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Biohybrid Microalgae Robots: Design, Fabrication, Materials, and Applications

Fangyu Zhang, Zhengxing Li, Chuanrui Chen, Hao Luan, Ronnie H. Fang, Liangfang Zhang, and Joseph Wang**

The integration of microorganisms and engineered artificial components has shown considerable promise for creating biohybrid microrobots. The unique features of microalgae make them attractive candidates as natural actuation materials for the design of biohybrid microrobotic systems. In this review, microalgae-based biohybrid microrobots are introduced for diverse biomedical and environmental applications. The distinct propulsion and phototaxis behaviors of green microalgae, as well as important properties from other photosynthetic microalga systems (blue-green algae and diatom) that are crucial to constructing powerful biohybrid microrobots, will be described first. Then the focus is on chemical and physical routes for functionalizing the algae surface with diverse reactive materials toward the fabrication of advanced biohybrid microalgae robots. Finally, representative applications of such algae-driven microrobots are presented, including drug delivery, imaging, and water decontamination, highlighting the distinct advantages of these active biohybrid robots, along with future prospects and challenges.

1. Introduction

1.1. Microscale Robots Based on Synthetic Materials and Living Cells as Engines

The development of microscale robots, based on micromotor engines, has led to powerful new capabilities and major innovations toward a variety of important biomedical, environmental, or industrial applications.[1–4] Traditional micromotor engines rely on purely synthetic metallic or polymeric materials that convert local chemical fuel or diverse external energies to mechanical force, leading to the effective propulsion of micro-objects.[5–8] However, the operation of synthetic micromotors is constrained by the requirements of additional complex and costly equipment for actuation and control, or of toxic fuels, and by short operational lifetime. It is thus highly desired to develop advanced microrobotic platforms with efficient autonomous motion ability, controllability, extended life span, and negligible toxicity.

To meet these growing demands, considerable recent attention has been given to the use of living cells as engines to form active long-lasting biohybrid microrobotic systems, powered by cellular actuation.[9–12] Over million years of evolution, microorganisms have evolved sophisticated motility systems with effective self-propulsion capabilities[13–15] and powerful tactic motility responding to diverse stimuli.[16–18] The natural dynamic systems enable living micro-creatures to adapt to versatile environments and extreme conditions.[19,20] To mimic the motility strategies of microorganisms, various microrobotic approaches based on advanced synthetic materials, such as artificial flagella made of magnetized helical or flexible structures, have been designed to achieve a mimetic motion under an external magnetic field.[8,21–23] However, synthetic micromotor designs cannot fully imitate the attractive intrinsic features of biological systems in terms of power for actuation, energy conversion efficiency, flexibility, complex control, along with taxis and sensing capabilities. One of the problems facing scientists and engineers in recent years has been the development of artificial propulsion systems that can mimic key aspects of living things for practical biomedical and environmental applications. Biohybrid microrobots, consisting of living organisms and synthetic counterparts, provide an attractive strategy to achieve biomimetic behaviors and advanced functionalities.[9,11] Many microorganisms, including bacteria, algae, and sperm, have been selected as the basic actuation elements for such biohybrid microrobots as they not only can generate strong long-lasting thrust for self-propulsion at a fast speed (with a displacement of more than ten times of their own body length per second) without external actuation, but also sense and react to changes or stimuli in their local surroundings.[24–26] In addition, the incorporation of synthetic components endows biohybrid microrobots with unique characteristics ranging from magnetic maneuverability, effective drug loading to controlled release, and controllable interaction with targeted cells. Biohybrid microrobots, combining these capabilities of natural actuation elements and synthetic functional units, have thus shown considerable promise for a variety of applications, including biomedical imaging, drug delivery, and water remediation.[27–37] Particular recent attention has

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been given to biohybrid microrobots based on algae swimmers, demonstrating remarkable long-lasting self-propulsion, adaptation to complex and harsh environments, and effective cargo towing capabilities.[26,38] Such attractive capabilities have led to the development of powerful algae-based biohybrid robots fulfilling effectively diverse and important tasks ranging from the removal of SARS-CoV-2 in wastewater to the treatment of pulmonary bacterial infections.[30,39]

The goal of the article is to present a thorough review of microalgae-based biohybrid microrobots by discussing their design, fabrication, functionalization, motion capabilities and performance along with major recent applications. Microalgae are a variety of collection of organisms that undergo photosynthesis and are predominantly found in aqueous matrices.[40] Microalgae possess an abundance of different photosynthetic pigments, such as chlorophyll, that enable them to capture sunlight and convert it into chemical energy through the process of photosynthesis. This energy is then stored in the form of photosynthetic products.[41] These microorganisms are thought to be the fastest-growing species due to their remarkably effective energy production process.[42] As a result, microalgae are abundant on earth and recognized as one of the most important oxygen sources.[43] Due to their potential applications in the fields of energy, agriculture, and healthcare, microalgae are currently attracting tremendous global attention.[44–48] The unique morphological characteristics and easily functionalized surfaces enable the binding of diagnostic or therapeutic agents onto the alga surface. This capability makes them highly promising options for developing innovative and effective biohybrid microrobots, serving as dynamic chemical probes, active drug carriers, or biomedical scaffolds.[26,30,32,38,49] In addition, many types of microalgae are regarded as nontoxic, biocompatible, and biodegradable natural materials for meeting the requirements of in-vivo biomedical applications.[30,32,38,50] Such advantages and unique properties of the microalgae make them extremely attractive candidates for designing biohybrid microrobots.

1.2. Exploiting the Unique Features of Algae for Producing Microrobots

Algae used for the fabrication of biohybrid microrobots can be typically classified into three types. First, green algae are a diverse group of photosynthetic organisms with significant ecological and scientific importance. They have been widely employed as models for studying microorganism motility. Take *Chlamydomonas reinhardtii* as an example, they can serve as a living actuation element by transforming ATP to mechanical energy for self-propulsion by beating flagella presented on the algae surface. Briefly, the activation of dynein motor proteins, which is powered by ATP hydrolysis, results in the movement of pairs of microtubules in the flagella axoneme. This sliding action induces bending and curvature of the flagellum, ultimately generating propulsive forces. Their flagella beating in a synchronized pattern, can be described by a stochastic Adler equation:[51,52]

$$\dot{\Delta} = \delta \mathrm{v} - 2\pi\varepsilon \cdot \sin(2\pi\Delta) + \xi(\mathrm{t}) \tag{1}$$

where $\delta\nu$ is the intrinsic frequency difference between the two flagella, ϵ is their effective coupling, and ξ is an effective noise term responsible for the slips. This unique beating behavior offers *Chlamydomonas reinhardtii* fast propulsion speed, up to ≈120 µm s^{-1}. Unlike the unicellular Chlamydomonas, another type of multicellular green algae named *Volvox* is well known for its spinning motion. *Volvox* is a spherical colonial green alga with thousands of surface somatic cells. This unique structure allows *Volvox* to spin at an inclination angle with respect to the vertical, as described by:

$$\zeta_r \dot{\theta} = -\left(4\pi R^3 \rho_c g l/3\right) \sin(\theta) \tag{2}$$

where $\zeta_r = 8\pi\eta R^3$ is the rotational drag coefficient, l is the distance between the center of gravity and d geometry, η is the fluid viscosity, g is the acceleration of gravity[53,54]

In addition, integrating the onboard actuation of green algae and synthetic components provides an effective way for creating microrobots for specific tasks, including targeted drug delivery. The advantages of using green algae-based biohybrid microrobots over synthetic micromotors are their simplicity for production, ease of cargo conjugation and long-lasting propulsion (without external actuation). For example, *Chlamydomonas* can grow in large scalability under light/dark cycles in a simple and fast way compared to the complex fabrication processes of synthetic micromotors. The easily adaptable surfaces of microalgae facilitate the binding of wide range of payloads, including diagnostic and therapeutic agents. For example, versatile functional groups, e.g., carboxyl, amino, and phosphate moieties, present on its cell surface, provide sites for anchoring external payloads via chemical bonds or physical adsorption. In addition, taking advantage of ATP and ion gradients generated by the cells, flagella and eyespot present in the cell can be used for fast long-lasting propulsion and guidance of payload, respectively, in complex environments.

The second type of microalgae—blue-green algae (also called cyanobacteria)—performs photosynthesis to absorb energy from light, and can be readily combined with synthetic materials, for preparing biohybrid microrobots. For example, *Spirulina*, a typical strain of blue-green algae, has been introduced to form biohybrid robots by adding external magnetic materials (e.g., Fe_3O_4 nanoparticles). The integration of magnetic materials on the unique helical shape provides a magnetic torque for a controllable motion of biohybrid structure under magnetic fields. Thirdly, diatoms are 2–200 micrometer unicellular photosynthetic algal cells in hierarchical shapes. The surface of diatoms has a unique cell structure composed of a silica shell called a frustule. This structure provides chemical and physical protection to diatoms and allows them to survive in more challenging conditions.[55,56] As a result diatoms are widely found in freshwater and marine environments, and account for the major primary production of the biosphere.[57] Since most diatoms lack flagella or self-actuated elements, they need extra materials and fuels for achieving propulsion. Typically, diatom can combine with catalytic materials to make bio-inspired 3D micromotors. The distinctive 3D hierarchical structure of diatoms possessed the capability to generate a powerful and directional bubbling force in H_2O_2 fuel, allowing it to accomplish desired tasks effectively.[58]

To gain an understanding and knowledge of the distinct capabilities of algae-based microrobots, our review takes a critical look at the existing microalgae motility approach and highlights

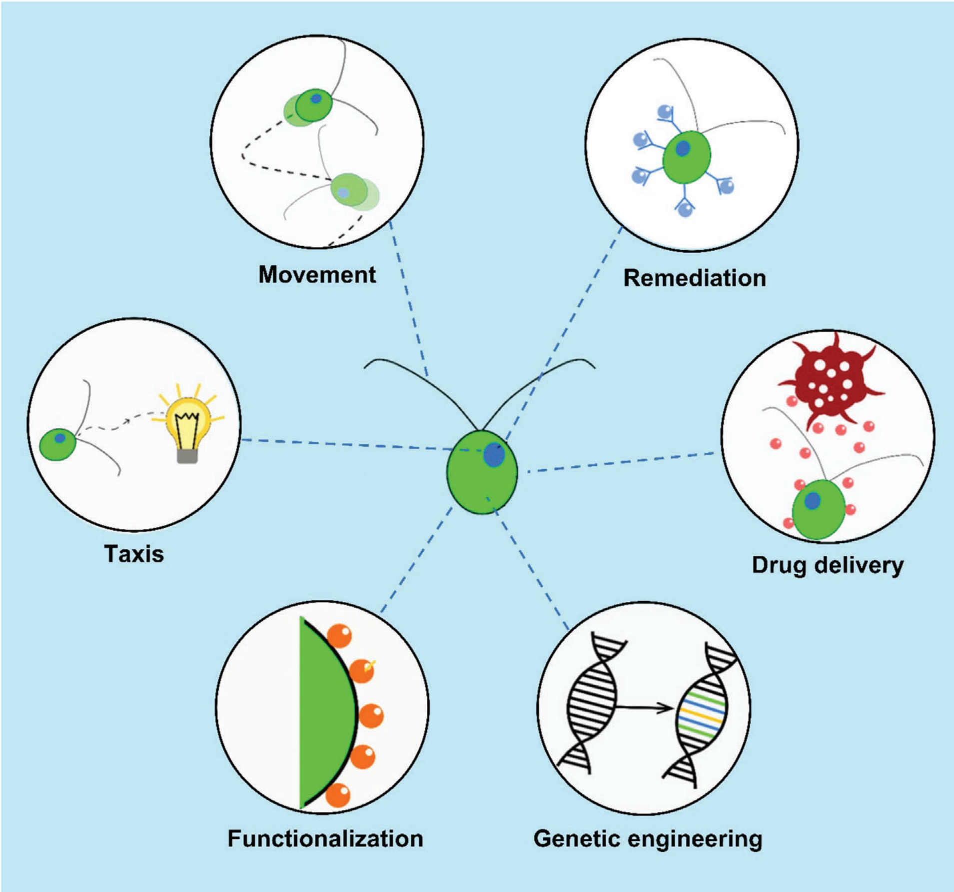

Figure 1. Schematics depict intrinsic motion properties, surface functionalization, and applications of microalgae-based microrobots.

the foundation of microalgae-based biohybrid microrobots from three aspects: intrinsic motion properties of microalgae, surface functionalization of microalgae to establish biohybrid systems, and versatile applications using as-fabricated algae-based biohybrid microrobots (**Figure 1**). Initially, we discuss the motion mechanisms of microalgae and establish a basic understanding of their motility principles within the microscopic realm. In the following section, we undertake a critical review of the attractive properties of synthetic materials and the methods employed to incorporate them into the microalgae. Lastly, we elucidate important biomedical and environmental applications of algae-based biohybrid robotic designs and discuss their future opportunities and key challenges for practical operations.

2. Fundamentals of Microalgae-Based Robots

Algae is a collection of highly diverse organisms that contain photosynthetic organelles to produce energy and food.[59] Algae may be motile or not motile, depending on the species and cell structure, and their size may range from a few microns to hundreds of microns. The typical algae cell structure consists of a cell wall, cell body, eye spot, and flagellum, as shown in **Figure 2**A. The algae cell wall is composed of an integrated biopolymers network such as polysaccharides and protein matrix. The cell wall plays a crucial role in maintaining the algae structure, providing physical protection, defense against microbial attack, and supporting the mass exchange between algae and its surroundings.[60] The cell wall composition varies among different algae types, for example, the *Charophycean* green algae possess cell walls containing polymers ranging from cellulose–pectin complexes to hydroxyproline-rich glycoproteins.[61] While for other types of algae, such as *Ulvophyceae* green, the algae cell wall contains sulfated polysaccharides and fibrillar constituents such as cellulose, β-mannans, and β-xylans.[62] The rich chemistry on algae cell walls offers the possibility for a variety of options for functionalization and application, which will be detailed discussed in the following sections.

The flagellum beating is responsible for a variety of algae movements, there is a significant interest in how the movement of the flagellum is behaved and synchronize.[63–66] Such flagellum beating generates hydrodynamic force to propel the algae cell. Taking the freshwater green microalga *Chlamydomonas reinhardtii* as an example, its flagellum beats at 60–70 Hz, following a repeating pattern shown in Figure 2B.[64] Such motile gives algae the ability to migrate to the nutrition-rich area or away from harm. This ability has recently been utilized as self-propelled robots for multiple applications. Such movement and flagellum beating of the algae causes the fluid to flow around, as demonstrated in Figure 2C.[67,68] Due to the fast movement of algae (up to a few hundred micrometers per second) and its flagellum

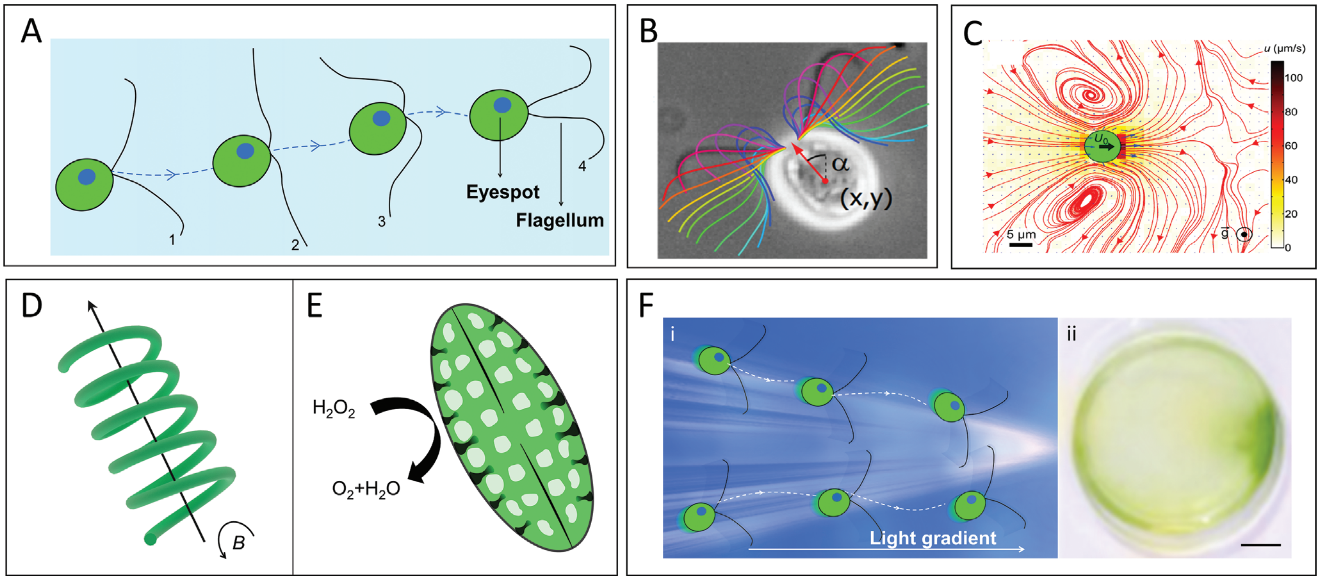

Figure 2. Fundamentals of microalgae-based robots. A) The flagellum beating process of a moving algae micromotor. B) The flagellar shapes of green algae, *Chlamydomonas*, shown in different colors in one beating cycle, tracked with over time-lapse of 2 ms. Reproduced with permission.[64] Copyright 2013, National Academy of Sciences. C) The hydrodynamic flow generated by moving algae. Reproduced with permission.[67] Copyright 2010, American Physical Society. D) Magnetic-driven propulsion of magnetic nanoparticles-functionalized spiral cyanobacteria (*Spirulina*). E) Chemical reaction-activated motion of catalyst decorated hierarchical diatom (*Achnanthes*). F) Schematic illustration (i) and real-time image (ii) showing phototaxis of algae motors. Scale bar, 1 cm. Reproduced with permission.[74] Copyright 2016, National Academy of Sciences.

beating, the induced fluid mixing around the algae is significantly enhanced. The significant fluid mixing associated with the collective motion of microalgae has a profound impact on robotic applications ranging from environmental cleaning to drug delivery.[69] For instance, mass transfer is enhanced with the presence of algae due to active mixing and transport, which subsequently leads to improved therapeutic and remediation outcomes.[39]

Two other major mechanisms for the movement of microalgae robots are also demonstrated in Figure 2D,E. For example, the spring-like *Spirulina platensis* can be functionalized with magnetic nanoparticles and actuated via a rotating magnetic field.[70] Such ability offers them movement in complex biological medium without any additional fuel and could perform tasks ranging from cancer therapy to neural-like stem cell stimulation.[70,71] Meanwhile, the diatom is a class of microalgae with 3D anisotropic structure and a cell wall composed of SiO_2, Fe_2O_3, and Al_2O_3 (named frustule). Among them, the Fe_2O_3 can be converted into Fe_3O_4 and catalytic decomposing H_2O_2 fuel to generate bubble propulsion. Interestingly, the motion of the diatom motor can be tailored with an EDTA molecule break, which blocks catalytic sites on the motor.[72] These features make diatom a promising self-propelled micromotor with responsible motion behavior.

Typically, the living environment of algae is mild as the majority of them are found in natural environments, such as in freshwater or the ocean. However, a class of extremophilic algae—grown under harsh conditions—can survive in harsh environments such as acidic or alkaline media, high temperature, elevated CO_2 levels, or high metal concentration.[73] Such ability of extremophilic algae to operate under extreme conditions holds considerable promise for a variety of important in vivo or environmental microrobotic applications in extreme environments or under extreme conditions. The photo-responsiveness of algae is another major characteristic of algae robots. The eyespot of algae can sense the environmental light and also acts as an ion channel to trigger downstream signal transduction.[74] As a result, the algae swim toward a light source to improve photosynthesis or move away to avoid harm to the photosynthesis molecular complexes (Figure 2F). The scheme of the positive phototaxis behavior is illustrated in Figure 2F-i, showing the algae change their trajectories to swim toward the light source. Figure 2F-ii demonstrates the phototaxis of a swarm of algae in a petri dish, with the algae aggregate toward the light source (irradiating from the right to the left side). Such a phenomenon is particularly useful in designing advanced biohybrid microrobot systems, which could respond to external stimuli and perform specific tasks. For example, phototaxis provides an attractive way to navigate cargo-loaded microalgae in microfluidic channels, including swimming back and forth.[40]

3. Surface Functionalization and Integration Routes for Preparing Microalgae-Based Biohybrid Robots

Microalgae-based biohybrid robots have two main parts: living motile/non-motile algae and synthetic cargo. Microalgae biological cells, with their diverse shapes and sizes and rich surface chemistry, are thought to be appropriate substrates for the modification of useful nano/micro cargo. The synthetic counterparts need to be properly combined with algae for creating an effective multifunctional biohybrid robotic system. It is worth noting that the interactions between biological cells and synthetic elements could have a significant impact on the operation of biohybrid systems. Consequently, the judicious selection of suitable approaches to linking diverse functional materials is the key design factor to ensure the high performance of biohybrid microrobots. This section focuses on the three techniques—noncovalent binding, covalent interactions, and other approaches including cell penetration and encapsulation—that have been used to manufacture biohybrid microrobots.

3.1. Noncovalent Binding

Noncovalent binding is a versatile approach to functionalize biohybrid systems, which involves the integration of biological and artificial components. Noncovalent interactions, including electrostatic interaction, hydrogen bonding, hydrophobic interactions, and van der Waals force, are generally reversible, allowing for dynamic and controllable assembly and disassembly of biohybrid systems. These interactions can be performed under mild conditions and further tailored to be applicable to various biomolecules and synthetic materials. Since these interactions do not involve the formation of chemical bonds, they can preserve the native structure and functionality of biomolecules. Although noncovalent binding shows many advantages for forming biohybrid system, it still has some limitations specifically for in vivo applications. For example, the susceptibility of noncovalent bond to environmental factors, such as pH, temperature, and ionic strength, may result in the loss of the desired functionality over time. The lower binding strengths between biological and synthetic materials can also affect the stability and reliability of the biohybrid system. These factors need to be considered when selecting the appropriate strategy for specific applications.

Given that the majority of biological cells have a net negative surface charge, electrostatic interaction has been extensively studied to fabricate biohybrid microrobots.[28] The surface of microalgae is also electrostatically charged, providing required binding sites for opposite-charged cargo.[75] By tuning the surface characteristics of materials, the simple strategy with charge-charge interaction can be used for creating algae-based biohybrid microrobots. For example, layer-by-layer coating of PSS/PAH polymers was applied to change the surface composition of polystyrene microparticles, allowing positively charged polymeric microparticles to interact with negatively charged algae (**Figure 3**A).[38] Electrostatic deposition of nanoparticles onto the algae is also one of the most straightforward methods for nanomaterials immobilization. Akolpoglu et al. demonstrated the attachment of chitosan-coated iron oxide nanoparticles on *C. reinhardtii*.[76] In this way, drug-loaded motile microalgae can be guided by external light (phototaxis) and applied for in vitro drug delivery. Looking forward, such design of biohybrid microrobotos can potentially reach easily the illuminated body part, such as deep skin and bone tissue instead of passive nano/microparticles or microalgae extracts. Other polymers, such as poly-l-lysine (PLL) and their copolymers are commonly used as noncovalent methods for cell surface engineering without compromising cell viability.[77] To this end, a similar approach was utilized to modify the surface of acidophilic algae *C. pitschmannii* with PLL layers of Poly(lactic-co-glycolic acid) nanoparticles.[78] Asides from electrostatic binding, peptide-protein interactions—which are prevalent in the cell—play a vital role in the binding of the cargo to the cell surface of algae. The pioneering work of Whitesides in 2005 presented that synthetic glycopeptide-decorated polystyrene microparticles were tightly bound to the outer surface of algae via non-covalent peptide-peptide interaction (Figure 3B).[26] A 4-hydroxyproline oligomer and antibiotic complex were modified to the cell wall of *C. reinhardtii* via a similar surface engineering method to develop vancomycin-functionalized microalgae for bacterial treatment.[49] Additionally, N-hydroxy succinimide biotin can be incorporated onto the algae cell surface, allowing for subsequent functionalization of specific biomolecules through a streptavidin connection (Figure 3C).[79]

3.2. Covalent Interactions

Using covalent binding to functionalize biohybrid systems also offers several advantages and disadvantages. Considering the complex conditions in the body (e.g., pH, enzyme, and proteolytic degradation), the formation of biohybrid system needs to be highly stable and resistant to degradation. Compared to noncovalent bond molecules, the highly stable covalent bond provides durability, ensuring the long-term integrity of the biohybrid system and higher resistance to harsh conditions. The specificity of covalent binding allows for precise and controllable attachment of molecules to the desired sites with minimal non-specific interactions. The potential limitation of using covalent interactions for fabricating biohybrid systems is the complexity and irreversibility of covalent bonds. It often requires specific reaction conditions and chemistry expertise, which can add complexity to the fabrication process. In addition, covalent interactions between biological counterparts and artificial components are typically irreversible, making it challenging to further modify or remove the attached materials once they are bound. Selection of a suitable covalent binding strategy is critical to meet the specific requirement and goals of the application.

Natural functional groups (—COOH and —NH_2), present on the alga surface, originating from its protein or sugar components, are attractive binding sites for the covalent conjugation of exogenous cargo. The simplest strategy entails a chemical reaction of an amino group displayed on the algae surface with an appropriate reactive group on the other components. This strategy has been used to fabricate functionalized algae microrobots by conjugating versatile payloads, including small molecules, proteins, nanoparticles, or microparticles. The linkage of succinimidyl esters labeled fluorescent dye exemplifies the direct modification of artificial metalloenzyme.[79] The self-propulsion of algae is not affected by NHS-fluorescein conjugation, further verifying that the covalent strategy is an alternative noninvasive process for constructing biohybrid algae robots.[80] Click chemistry is another approach that offers considerable opportunities for the integration of algae with artificial elements since it can easily take place in a mild aqueous solution. For example, Zhang et al. linked amine reactive DBCO following azide-modified ACE2 receptor conjugates to algae surface toward efficient active removal of SARS-Cov-2 pseudovirus in wastewater (Figure 3D).[39] Using similar chemistry, two different antibiotics, vancomycin and ciprofloxacin, were attached to the cell wall of *C. reinhardtii* through a covalent bond.[81,82] A strong

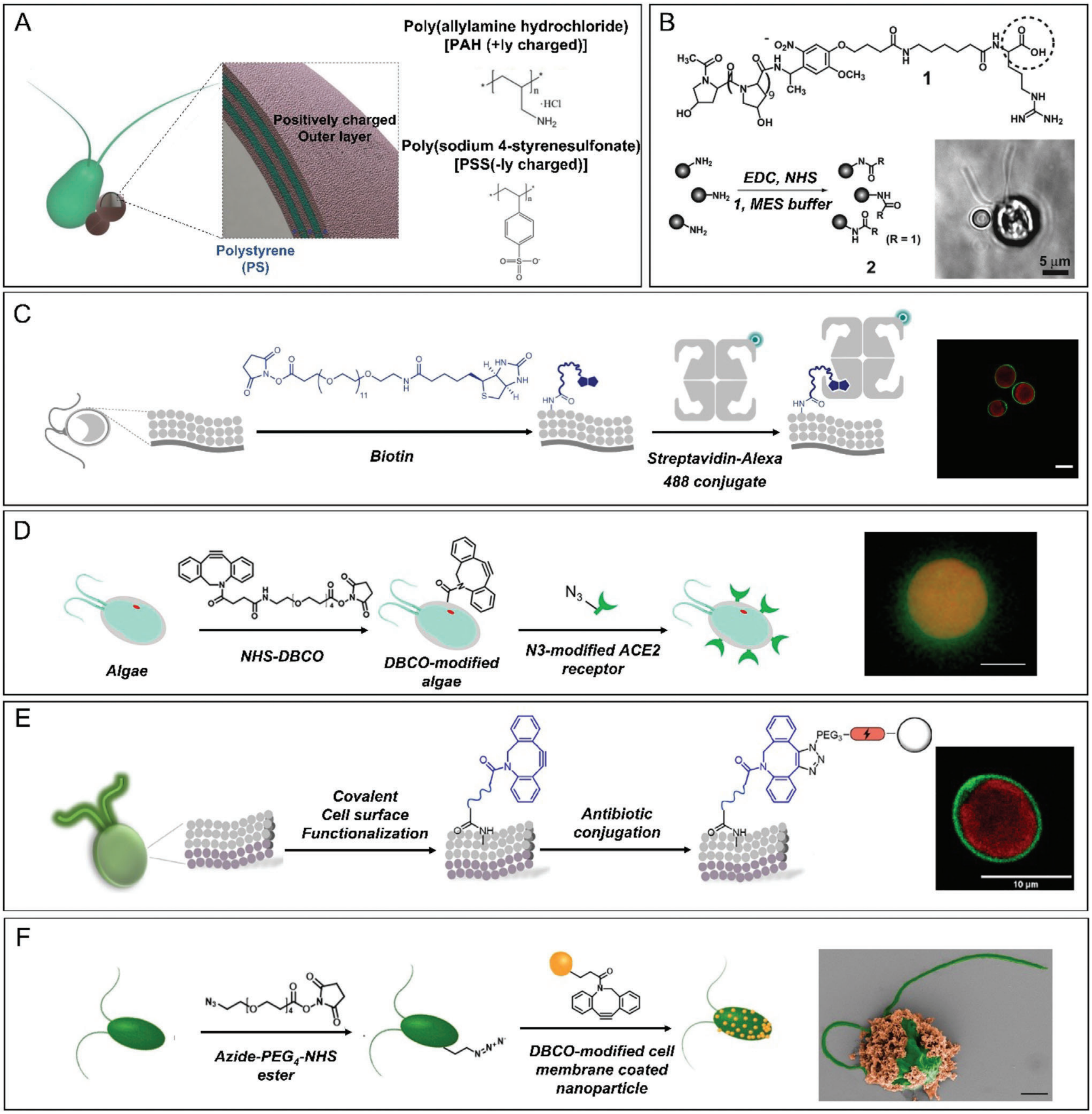

Figure 3. Surface modification for the preparation of biohybrid algae-based microrobots. A) The attachment of Layer by layer-coated polystyrene microparticles onto algae via electrostatic interaction. Reproduced with permission.[38] Copyright 2018, Wiley-VCH. B) The binding between hydroxyproline-modified PS microparticle and microalgae using peptide-peptide interaction. Reproduced with permission.[26] Copyright 2005, National Academy of Sciences. C) Binding of dye-conjugated streptavidin onto the microalgae surface via biotin-streptavidin binding. Reproduced with permission.[79] Copyright 2018, Springer Nature. D) The chemical linking of ACE2 receptor to algae surface through click chemistry. Reproduced with permission.[39] Copyright 2021, American Chemical Society. E) Conjugation of small molecules of antibiotics to algae surface via covalent cell surface functionalization. Reproduced with permission.[82] Copyright 2021, Elsevier. F) Functionalization of green microalgae by incorporation of neutrophil cell membrane-coated nanoparticles via the reaction between DBCO and azdio group on their surface, respectively. Reproduced with permission.[30] Copyright 2022, Springer Nature.

fluorescent signal was detected after surface conjugation of fluorescein-containing antibiotics, supporting the effective chemical binding. The drug was further released by UV cleavage for antibacterial treatment in vitro (Figure 3E).[82] Covalently attached cargo to the algae robots can also be used for the controlled in-vivo release of therapeutic payloads. To make drugs suitable for practical in vivo use, cell membrane-coated biodegradable polymeric nanoparticles have been designed to load and release antibiotic drugs in a controlled manner. In the design, the cell membrane provides a primary amine group to react with NHS-PEG$_4$-DBCO group toward modifying the alga surface with NHS-PEG$_4$-azide. The drug-loaded nanoparticles were thus conjugated with algae via click chemistry for the fabrication of biohybrid microrobots to treat acute bacterial pneumonia (Figure 3F).[30] The covalent binding of therapeutic nanoparticles onto microalgae surface allows the biohybrid robots to deliver the drugs to hard-to-reach area of deep lung and realize effective in-situ drug release in a controlled manner toward effective treatment of bacterial infections in a mouse model compared with ineffectiveness of inert nanoparticles. In addition, a model chemotherapeutic drug, doxorubicin in nanoparticles, was also functionalized to algae surface via covalent bond for GI delivery.[80] Notably, these studies demonstrated that antibiotics, proteins, and polymeric particles, with sizes ranging from sub-nm to ≈100 nm, can be linked to living algae via click chemistry without compromising their motility and phototactic performance.[30,39,80]

3.3. Surface Coating, Cell Penetration and Encapsulation

Chemical binding has provided an effective way to load external carriers to the surface of algae. Nevertheless, a major limitation of this approach is that the reactive group must be created through chemical treatment of pre-existing cell surfaces. Recently, Qiao et al. demonstrated a gentle facile method to coat live *Chlorella vulgaris* with desirable red blood cell (RBC) membranes without surface treatment (**Figure 4**A).[83] The RBC membrane coating provides biohybrid microalgae with the new capability of escaping from macrophage uptake and reducing clearance of the immune system. In addition to surface modification, cell penetration and encapsulation offer high loading of therapeutic reagents. Cell-penetrating peptides have been widely utilized for delivering impermeable cargo, including small molecules, peptides, proteins, nucleic acids, and nanoparticles into the cells.[84] However, the effective translocation of chemical and biological reagents into the algal chloroplast was hindered by the biological barrier of the algal cell wall. To solve the challenge, a guanidinium-rich molecular transporter-assisted approach was used to transform an optical probe into the cell (Figure 4B). The fluorescent dye was internalized to *C. reinhardtii* with both cell-wall intact and deficient mutations as well as two less-studied algae strains, confirming that the technology is effective for molecular manipulation of algae.[85] Similarly, microalgae can be modified utilizing genetic engineering to construct a biohybrid platform to produce high quantities of the desired metabolite.[86] Looking forward, it is necessary to evaluate whether cargo penetration and genetic engineering have an influence on intrinsic motility and other cellular activities. Additionally, blue-green algae were incorporated with magnetite coating for the formation of magnetic biohybrid microswimmers via a dip-coating process (Figure 4C).[32] The annealing procedure of magnetite precursors removed the helix *Spirulina platensis* core and thus enabled a hollow structure for cargo loading. To obtain high cargo loading efficiency in the microcarrier, a facile dehydration-rehydration method was used to maintain the helical structure of lyophilized *S. platensis*. Amifostine was encapsulated in the microalgae for building an oral drug delivery biohybrid platform (Figure 4D).[87] It was also demonstrated that the anti-inflammation drug curcumin can be highly loaded into microalgae, leading to an effective treatment of *S. platensis* (Figure 4E).[88]

4. Drug Delivery Applications of Microalgae-Based Robots

Microalgae-based robots have shown substantial capabilities as efficient active drug carriers, capable of convenient loading of various therapeutic payloads onto the surface of the self-propelled microswimmers. Compared to the administration and distribution of free passive drugs in living organisms, drug-loaded motile algae-based microrobots have shown to offer superior retention time, controllable drug release, and remote guidance for better precise targeted delivery.[30] By combining their drug loading capability and natural motility, algae-based microrobots have thus proven effective in enhancing conventional treatment. This section aims to provide detailed information on microalgae-based robots for in vitro and in vivo drug delivery toward various disease models, along with additional applications beyond disease treatments.

4.1. In Vitro Drug Delivery

Bacterial infections caused by versatile strains of bacteria such as *Bacillus subtilis* or *Escherichia coli*, require antibiotics as treatment methods. Vancomycin was one of the selections that can be bound to the surface of *C. reinhardtii* for microrobotic-assisted drug delivery (**Figure 5**A). The antibiotics can be released via a photocleavable linker under UV light to inhibit bacterial growth.[49,81] The same group also demonstrated that two different antibiotics, Vancomycin and Ciprofloxacin were confined to the algae surface via covalent bond. The biohybrid microalgae were controlled by external light for phototaxis-induced drug delivery in a petri dish (Figure 5B). After incubation of antibiotics-loaded algae with Gram-positive strain, *Bacillus subtilis*, the active algae group was illuminated with a side light source, allowing for light-guided targeted delivery. Compared to the negative control groups, the phototaxis-assisted algae microrobot drug delivery system displayed a remarkable inhibition of bacterial growth, indicating the effective bacterial resistance ability of the functionalized swimming microalgae.[82]

Traditional cancer treatments typically involve large amounts of dosage, which commonly leads to a cascade of severe side effects influencing healthy cells. Taking advantage of active algae-based microrobots as carriers, however, offers enhanced treatment efficacy compared to free drugs, such as doxorubicin (DOX). By loading doxorubicin into nanoparticles, the drug can therefore be attached to algae surfaces, granting the microswimmers anticancer ability. An example utilizing DOX-nanoparticle

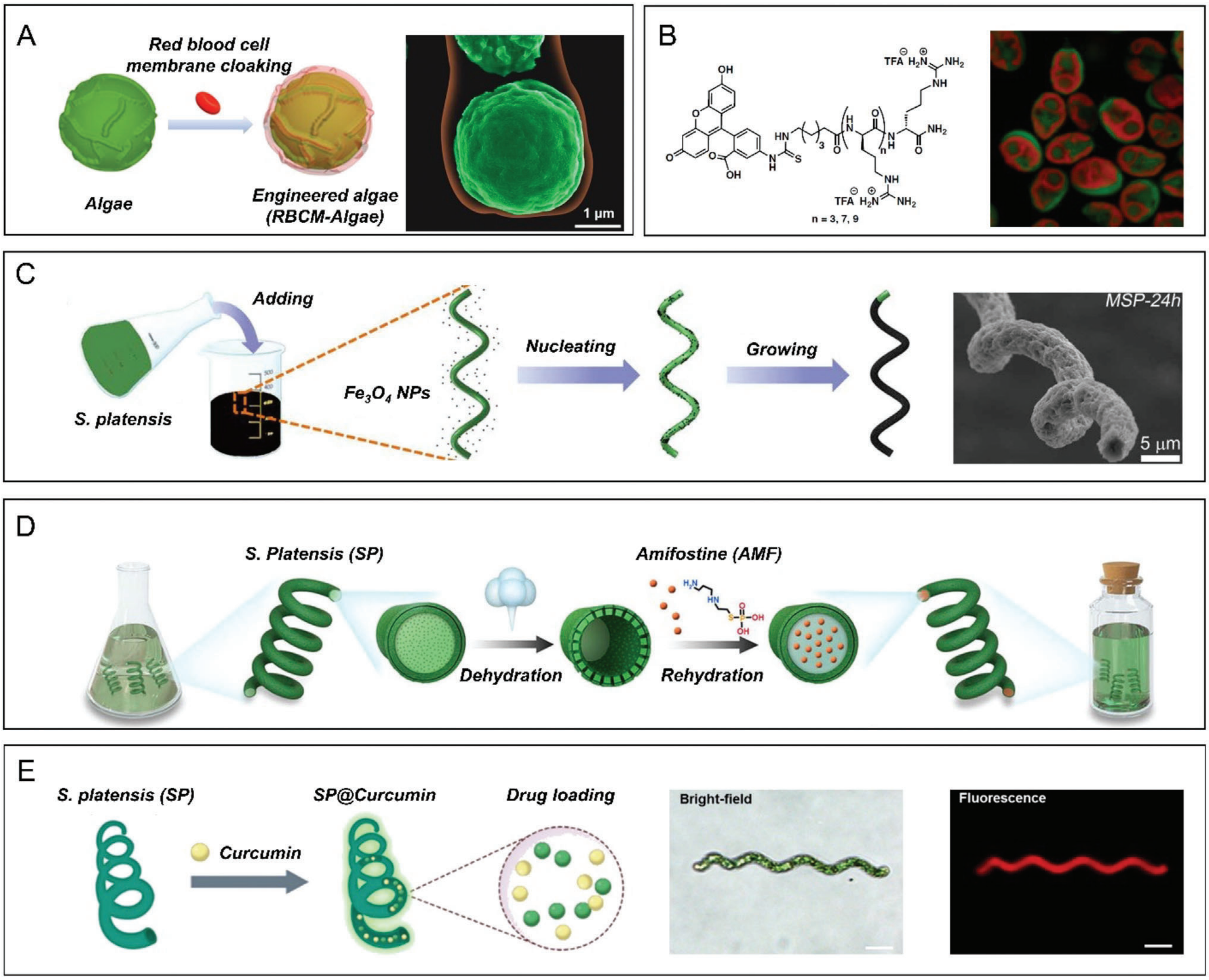

Figure 4. Additional routes for preparing biohybrid algae-based system. A) Red blood cell membrane clocking onto Chlorella via gentle stirring overnight. Reproduced with permission.[83] Copyright 2020, AAAS. B) Penetration of small molecules and proteins in the cell wall of algae using cell-penetrating peptides. Reproduced with permission.[85] Copyright 2012, National Academy of Sciences. C) Dip-coating process for Fe3O4 NPs coating onto spirulina surface. Reproduced with permission.[32] Copyright 2017, AAAS. D,E) Drug (Amifostin (D) and Curcumin (E)) loading into spirulina by dehydration (lyophilization) and rehydration procedures. Reproduced with permission.[87] Copyright 2022, Springer Nature. Reproduced with permission.[88] Copyright 2021, AAAS.

and *C. Reinhardtii* green algae was conducted by Sitti and coworkers.[76] In this study, doxorubicin was encapsulated in chitosan-coated iron oxide nanoparticles and bound onto algae surfaces along with a photocleavable linker, which endowed the microrobots with an external magnetic remote trackable control and a controllable light-induced drug release (Figure 5C). The established drug-loaded algae microrobots demonstrated a reduced SK-BR-3 cancer cell viability, indicating a successful release of the anticancer drug and proving the anticancer ability of the biohybrid system.

Other types of microalgae species, such as *Spirulina Platensis*, attracted research attention as well on their drug delivery fitness. Zhang et al. fabricated (Pd@Au)/Fe_3O_4@Sp.-DOX utilizing *Spirulina Platensis*.[89] The Fe_3O_4 nanoparticles enabled the microrobot to a magnetic remote control, which benefits in the precision of targeted delivery. Such guided motion ability is presented to show assistance in the target delivery of the Dox-loaded *Spirulina Platensis* when incubated with 769-P and EC-109 cancer cells, which effectively suppressed cancer cell viability (Figure 5D). Additional drug delivery platforms have been explored for the construction of versatile drug-loaded *Spirulina Platensis* microrobots. For example, metal–organic framework was conjugated to gelatin-magnetite coated microalgae via electrostatic interaction to assist drug loading and remote guidance.[90] The biodegradability of MSPs results in the controlled release of a model biomacromolecule (TGR-β1). The bioactivity of TGR-β1 released from microrobots was evaluated using human mesenchymal stem cells, showing higher gene expression than control groups.[91]

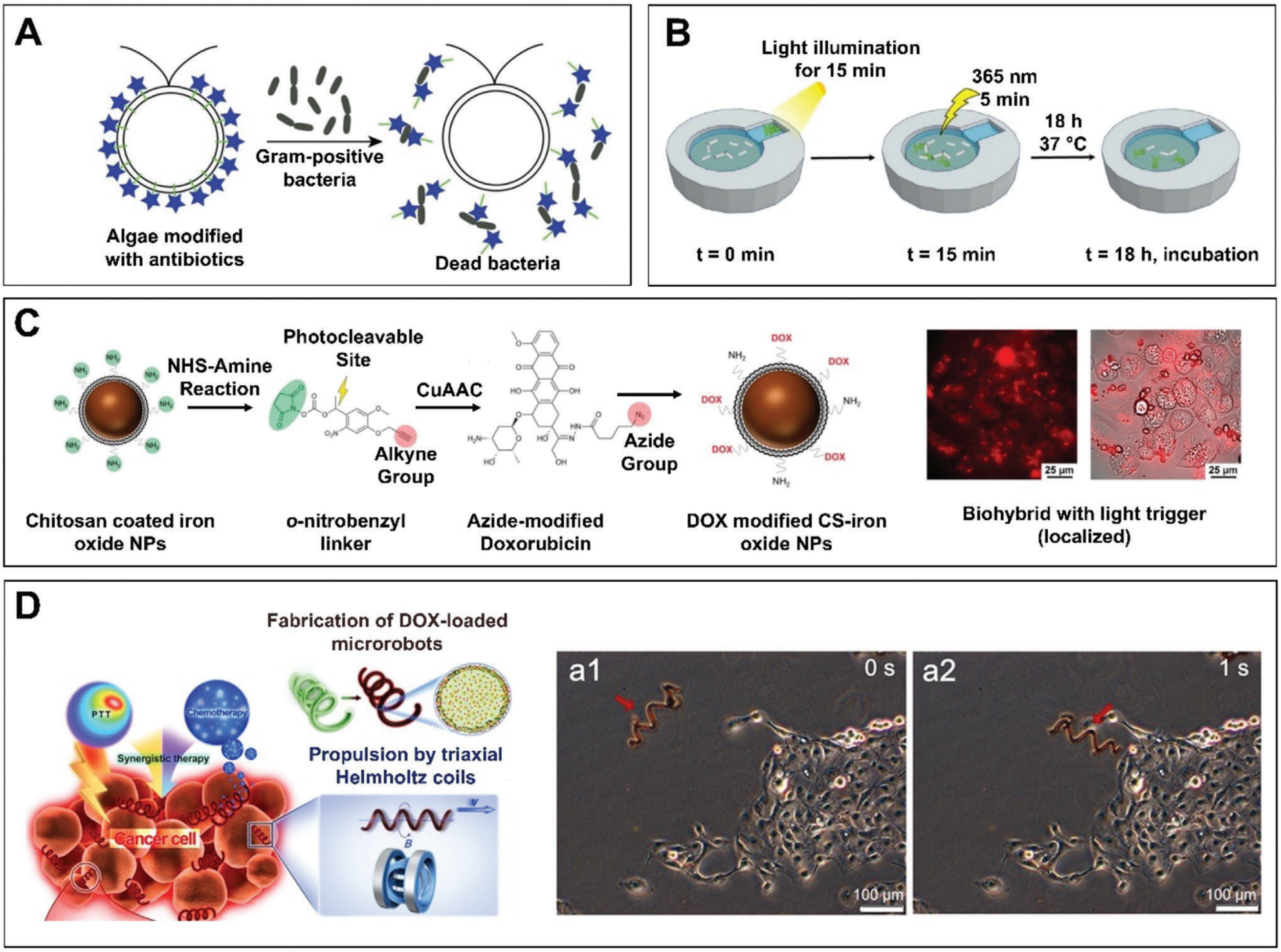

Figure 5. Algae-based biohybrid microrobots for in vitro cargo delivery. A) Antibiotics loaded algae for inhibition of bacterial growth. Reproduced with permission.[49] Copyright 2018, Wiley-VCH. B) Phototaxis-induced antibiotics-bound green algae for in vitro sterilization. Reproduced with permission.[82] Copyright 2021, Elsevier. C) Microalgae functionalized with Doxorubicin via photocleavable linker used for in vitro drug delivery to cancer cells under light trigger. Reproduced with permission.[76] Copyright 2018, Wiley-VCH. D) Doxorubicin loaded (Pd@Au)/Fe_3O_4@Spirulina for targeted cancer cell delivery and synergistic chemo-photothermal therapy. Reproduced with permission.[89] Copyright 2019, American Chemical Society.

Diatom-based drug delivery systems possess a unique type of shell known as frustule—a substance that abounds in hydrated silicon dioxide, which makes diatoms an appealing natural substitution for silicon dioxide nanoparticles. One of the directions of drug loading on diatoms is the anti-inflammatory medicine, as Santos et al. fabricated the algae into diatom silica microparticles, and used it to deliver mesalamine and prednisone,[92] along with indomethacin via the pores of purified diatoms.[93] Antibiotics serve as another drug option to be delivered via diatom, such as streptomycin and levofloxacin.[94] Diatoms were also seen to be effectively conveying anticancer medications. Zobi's teamloaded anticancer complexes onto diatom surfaces and inhibited colorectal cancer cells along with HCT-116 cells in simulated gastric fluid.[95] Another application utilizing diatoms is dopamine. Losic et al. modified the diatom surface with dopamine and iron oxide nanoparticles, granting the drug-loaded diatoms a remote magnetic control for target delivery.[93]

4.2. In Vivo Drug Delivery

Capable of being motile in multiple tissue fluids, such as lung fluid, antibiotic-loaded algae microrobots possess advantages for in vivo applications equivalent to the promising results shown in in vitro experiments. In the animal study conducted by Zhang et al., *C. reinhardtii* microswimmers were modified via click chemistry with ciprofloxacin (Cip) loaded cell membrane-coated nanoparticles (denoted as "algae-NP(Cip)-robot") and were subsequently introduced to *P. aeruginosa* infected lungs of mouse models through Intrathecal administration (**Figure 6**A).[30] The active Algae-NP(Cip)-robot group was shown explicitly the ability to escape from the lung clearance mechanism while residing in the lung with significantly longer retention times than the corresponding static algae-NP(Cip) control. Such prolonged retention in the lung tissue resulted in significant therapeutic efficacy in reducing bacterial burden and substantially lessening animal mortality. The treatment effect of

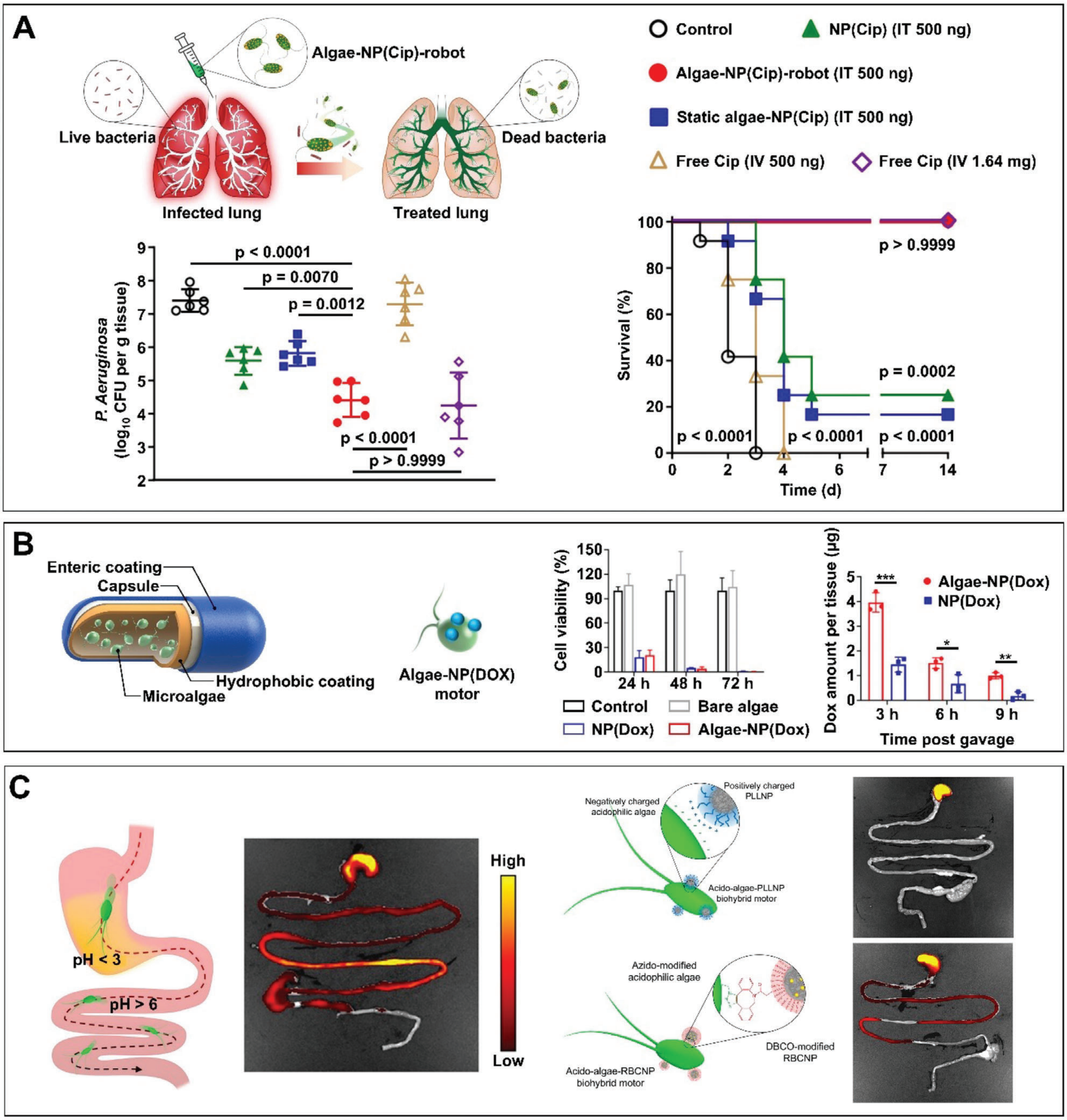

Figure 6. Algae-based biohybrid microrobots for in vivo drug delivery. A) Antibiotic delivery using a green algae microrobot platform for treating fatal bacterial pneumonia. Reproduced with permission.[30] Copyright 2022, Springer Nature. B) Doxorubicin-modified algae biohybrid microrobot-loaded capsule platform, combining oral capsule protection with the long-lasting movement of natural algae, shows in vitro anticancer activity and improved drug retention in the small intestine compared with static drug-loaded nanoparticles. Reproduced with permission.[80] Copyright 2022, AAAS. C) Model fluorescent dye-loaded nanoparticle-bound acidophilic green algae for site-specific gastrointestinal tract drug delivery. Reproduced with permission.[78] Copyright 2022, AAAS.

Algae-NP(Cip)-robot with a dosage of 500 ng by intratracheal administration (IT 500 ng) was only challenged with a similar result of conventional treamentment of free Cip with a dosage of 1.64 mg by intravenous administration (IV 1.64 mg). The 3000-times reduced fraction in dosage amount, however, soundly attests to the delivery effectiveness of active algae-based microrobots in this anti-bacterial treatment.[30]

The possibility of algae-based microrobots to perform GI tract anticancer drug delivery was also investigated. To protect *C. reinhardtii* algae from the gastric fluid, Zhang et al. prepared capsules that preserve algae motility through the harsh gastric environment (Figure 6B).[80] Upon passing the stomach and reaching the intestinal region, the capsules were dissolved by neutral intestinal fluid, releasing the unaffected active algae. The study further demonstrated a successful targeted delivery of doxorubicin (DOX)-loaded algae microrobots in mice's intestines, along with an improved retention time for consistent DOX release. Such a result indicates a practical approach for biohybrid robotic-assisted GI delivery, showing considerable promise toward the treatment of GI disease.[80] To overcome the highly acidic conditions in the stomach, the same group developed an acidophilic algae-based biohybrid robotic platform to deliver model payload (fluorescent dye) to the entire GI tract (Figure 6C).[78] The acidophilic algae displayed efficient long-lasting movement in both highly acidic gastric fluid and neutral intestinal fluid, thus enabling them to pass through the stomach and distribute the entire GI tract. By adjusting the surface physicochemical properties of cargo, multifunctional biohybrid algae microrobots can deliver their payload to selectively targeted biological sites in the GI tract, suggesting considerable promise for GI-related biomedical applications.[78]

Spirulina Platensis (Sp.), the microalgae process a helical structure, also serves as a potential practical drug carrier for in vivo delivery. Zhou et al. extensively investigated the GI tract application by these blue-green algae. In one of their lung metastases of breast cancer study, doxorubicin was loaded onto *Spirulinus Platensis* and distributed in mouse models. The hybridized Sp. displayed a tendency of being trapped by pulmonary capillaries so that the algae were passively targeted to the lung and therefore release DOX at the preferred location.[96] Proceeding to their study of the lung, Zhou et al. demonstrated the potential of using drug-loaded *Spirulina Platensis* for oral delivery study. The hybridized Sp. microrobots were proved to be capable of passing the stomach with an intact structure while reaching the intestine for drug release.[88] Amifostine was also considered as an alternative drug choice. Amifostine-loaded Sp. displayed a significantly enhanced drug accumulation and effective radioprotection in the entire small intestine compared to free drug and enteric capsule controls.[87]

5. Algae-Based Biohybrid Microrobots for Other Applications

5.1. Wound Healing

Wound healing is one of the key processes involved in the recovery of inflammatory disease. Oxygen affects wound healing by regulating various procedures, including cell proliferation, angiogenesis, and vascular regeneration. However, wounds lack oxygen supply in diabetes and thus become hypoxia, which substantially impedes tissue restoration. To meet the requirement of effective oxygen transport, a wound dressing was established by incorporating living microalgae, *Synechococcus elongatus*, into the hydrogel patch. The autotrophic microalgae produced high concentrations of oxygen by photosynthesis using inorganic carbon sources. The microalgae patch further improved the penetration of dissolved oxygen, resulting in greatly improved wound healing in the chronic diabetic mice model.[97] Other algal scaffolds, coupled with synthetic materials such as hydrogel and polymeric patches, have also been applied for promoting wound healing.[98–100] Besides, biohybrid microrobots consisting of chitosan-heparin nanocomplex-coated microalgae have demonstrated effective binding to wound sites for the acceleration of wound healing in diabetes (**Figure 7**A). In the design, green algae *C. reinhardtii* can self-propel to the therapeutic sites and release oxygen to the hypoxia cells under external white light. The payload of polyanion heparin on the algae surface served as a cytokine scavenger by binding with the positively-charged amino acid residues of cytokine via electrostatic interaction in the wound sites. Compared with passive diffusive therapeutic agents to deep wound healing area, the biohybrid algae robotic approach not only provides free oxygen to alleviate the hypoxic conditions in the wounded site but also enhances the penetration and retention of therapeutics due to the active motion of microalgae. The synergistic effect thus led to improvement of the diabetic wound healing. The platform has also shown the feasibility of regulating the immune system for efficiently promoting wound healing.[101]

5.2. Imaging

In vivo or ex vivo imaging techniques is critical to trace microrobots and study their operation inside the body in real-time. Fluorescence imaging is a non-invasive tool to track fluorescent dyes and proteins, which enables a wide range of studies on biological processes occurring at the cellular and tissue levels. Recently, fluorescence imaging has been used in the field of microrobots to facilitate the observation of swarms of artificial flagella.[102] However, synthetic microrobots require the modification of additional fluorophores to generate detectable signals. Natural green algae have shown strong fluorescent signals in the wavelength of red to far-red light due to the chlorophyll fluorescence, thus enhancing their further observation by ex vivo imaging in different body locations from the stomach and intestine to the lung.[30,78,88] Additionally, volvox-based biohybrid microrobots have been established as a multi-mode of imaging platform in a subcutaneous tumor mouse model (Figure 7B). The self-propelled microalgae-based multifunctional robot was fabricated by functionalization of Chlorin 6-loaded chitosan and polydopamine-coated magnetic nanoparticles to the algae surface. The volvox served as a self-propulsion engine, oxygen-generating depot, and fluorescent contrast for imaging trackable relief of hypoxia around tumors. The functional nanoparticles consisted of photodynamic agents (Chlorin 6) and magnetic contrast (Fe_3O_4) can be applied for photothermal, photoacoustic, and magnetic resonance imaging. These natural biohybrid robots further improved synergistic photodynamic and photothermal tumor therapy by enhancing the flow and mixing of localized biofluids.[103]

Magnetic resonance imaging (MRI) is another approach to offer detailed information on biological images. MRI demonstrates deep tissue imaging since it has a high spatiotemporal resolution and enhanced soft tissue contrast. The technique has been widely applied to the diagnosis of disease and imaging-guided drug delivery. Recently, MRI has been employed for localizing biohybrid microrobots in the body.[32] For example, the collective motion behavior of Spirulina-based helical microrobots was tracked by MRI in the rat stomach (Figure 7C). First, the microrobots were fabricated by coating superparamagnetic nanoparticles onto the

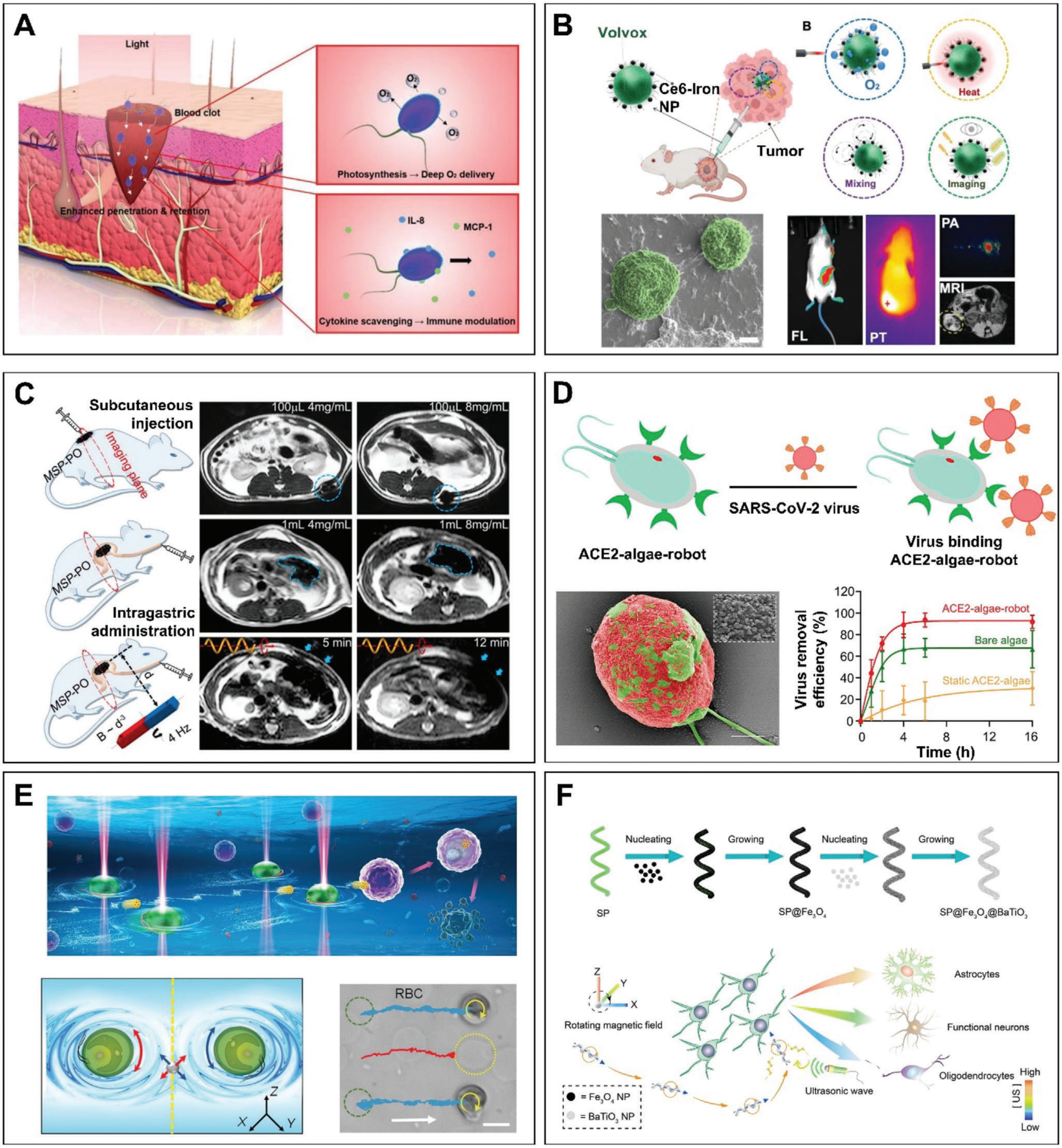

Figure 7. Additional applications of biohybrid algae robotic system. A) Biohybrid algae-based microrobots for promoting chronic wound healing in diabetes. Reproduced with permission.[101] Copyright 2022, Wiley-VCH. B) Photodynamic and magnetic agents loaded *Volvox* biohybrids microrobots for enhancing multi-mode imaging in the subcutaneous tumor mice model. Reproduced with permission.[103] Copyright 2022, Wiley-VCH. C) Fe3O4-nanoparticles loaded *Spirulina* biohybrid magnetite microrobots for in vivo MRI imaging-guided therapy. Reproduced with permission.[32] Copyright 2017, AAAS. D) ACE2-receptor functionalized *Chlamydomonas reinhardtii* micromotor for efficient capture and removal of target SARS-CoV-2 virus from diverse aquatic environments. Reproduced with permission.[39] Copyright 2021, American Chemical Society. E) Light-induced swimming algae microrobot tweezers for cargo transportation. Reproduced with permission.[117] Copyright 2021, American Chemical Society. F) Magnetic-powered biohybrid *Spirulina* microrobots for cargo delivery to stem cells and further cell modulation using the acoustic field. Reproduced with permission.[121] Copyright 2021, American Chemical Society.

microalgae surface. The swarm of biohybrid magnetic microrobots was examined by external MRI after administration to subcutaneous tissue and stomach. The MRI contrast was dependent on the concentration of delivered microrobots and Fe_3O_4 coating thickness. The degradability of the chemical composition of microalgae in physiological media in vitro further meets the designated task requirement for in vivo applications.

Imaging-guided drug delivery of microrobots appears to be an attractive platform for the treatment of pathogenic infections. Photoacoustic (PA) imaging provides a powerful imaging modality based on PA effects when ultrasound waves identify differences in optical absorption. PA imaging has also been proposed as a promising approach for tracking moving objectives in the body since it allows deep tissue imaging and high resolution for detecting the spectral characteristics of microswimmers, which is necessary for ex vivo and in vivo studies. For example, a magnetized Spirulina matrix combined with polydopamine coating (PDA-MSP) was made to enhance the photoacoustic imaging capability and photothermal effect in real-time monitoring. Using a pathogenic bacterial infection as an example, swarms of PDA-MSP microswimmers can perform real-time image tracking and have precise theranostic characteristics.[104]

5.3. Water Remediation

The contamination of water sources is a major problem in today's society. In order to provide people with potable water and protect aquatic ecosystems and other forms of life from contamination, there is an urgent need for the development of more efficient and cutting-edge water treatment. The use of active microrobots represents a novel and effective method for the fast removal of various environmental pollutants from contaminated water.[105,106] Based on material design and motion mechanisms, synthetic microrobots driven by fuels or external fields were able to improve the removal of heavy metal,[35] organic dyes,[107] chemical warfare agents,[108] oil spills,[109] microplastics,[110] and biological pollutants.[111] The scope of using traditional microrobots for water purification has been well summarized by a recent review article.[2] Such motile microscale robots add a new dimension, based on the rapid motion and induced mixing, to water decontamination protocols, offering considerable promise to increase substantially the decontamination efficiency while reducing the cleanup time and costs. However, conventional microrobotic remediation schemes have been limited by the complex actuation apparatus, short operation period, and restricted operating media. In nature, microorganisms are capable of swimming constantly and generating turbulence strong enough to enhance water mixing in various aqueous matrices.[112] Besides transporting the reactive materials throughout the contaminated aquatic media, the collective motion of microorganisms has been shown to enhance diffusion processes. For example, rotifer—a marine microswimmer—was modified with functionalized microbeads and showed notable capability of removing insecticide and nerve agent.[113] Specifically, the active motion of microalgae based on the flagella beating improves the water mixing and mass transfer, greatly accelerating the solution cleanup processes while obviating the need for external stirring.[67] Thus, creating microalgae biohybrid microrobots—combining the autonomous long-lasting swimming capability of microalgae with the decontamination properties of their functional moieties—is an attractive approach for water remediation. For example, an active green algae-based biohybrid microrobot system was designed to offer a remarkably efficient means of capturing and removing target virus from diverse aquatic environments (Figure 7D). The fabrication of algae-based microrobot involved the use of click chemistry to functionalize microalgae with angiotensin-converting enzyme 2 (ACE2) receptors that target specifically the spike protein of SARS-CoV-2 virus.[39] The ACE2-functionalized algae robots display greatly improved "on-the-fly" binding virus removal efficiency from wastewater compared to bare algae without surface functionalization and static counterparts, highlighting the specific virus-binding properties of ACE2 receptors on the alga surface and the significance of the motion behavior of biohybrid microalgae robots, and the prospects for future environmental decontamination applications.

5.4. Cargo Transportation

Transport and delivery of cargo represent a major function of modern microrobotic systems.[4] Manipulation of objects by optical or acoustic tweezers for precise cargo transportation holds great promise for many biomedical applications.[114,115] Using a similar method, biflagellate unicellular algae were regarded as microrobot tweezers to trap cargos for controllable cargo delivery (Figure 7E).[116] In the design, versatile cargos, including SiO_2 microparticles, red blood cells, or bacteria, can be trapped within two green algae by the strongly localized fluid flow fields generated by the rotating microalgae. This strategy is also beneficial to deliver therapeutic cargo to a single cell for precise therapy. In another optical system, a bio-tweezer was able to maneuver the cargo position via self-actuation of microalgae-based on the light-triggered high concentration of motile algae.[117,118] In addition, the response of algae to light stimuli can be utilized to control the direction of algae to a designated location. Xie et al. developed an optical microalgae-based guiding system by integrating swimming algae with micro-objects of different shapes.[119] The phototaxis property of algae was employed to control the swimming direction and assembly of algae to the micro gear shape of cargo. The cargo-loaded microalgae robots can travel 270 mm within 60 min operation under external light control. Additionally, magnetically driven *Spirulina*-based biohybrid microrobots were demonstrated for targeting neural stem cells (Figure 7F).[120] The microrobot platform was constructed with a biodegradable helical microalgae template, superparamagnetic Fe_3O_4 nanoparticles and piezoelectric $BaTiO_3$ nanoparticles as functional units. Under a rotational magnetic field, the microrobot performs precise cargo transportation to the predetermined site of a single neural stem cell. The piezoelectric material was responsible to generate electric stimulation on the modulation of the targeted stem cells to differentiate into versatile cell types.[120]

6. Conclusions and Perspectives

We have reviewed the latest progress of biohybrid microrobots using algae as living actuation elements. In particular, we have discussed the primary properties of microalgae involved in the design and operation of microrobots, recent approaches for preparing integrated algae biohybrid robotic systems, and algae robotic-driven applications including drug delivery, bioimaging, and water remediation. The unique capabilities of algae-based microrobots have been presented, along with the pros and cons of such biohybrid platforms compared to other biohybrid microrobots as well as to common synthetic microrobots.

A major advantage of using algae for establishing microrobotic systems is the fast growth rate of algae, which is beneficial for scalable use. Typically, the model strain, *Chlamydomonas reinhardtii*, grows rapidly with a doubling time of around 6–12 h. It can achieve a high density of 2×10^7 mL^{-1} after 4 days of cultivation in an optimal culture environment. The ease of cultivation also offers a cost-effective way for rapid and scalable production since algae growth is only dependent on the water, nutrition from carbon and nitrogen salts, as well as the suitable temperature and light-dark cycles. Additionally, many kinds of microalgae, ranging from *Chlamydomonas*, *Volvox*, and *Euglenida*, can be selected to construct the biohybrid microrobots considering their unique flagellate structure for self-motility. The small-scale dimensions of algae enable the biohybrid system to use in many complex surroundings, e.g., passage through narrow microchannels and navigation in human blood vessels. Some strains can thrive in harsh conditions, such as hot springs, cold water, acidic and alkaline lakes, and hypersaline marine environments.[73] The adaptation of extremophiles with continuous and autonomous swimming further extends the utility of microalgae-based robots in challenging conditions and extreme environments, whereas synthetic devices consisting of metallic components show poor lifetime or failure to use, making their adoption in robotics unlikely in the future. Due to the advantages of instinctive unicellular structure, the microalgae are biodegradable and can be metabolized in gastrointestinal tract delivery. Furthermore, it should be noted that algae can be also swallowed by immune cells, e.g., alveolar macrophages, and thus be cleared after their robotic operations in the deep lung without triggering an immune response. Unlike the safe in vivo use of microalgae biohybrid drug delivery systems, utilization of other microbes, such as bacteria biohybrids, will result in severe toxicity and immunogenicity.

One of the challenges of using biohybrid robots is their controllability. Phototaxis offers an accurate and attractive steering mode for the navigation of self-propelled microalgae robots to the desired sites in different applications. Using the same strategy, swarming algae robots, where the large group of algae executes a collective behavior, are expected to reach the polluted area and complete the desired tasks together. In the biomedical field, however, the visible light used for controlling the algae directionality cannot penetrate the tissue at a deep level, limiting its further use in desired body locations. The current state of the art can only be applicable for the controlled delivery to skin or would infections. To address the issue of limited control by external light source with low tissue penetration, optogenetic strategies can provide an alternative approach to shed light on cells and assist the algae-targeted delivery. In addition, synthetic biology can be also introduced in the future to equip algae with engineered sensors to follow the detectable signals, e.g., chemicals, infrared light, or heat. The magnetic control of biohybrid robots based on their decoration with magnetic particles, is another attractive option because magnetic fields can effectively penetrate the tissue and provide a precise spatiotemporal adjustment of microrobots. Versatile chemical groups on the alga surface will enable the conjugation of functional probes for the recognition and detection of different biomarkers related to disease in future studies. Future developments and applications of algae-based biohybrid microrobots require joint multidisciplinary efforts of researchers from diverse fields ranging from materials science, physics, chemistry, biology, clinical medicine, and artificial intelligence. Overall, biohybrid microrobots, combining the powerful capabilities of algae actuation elements and diverse functional synthetic components, have the potential to bring in a new era of powerful microrobots for diverse biomedical and environmental applications within the next ten years.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

algae microrobots, biohybrid micromotors, drug delivery

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