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Recent Progress in Enzyme-Driven Micro/Nanoswimmers: from Fundamentals to Potential Applications

Gerardo Salinas, Seyyed Mohsen Beladi-Mousavi, Alexander Kuhn

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27 their use for biomedical applications, such as biorecognition, biosensing, imaging and
 28 nano-surgery. In order to circumvent these limitations, more recent studies suggested
 29 miniaturized engines based on enzymatic catalysts, providing unique characteristics such as
 30 biocompatibility of the swimmers and fuels, as well as adaptability to different
 31 environments. Such self-propelled enzymatic micro/nanoswimmers, powered by different
 32 enzymes, have been proposed for exciting potential applications e.g. active targeted drug
 33 delivery [3] or blood-brain barrier crossing [4], which might be important for transporting
 34 pharmaceutical compounds toward localized areas inside organs. The rational design of
 35 these swimmers, incorporating various enzymes, is a critical factor concerning their
 36 performance, in particular the efficiency of their motion in complex environments. Hence,
 37 swimmers with different shapes (spherical or tubular) and sizes (from 200 nm to 5 mm),
 38 decorated with single or multiple enzymes, have been developed [5•]. Among the different
 39 enzymes used to power motion of micro- and nano swimmers, two different enzymatic
 40 processes are mostly used. The first category is based on redox reactions like it is the case
 41 for glucose oxidase, catalase, bilirubin oxidase or peroxidase, whereas a second category
 42 employs hydrolysis reactions e.g. urease and lipase (Table 1). The present review aims to
 43 discuss the recent advances concerning the mechanisms of propulsion and the potential
 44 applications of single- and multiple-enzyme powered micro/nanoswimmers. In addition,
 45 this report especially focuses on devices where motion is achieved by enzymatic process
 46 based on redox reactions or fully triggered by electrochemical processes.

47 Table 1. Representative enzymatic reactions used for the propulsion of micro and nanoswimmers.

Enzymatic processes using redox reactions	
Enzyme	Reaction
Glucose oxidase (GOx)	β -D-Glucose + O ₂ + H ₂ O → H ₂ O ₂ + D-glucono-1,5-lactone
Catalase	H ₂ O ₂ → 2H ₂ O + O ₂

Bilirubin oxidase (BOD)	$\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow 2\text{H}_2\text{O}$
Peroxidase	$\text{H}_2\text{O}_2 + \text{AH}_2 \rightarrow 2\text{H}_2\text{O} + \text{A}$
Enzymatic processes using hydrolysis reactions	
Urease	$(\text{NH}_2)_2\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + 2\text{NH}_3$
Lipase	triglyceride + 3H ₂ O → glycerol + fatty acids

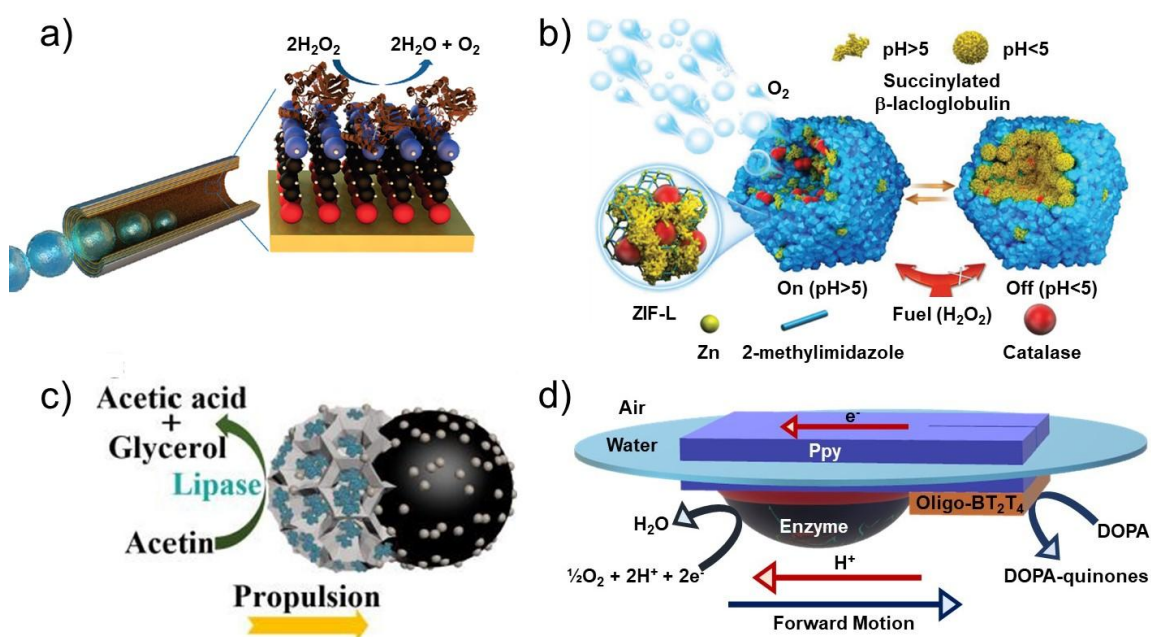
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49 2. Single-enzyme-powered micro/nanoswimmers

50 In the majority of the literature examples, the motion of single-enzyme-powered swimmers
51 is achieved via bubble-propulsion or self-diffusiophoretic mechanisms. Self-propulsion
52 allows decreasing mass transport limitations and enabling selective directional motion
53 towards specific locations. These swimmers are mostly built by immobilizing various
54 enzymes, such as urease [3,6-8], acetylcholinesterase, glucose oxidase, aldolase [9],
55 catalase [10-12], and lipase [13,14] on a large variety of miniaturized objects with different
56 architectures, by covalent binding, encapsulation, adsorption or drop-casting. For example,
57 Schmidt, et al. designed hybrid Ti/Au-catalase micro-tubes, where motion is based on the
58 enzymatic decomposition of H₂O₂ into water and oxygen (Figure 1a) [15•]. These devices
59 move faster, and with higher efficiency at low H₂O₂ concentrations compared to those
60 comprising a Pt catalyst. Recently, pH-responsive biocatalytic microswimmers were
61 designed by assembling catalase and succinylated β-lactoglobulin in a zeolitic imidazolate
62 framework-L (ZIF-L) (Figure 1b) [16•]. Motion control is achieved due to the pH-induced
63 reversible gelation process of β-lactoglobulin. At neutral pH, β-lactoglobulin is permeable,
64 enabling H₂O₂ to reach the enzymatic sites, causing motion due to a bubble propulsion
65 mechanism. However, at slightly acidic pH, gelation occurs, blocking the access of fuel and
66 stopping the motion. A similar principle was used to produce submarine-like
67 microswimmers that use buoyancy forces to control vertical motion. In this case poly-(2-

68 diisopropylamino)-ethyl methacrylate (PDPA) and catalase were incorporated into the ZIF-
69 L structure [17]. At neutral pH, the oxygen generated by the enzymatic reaction binds to the
70 hydrophobic PDPA, leading to an ascending motion. In contrast, at slightly acidic pH,
71 PDPA becomes hydrophilic, causing the release of oxygen, and consequently a sinking of
72 the device. In a recent work, protein micro-tubes, functionalized with urease, exhibit self-
73 propulsion in the presence of urea, due to a concentration gradient established by the
74 enzymatic reaction in the inner part of the tube [18] Motion of dissymmetric magnetic
75 microparticles, asymmetrically modified with multilayers of biotinylated urease, has also
76 been reported [19]. Most importantly, these devices move at physiological urea
77 concentrations (10 mM) and in liquids with viscosities four times higher than the viscosity
78 of water, which is important for future *in vivo* applications. Ma et al. synthesized hollow
79 mesoporous SiO₂ microspheres functionalized with urease at the sphere surface [20]. The
80 resulting propulsion is due to the intrinsic asymmetry of the SiO₂ spheres, generating ionic
81 self-diffusiophoresis caused by the enzymatic decomposition of urea. An interesting
82 alternative is the design of systems that can be triggered by different stimuli, thus
83 facilitating motion in complex fluids. For example, lipase-modified dendritic
84 silica/carbon/Pt dissymmetric nanoparticles can move either via self-diffusiophoresis or
85 bubble propulsion, as well as self-thermophoresis (Figure 1c) [21]. In these devices, the Pt
86 nanoparticles catalyze the disproportionation reaction of H₂O₂, the asymmetric
87 photothermal effect of the carbon part causes a thermal gradient when irradiated with near-
88 infrared light, and lipase, loaded in the pores of the dendritic structure, decomposes a
89 triglyceride, causing concentration gradients. Finally, Arnaboldi et al. developed hybrid
90 bioelectrochemical swimmers, for which motion is achieved when coupling the
91 spontaneous reduction of oxygen by bilirubin oxidase (BOD) with the enantioselective

92 oxidation of 3,4-dihydroxyphenylalanine (L- or D-DOPA) by inherently chiral oligomers
 93 ((R)- or (S)-2,2'-bis[2-(5,2'-bithienyl)]-3,3'-bithianaphthene (oligo-BT₂T₄)) (Figure 1d)
 94 [22••]. Both, BOD and the enantiopure oligomers are immobilized on opposite extremities
 95 of a freestanding miniaturized polypyrrole film, thus allowing electron transfer between the
 96 cathodic and anodic sites. This electron transfer across the microswimmer is accompanied
 97 by a proton flux, resulting in self-electrophoretic propulsion.



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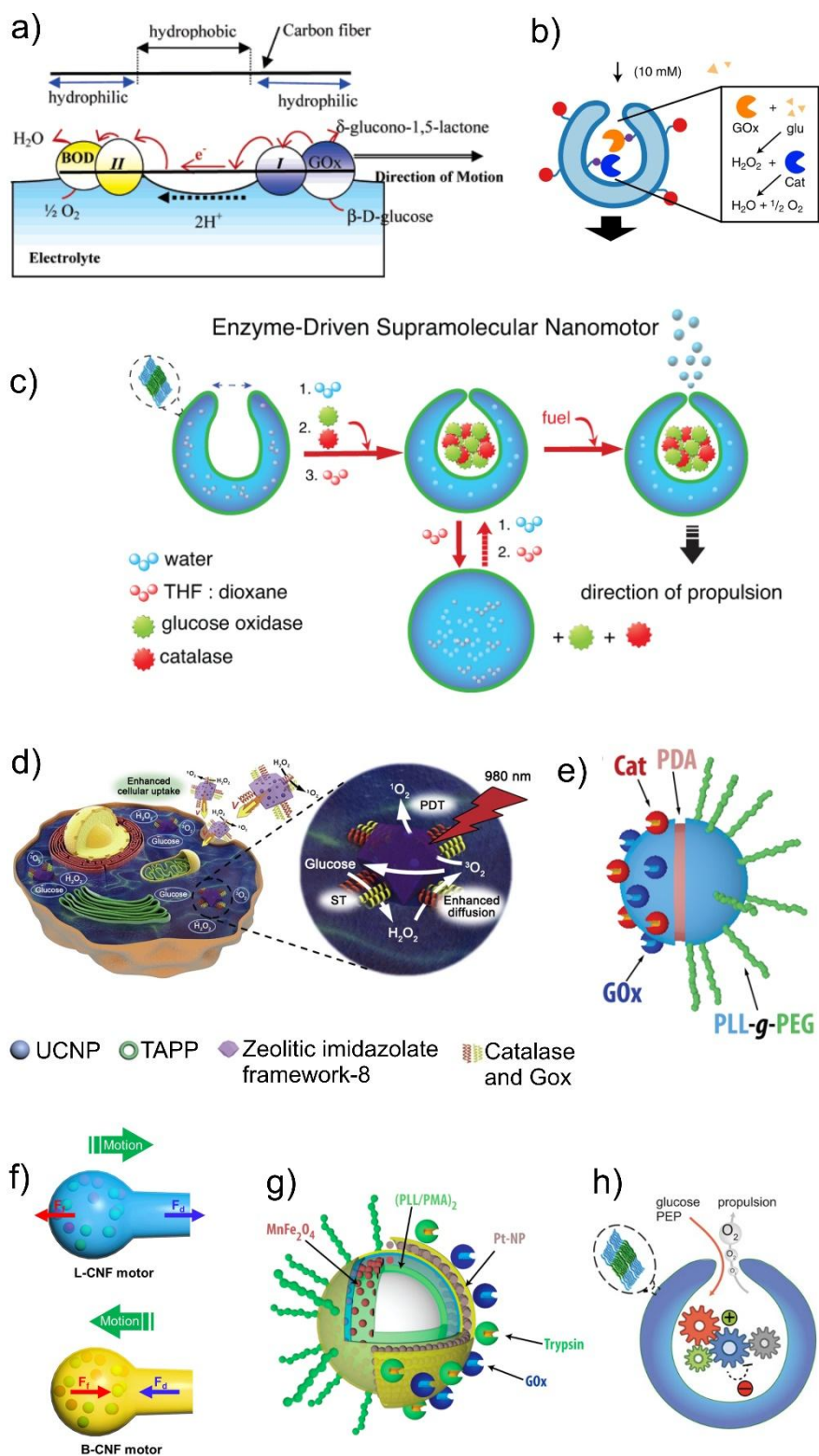
99 **Figure 1.** Schematic illustrations of different single-enzyme-powered
 100 micro/nanoswimmers. a) Open view of a hybrid biocatalytic micro-tube (left), and surface
 101 modification of the inner Au layer allowing the enzymatic decomposition of H_2O_2 . Adapted
 102 from reference [15•]. b) Structure and propulsion mechanism of a biocatalytic
 103 microswimmer with pH-responsive on/off motion. Adapted from reference [16•]. c) Motion
 104 of a lipase-modified dendritic silica/carbon/Pt nanoparticles Janus-type swimmer, based on
 105 self-diffusiophoresis. Adapted from reference [21] d) Design of a hybrid

106 bioelectrochemical swimmer in an upside-down configuration at the air/water interface
107 together with a representation of the mechanism of selective motion induced by proton flux.
108 Adapted from reference [22••].

109 3. Multiple-enzyme-powered micro/nanoswimmers

110 Multiple-enzyme-powered micro/nanoswimmers have been introduced (i) to achieve higher
111 velocities via combining multiple propulsion mechanisms; (ii) to avoid toxic fuels,
112 particularly H_2O_2 ; (iii) to facilitate the adaption to different environments; and (iv) to
113 generate more functionalities. Hence, swimmers modified with different enzymes,
114 promoting enzymatic domino reactions have been developed. [23•-28]. From a more
115 historical point of view, Mano et al. decorated a carbon fiber with GOx/redox polymer I
116 (RPI) as a glucose oxidizing microanode at one extremity, and BOD/RPII as an O_2
117 reducing microcathode at the other end (Figure 2a). In the presence of glucose, the electron
118 flow $\text{Glucose} \rightarrow \text{GOx} \rightarrow \text{RPI} \rightarrow \text{fiber} \rightarrow \text{RPII} \rightarrow \text{BOD} \rightarrow \text{O}_2$ is accompanied by an ion
119 flow along the carbon fiber, resulting in its propulsion at the water/oxygen interface [29••].
120 Feringa, et al. designed swimmers based on multi-wall carbon nanotubes (MWCNTs),
121 decorated with GOx and catalase to transform glucose into H_2O_2 and then to water and
122 oxygen, respectively. Such domino reactions avoid the addition of H_2O_2 and hence lower
123 the biotoxicity [30]. Following a similar elegant principle, Wilson et al. proposed bowl-
124 shaped polymeric systems with a narrow opening containing GOx and catalase enzymes
125 (Figure 2b) [31•]. These systems not only prevent the hydrolysis of the protected enzymes,
126 but also allows generating motion of the biocompatible swimmers in the presence of
127 physiological amounts of glucose (Figures 2b-c) [32]. In another example, Ma et al.
128 assembled a core-shell nanoswimmer utilizing metal-organic frameworks to promote

129 photodynamic therapy (PDT) and starvation therapy (ST) (Figure 2d). In the involved
130 domino reaction, GOx initially catalyzes the decomposition of intracellular glucose to
131 promote cell starvation and H₂O₂ generation, whereas catalase decomposes the generated
132 H₂O₂, thus triggering motion and oxygen production, which promotes PDT [33]. An analog
133 enzymatic system was employed by Städler et al., based on Janus microswimmers
134 decorated by enzymes only on one hemisphere (Figure 2e). The diffusion of these
135 biocompatible swimmers is enhanced in the presence of glucose [34]. In a more recent
136 study, He et al. elaborated a nanoswimmer powered by GOx and catalase, trapped in a
137 carbonaceous nanoflask (CNF), moving in a glucose solution via a domino reaction
138 mechanism[35], similar to previous studies (Figure 2f)[30-34]. In this work, it was
139 demonstrated that changes in surface wettability (hydrophobicity or hydrophilicity) of the
140 nanoswimmer can dictate the direction of motion [35]. In another study, a dissymmetric
141 microparticle was proposed where one side included two enzymes, GOx and trypsin, which
142 were working as independent engines using different fuels, namely glucose and
143 bis(benzyloxycarbonyl-L-arginine amide) (Figure 2g). Both enzymes contribute to the
144 enhanced diffusion of swimmers using biocompatible fuels [36]. Finally, Van Hest et al.
145 reported swimmers with a shape similar to the one of Figure 2b, containing multiple
146 enzymes, promoting several feedforward loops using various substrates to produce kinetic
147 energy as the output of the enzymatic network (Figure 2h) [37••].



148

149 **Figure 2.** Schematic illustrations of dual/multiple-enzyme-powered micro/nanoswimmers.

150 a) The structure and propulsion of a carbon fiber decorated with GOx and BOD. Adapted

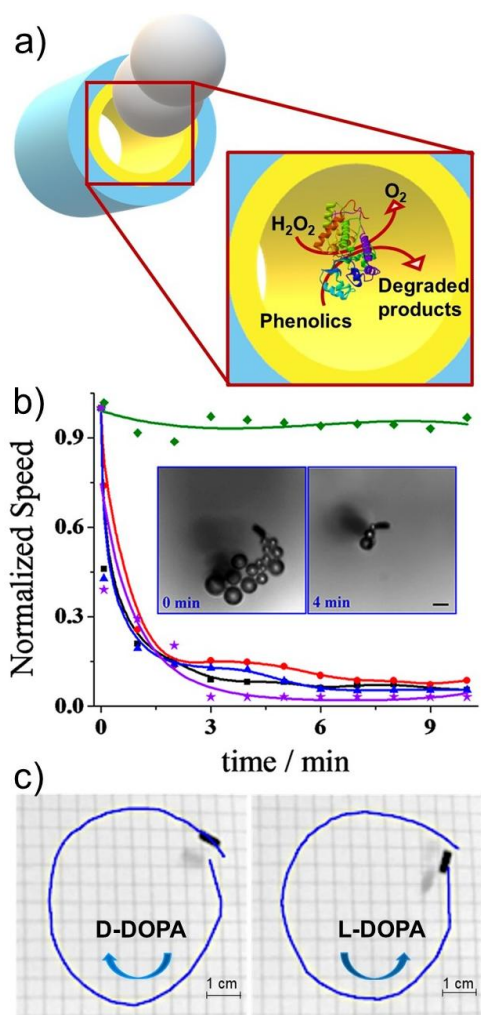
151 from reference [29••]. b) Biodegradable polymeric nanoswimmer encapsulating GOx and
152 catalase. Adapted from reference [32]. c) Dual-enzyme (GOx-catalase) loaded
153 supramolecular bowl-shaped nanoswimmer. Adapted from reference [31•]. d) Core-shell
154 enzymatic nanoswimmer for synergetic photodynamic (PDT) and starvation therapy (ST).
155 Adapted from reference [33]. e) Janus microswimmer with one hemisphere decorated with
156 GOx and catalase. Adapted from reference [34]. f) Nanoswimmer powered by GOx and
157 catalase trapped in a carbonaceous nanoflask (CNF). Adapted from reference [35]. g) Janus
158 microswimmer decorated with GOx-Pt and trypsin. Adapted from reference [36]. h)
159 Nanoswimmer containing four enzymatic cycles to convert glucose and
160 phosphoenolpyruvate (PEP) into mechanical energy for the propulsion of the nanoparticle.
161 Adapted from reference [37••].

162 4. Applications

163 Enzyme-powered micro/nanoswimmers have gained considerable attention in sensing,
164 cargo delivery [38], and bioremediation [39•]. The enzymatic degradation of azo-dye
165 pollutants by using laccase-based poly-(3,4-ethylenedioxythiophene)-polypyrrole/Pt
166 (PEDOT-PPy-COOH/Pt) tubular microswimmers has been reported [40•]. In this case,
167 disproportionation of H₂O₂ on Pt, present in the inner part of the tubes, is used to produce
168 motion, whereas, laccase is immobilized at the outer part of the swimmer in order to
169 catalyze the oxidation of the azo-dye compounds. An interesting alternative is a design of
170 “2 in 1” systems, where the enzymatic reaction enables the propulsion mechanism and
171 catalyzes the decomposition of organic pollutants. For example, lipase-modified
172 mesoporous silica nanoparticles present random-walk in triglyceride/PBS solutions [41].
173 As motion is triggered by the catalytic decomposition of triglycerides, causing a

174 concentration gradient, these devices can act as active cleaners of fully and partially soluble
175 oils. In a recent study, PEDOT-Au/peroxidase microswimmers were used as dynamic
176 catalytic systems for the removal of phenolic compounds, such as phenol, bisphenol A,
177 guaiacol, pyrogallol and catechol [39•]. In these devices the immobilized peroxidase not
178 only catalyzes the decomposition of H_2O_2 to form oxygen (bubble propulsion), but also
179 degrades the phenolic compounds (Figure 3a). Different urease-powered pH-responsive
180 swimmers have been designed for the delivery of chemotherapeutic agents and bioimaging
181 probes [3,42,43]. Drug-loaded catalase-powered nanoswimmers have been used for local
182 drug delivery against inflammations [44]. These devices present positive chemotaxis
183 towards H_2O_2 concentration gradients, produced by phorbol ester-stimulated macrophages.
184 Recently, catalase-powered Au-mesoporous silica nanoparticles, functionalized with
185 disulfide-linked oligo-(ethylene glycol) chains, acting as Janus gatekeepers have been
186 reported [45]. These devices exhibit motion via the catalytic decomposition of H_2O_2 and
187 deliver their cargo upon recognition of a reducing agent (glutathione). Finally, enzyme-
188 powered swimmers, equipped with different transducers for pH, DNA, and biomarkers,
189 have been used for sensing [46-48]. An interesting alternative is to take advantage of the
190 *on-off* mode of light emission in the presence of a fluorescent molecule. For example,
191 catalase-powered dissymmetric rods, functionalized with tetraphenylethene (TPE)
192 derivatives and fluorescein isothiocyanate (FITC) as fluorophores, exhibit self-propulsion
193 due to the enzymatic decomposition of H_2O_2 , and fluorescence changes from blue to green
194 after the capture of tumor cells [49]. Another approach is the use of the changes in the
195 swimming behavior, *i.e.* trajectory or speed, to detect species of interest. For example,
196 PEDOT/Au-catalase micro-tubes exhibit biocatalytic inhibition of the enzyme in the
197 presence of chemical stress (*e.g.*, heavy metals, pesticides and herbicides), which results in

198 a decrease of bubble production, directly detectable via their swimming behavior (Figure
 199 3b) [50•]. Recently, the directional control of self-electrophoretic BOD/Ppy/oligo-BT₂T₄
 200 swimmers has been demonstrated [22••]. Enantioselective clockwise or anti-clockwise
 201 motion is caused in this case by a site-specific proton flux associated with the oxidation of
 202 an enantiomer present in the solution (Figure 3c). In addition, the curvature of the track can
 203 be used for the direct visualization of the degree of enantiomeric excess in the solution.



204

205 **Figure 3.** a) Scheme of a “2 in 1” peroxide-driven micromotor for bioremediation of
 206 phenolic pollutants. The active inner part of the swimmer catalyzes hydrogen peroxide

207 decomposition (propulsion) and the degradation of phenolic compounds by the
208 immobilized peroxidase Adapted from reference [39•]. b) Normalized speed as a function
209 of time for a PEDOT/Au-catalase micro-tube in the presence of: 100 μM Hg (black square),
210 0.6 mM Cu (purple stars), 25 μM sodium azide (red circle), 625 mM aminotriazole (blue
211 triangle), and a control experiment without the toxins (green diamond). Inset: time-lapse
212 images of the microswimmer recorded after 0 and 4 min swimming in a 100 μM Hg
213 solution. Scale bar, 6.0 μm . Adapted from reference [50•]. c) Macroscopic enantiospecific
214 motion of hybrid bioelectrochemical swimmers at the air/water interface of a solution
215 containing 5 mM of D-DOPA (left) and 5 mM of L-DOPA (right). Adapted from reference
216 [22••].

217 5. Conclusions and perspectives

218 In this review, we have examined recent work in the field of enzyme-driven
219 micro/nanoswimmers based on different propulsion mechanisms. In the case of single-
220 enzyme-powered swimmers, the enzymatic reaction triggers either the asymmetric release
221 of bubbles or the self-generation of chemical or electric gradients, causing the propulsion of
222 the devices. In contrast to this, in multiple-enzyme swimmers, a cascade of enzymatic
223 reactions can generate motion based on bubble propulsion or self-electrophoresis. In
224 addition, different applications of these devices are presented, where the enzymatic reaction
225 is used either for the degradation of organic molecules or as analytical tools. These devices
226 allow biomimetic self-propulsion, associated with improved biocompatibility, and efficient
227 energy conversion. Their size and controlled trajectories might enable their use in different
228 organs and cells. Nevertheless, there are still many issues to address, e.g. the toxicity of
229 some fuels, the easy and direct visualization, the efficient biodegradability and the limited

230 life-time of the devices (recyclability). However, different approaches have been proposed
231 to solve these problems, like modifying the shape, increasing the catalytic performance of
232 the enzymes or using cascade reactions, and employing materials able to be digested
233 completely by enzymes (e.g., proteases) or in biological media. Finally, the enzyme-based
234 nanoswimmers, in particular those using redox reactions, have shown promises for
235 biomedical applications. However, in order to develop drug delivery systems for “real
236 world” *in vivo* applications, tiny robotic systems inspired by biological reactions in which
237 robots and fuels are entirely biocompatible are mandatory and deserve additional research
238 efforts. Furthermore, many other features of the robots, most importantly stability,
239 biocompatibility, selectivity, directionality and the velocity in different biological
240 environments need to be significantly improved prior to their commercialization.

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245

246 7. References and recommended reading

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