificial cilia in these areas are single in species and simple in functions.

Future of the artificial cilia actuators will concentrate on smarter designs, broader sensing methods, and more widespread applications. For example, closed-loop devices are pushing forward the new-generation intelligent devices because of their self-feedback, self-adjustment, automation, remote reporting abilities, and high integration. One possible closed-loop artificial cilia actuator can contain two linked modules: the sensor module to perceive the ambient environments and the motor module to provide propelling forces. In addition, most existing artificial cilia sensors translate detected signals into intuitionistic electric signals. Structural colors derive from materials themselves and structural color sensors can report information in a visualized manner by changing color. Thus, it is conceivable that the introduction of structural color into artificial cilia sensors by attaching structural-color plates to cilia tops or choosing suitable structural-color materials to fabricate cilia can promote visible-user interactions and boost the emergency of visualized cilia sensors. In addition, due to their large specific surface areas and controllable moving abilities, artificial cilia begin to be utilized in energy source fields such as photocatalysis and energy harvesting. Coupling artificial cilia with other catalytic technologies and integrating them into different energy harvesters (e.g., triboelectric generators, piezoelectric generators, electrostatic generators, etc.) are still eager to be explored. More than energy fields, the combination of artificial cilia actuators with system integration, smart devices, artificial intelligence, etc., is also promising research directions.

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Conflict of Interest
The authors declare no conflict of interest.

Author Contributions
Y.J.Z. designed the review topic and checked the review outline. X.X.Z. conceived the review framework, did the literature search, and wrote the review. J.H.G. assisted in writing and discussing the review. X.F. participated in revising the review. D.G.Z. helped modify the language.

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[1] Z. Y. Chen, F. F. Fu, Y. R. Yu, Y. X. Shang, H. Wang, Y. J. Zhao, Adv. Mater. 2019, 31, 1805431.
[2] A. Li, H. Z. Li, Z. Li, Z. P. Zhao, K. X. Li, M. Z. Li, Y. L. Song, Sci. Adv. 2020, 6, eaa5508.
[3] Y. Y. Yang, Y. S. Zhao, J. Liu, Z. K. Nie, J. Ma, M. T. Hua, Y. C. Zhang, X. F. Cai, X. M. He, ACS Mater. Lett. 2020, 2, 453.
[4] X. X. Zhang, Y. R. Yu, G. P. Chen, L. Y. Sun, Y. J. Zhao, Sci. Bull. 2019, 64, 1110.
[5] Y. S. Zhao, C. Xuan, X. S. Qian, Y. Alsaid, M. T. Hua, L. H. Jin, X. M. He, Sci. Robot. 2019, 4, eaa7112.
[6] Y. R. Yu, L. X. Shang, W. Gao, Z. Zhao, H. Wang, Y. J. Zhao, Angew. Chem., Int. Ed. 2017, 56, 12127.
[7] Y. Zhu, Q. Q. Shen, L. Y. Wei, X. Fu, C. Huang, Y. Q. Zhu, L. J. Zhao, G. S. Huang, J. R. Wu, ACS Appl. Mater. Interfaces 2019, 11, 29373.
[8] Y. R. Yu, J. H. Guo, L. Y. Sun, X. X. Zhang, Y. J. Zhao, Research 2019, 2019, 6906275.
[9] Y. Lei, Z. Z. Sheng, J. Zhang, J. Liu, W. Lv, X. Hou, J. Bionic Eng. 2020, 17, 405.
[10] Y. P. Wang, W. B. Niu, C. Y. Lo, Y. S. Zhao, X. M. He, G. R. Zhang, S. L. Wu, B. Z. Ju, S. F. Zhang, Adv. Funct. Mater. 2020, 30, 2000356.
[11] X. X. Zhang, L. Y. Sun, Y. R. Yu, F. K. Bian, Y. T. Wang, Y. J. Zhao, Proc. Natl. Acad. Sci. USA 2019, 116, 20863.
[12] Y. Wang, Z. X. Cao, J. R. Wu, C. S. Ma, C. B. Qiu, Y. C. Zhao, F. Shao, H. N. Wang, J. Zheng, G. S. Huang, Chem. Eng. J. 2019, 360, 231.
[13] Y. T. Wang, X. X. Zhang, L. R. Shang, Y. J. Zhao, Sci. Bull. 2020, https://doi.org/10.1016/j.scib.2020.07.030.
[14] J. K. Jiang, B. Mao, M. Z. Li, Z. Sun, C. Zhang, Y. Li, F. Y. Li, X. Yao, Y. L. Song, Adv. Mater. 2016, 28, 1420.
[15] H. Zhang, G. P. Chen, Y. R. Yu, J. H. Guo, Q. Tan, Y. J. Zhao, Adv. Sci. 2020, 7, 2000789.
[16] Z. Z. Sheng, H. L. Wang, Y. L. Tang, M. Wang, L. Z. Huang, L. L. Min, H. Q. Meng, S. Y. Chen, L. Jiang, X. Hou, Sci. Adv. 2018, 4, eaa06724.
[17] X. X. Zhang, G. P. Chen, F. K. Bian, L. Cai, J. Y. Zhao, Adv. Mater. 2019, 31, 1902825.
[18] J. Hou, M. Z. Li, Y. L. Song, Nano Today 2018, 22, 132.
[19] Y. X. Liu, C. M. Shao, Y. Wang, L. Y. Sun, Y. J. Zhao, Matter 2019, 1, 1581.
[20] P. A. Zhu, T. T. Kong, C. M. Zhou, L. Y. Lei, L. Q. Wang, Small Methods 2018, 2, 1800017.
[21] J. M. J. den Toonder, P. R. Onck, Trends Biotechnol. 2013, 31, 85.
[22] M. Wahl, K. Kröger, M. Lenz, Biofouling 1998, 12, 205.
[23] M. G. Stafford-Smith, Mar. Biol. 1993, 115, 229.
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