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1 Article

2 **Hollow Bioelectrodes based on Buckypaper Assembly. Appli-**
3 **cation to the Electroenzymatic Reduction of O₂**4 **Paulo Henrique M. Buzzetti, Anastasiia Berezovska, Yannig Nedellec, Serge Cosnier***

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7 **Abstract:** A new concept of hollow electrode based on the assembly of two buckypapers creating a
8 microcavity which contains a biocatalyst is described. To illustrate this innovative concept, hollow
9 bioelectrodes containing 0.16–4 mg bilirubin oxidase in a microcavity, were fabricated and applied
10 to electroenzymatic reduction of O₂ in aqueous solution. For hemin-modified buckypaper, the
11 bioelectrode shows a direct electron transfer between multi-walled carbon nanotubes and bilirubin
12 oxidase with an onset potential of 0.77 V vs RHE. The hollow bioelectrodes showed good storage
13 stability in solution with an electroenzymatic activity of 30 and 11% of its initial activity after 3 and
14 6 months, respectively. The co-entrapment of bilirubin oxidase and
15 2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) in the microcavity leads to a bioelectrode ex-
16 hibiting mediated electron transfer. After 23 h of intermittent operation, 5.66 × 10⁻⁴ mol of O₂ were
17 electroreduced (turnover number of 19245), the loss of catalytic current being only 54% after 7 days.

18 **Keywords:** hollow bioelectrode, buckypaper, microcavity, oxygen electroreduction, bilirubin oxi-
19 dase
20

21 **1. Introduction**

22 Enzymatic biofuel cells that convert chemical energy into electrical energy by
23 electroenzymatic reactions offer attractive potentialities for powering disposable elec-
24 tronic systems [1,2]. However, the development of enzymatic biofuel cells is confronted
25 with two major technological obstacles, namely their short operational and storage life-
26 time in solution and, to a lesser extent, their low power output [3,4]. The low stability of
27 the bioelectrodes of the enzymatic fuel cells is linked to the deactivation of the immobi-
28 lized enzymes and seems inevitable. Regarding the power of the biofuel cells, the latter is
29 partly related to the quantity of enzyme immobilized per unit of conductive surface and
30 to the efficiency of the electrical connection between the enzyme and the electrode.

31 The enzyme electrodes of biofuel cells result from the immobilization of different
32 redox enzymes on the surfaces of the electrodes for their electrical connection. This fixa-
33 tion of enzyme can be obtained by chemical grafting or affinity interactions or by physi-
34 cal entrapment. Regarding the immobilization by covalent or non-covalent bond, this
35 configuration offers good access of the substrate and redox mediators to the immobilized
36 enzyme but the quantity of biocatalyst is limited to a quasi-monolayer at the modified
37 electrode-solution interface thus strongly limiting the power.

38 Although immobilization in a 3D matrix increases the surface density of enzymes,
39 this entrapment process induces a denaturation process due to the non-biocompatible
40 environment. Additionally, the activity of the entrapped enzyme can be affected by the
41 permeability and hydrophobicity of the host structure. Steric constraints can drastically
42 reduce the permeation of substrates and redox mediators or even block the conforma-
43 tional flexibility of the protein. One way to increase the power of biofuel cells is to de-
44 velop porous electrodes that increase the effective surface area of the electrodes. How-

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45 ever, this approach does not solve the storage stability problem.

46 Recently, a new type of biofuel cell based on the non-immobilization of catalysts has
47 been developed based on compartments comprising a dialysis membrane and containing
48 enzymes, redox nanoparticles and an electrode [5]. As enzymes and mediators in solu-
49 tion can freely diffuse and rotate, this approach allows good orientation favoring elec-
50 trical wiring of the enzymes. However, this process requires a peristaltic pump to pro-
51 vide a constant flow of fuel and hence is difficult to miniaturize. More recently, Li et al.
52 reported a novel design of bioelectrode based on a carbon felt electrode and an aqueous
53 slurry of glucose oxidase, electron mediator and dispersed nanomaterial (graphene-like
54 Ti_3C_2 MXene) confined in an acrylic shell and a dialysis membrane [6]. The maximum
55 current density of this bioanode is maintained at 25 % of its initial value after 9 days, il-
56 lustrating the relatively good storage stability of the bioanode. In addition, for a low
57 continuous current discharge (5 μ A), the resulting hybrid biofuel cell exhibits a good
58 operational stability, losing only 34% of its initial power (2.75 μ W) after 19 days. How-
59 ever, the biofuel cell configuration based on an acrylic container wrapped in a dialysis
60 membrane and the stability of the dispersion of the nanomaterial can be limiting factors
61 for the miniaturization of the biofuel cell and its stability.

62 Recently, we have demonstrated that a deposit of thin layer of carbon nanotube
63 (CNT) on a non-conductive support could play the role of an electrode while offering
64 good permeation to low molecular weight compounds in an aqueous medium [7]. Taking
65 into account this property, we report here the original creation of a hollow planar
66 bioelectrode of very low thickness and large surface area containing the enzyme in
67 powder form. The enzyme is trapped during the bonding of two conductive sheets made
68 up of carbon nanotubes (buckypaper), the volume of the microcavity being defined by
69 the thickness of the glue film binding these buckypapers. The buckypapers being per-
70 meable to water and small molecules but not allowing the permeation of enzymes, the
71 bioelectrode presents a high density of protein in a microvolume. Moreover, the
72 bioelectrode can be stored dry and the enzyme is only solubilized during the use of the
73 bioelectrode.

74 To illustrate this innovative concept, a hollow bioelectrode configuration with en-
75 trapped bilirubin oxidase (BOx) was fabricated and applied to electroenzymatic reduc-
76 tion of O_2 . The electrocatalytic performance of the BOx bioelectrode was described as a
77 function of pH, temperature and the amount of entrapped enzyme. The operational and
78 storage stability of the bioelectrode in solution have been determined via the evolution of
79 the catalytic current.

80 In addition, the influence of the iron-protoporphyrin (hemin) adsorbed on
81 buckypaper on the orientation of BOx and therefore on the direct electron transfer (DET)
82 was studied. Moreover, the effect of adding
83 2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS) as a redox
84 mediator for mediated electron transfer (MET) on the electrical wiring of the BOx was
85 also investigated.

86 2. Materials and Methods

87 2.1. Materials and Reagents

88 Sodium phosphate dibasic (Na_2HPO_4) and sodium phosphate monobasic (NaH_2PO_4)
89 for the phosphate buffers preparation were purchased from Sigma-Aldrich. Multi-walled
90 carbon nanotubes (MWCNTs; $\varnothing = 9.5$ nm, purity > 95%, 1.5 μ m length) were obtained
91 from Nanocyl and used for Laboratory-made buckypaper (L_{bp}) fabrication. Commercial
92 MWCNT proprietary blend buckypaper (C_{bp}) was obtained from Nano-TechLabs, Inc
93 (reference number NTL-12218). N,N-dimethylformamide (DMF, 99.9%),
94 iron-protoporphyrin (hemin; $\geq 97\%$) and 2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic
95 acid) diammonium salt (ABTS, $\geq 98\%$) were purchased from Sigma-Aldrich. Bilirubin
96 oxidase (BOx) from *Myrothecium verrucaria* (E.C. 1.3.3.5; 1.96 U mg^{-1}) was purchased from
97 Amano Enzyme. Oxygen and argon were purchased from Air Liquide (France).

2.2. Laboratory-made buckypaper Preparation and Characterization

Based on a vacuum filtration method previously reported by our research group, two different compositions were used for laboratory-made buckypaper fabrication [8].

- Laboratory-made buckypaper (L_{bp}): 66 mg of MWCNTs (1 mg mL^{-1}) was added in 66 mL of DMF followed by sonication using a Bandelin Sonorex RK100 ultrasonic bath for 90 min. The resulting suspension was then filtrated using a diaphragm pump (MZ 2C NT model, Vaccubrand) on a Millipore PTFE filter (JHWP, $0.45 \mu\text{m}$ pore size). The L_{bp} was rinsed with water and left under vacuum for 1 h. Finally, the L_{bp} was been removed from the filter and then left to dry in air overnight.
- Laboratory-made buckypaper modified by (hemin- L_{bp}): 25 mg of hemin (0.6 mM) was added in 66 mL of DMF with 66 mg of MWCNTs followed by sonication using a Bandelin Sonorex RK100 ultrasonic bath for 90 min in a one-pot procedure. The resulting suspension was then treated following the previous procedure.

Scanning electron microscopic images of buckypapers surfaces were carried out by FEI/Quanta FEG 250 scanning electron microscope (SEM, Hillsboro, OR, USA) with an accelerating voltage of 5 kV. Water contact angles were measured after delivering a $5 \mu\text{L}$ droplet of water at room temperature onto buckypapers surfaces using a Dataphysics OCA 35 system. The surfaces coverage of hemin was calculated (Equation 1) by integration of the charge recorded under the one-electron oxidation peak of hemin by cyclic voltammetry at 20 mV s^{-1} for a 1.13 cm^2 hemin- L_{bp} working electrode.

$$\Gamma = \frac{Q}{nFA} \text{ Equation 1}$$

Where Q is the integrated charge, F is the Faraday constant, A is the geometric area of the electrode, and n is the number of electrons transferred.

2.3. Hollow Bioelectrode Preparation

A MWCNT commercial buckypaper (C_{bp} ; 60 gsm, reference number NTL-12218) from Nano-TechLab was first cut into individual conductive sheet ($\varnothing = 30 \text{ mm}$) to be used as a support. The circumference of the C_{bp} sheet was coated with carbon paste to create a hollow cylinder with a diameter of $\varnothing = 12 \text{ mm}$ dedicated to the trapping of a biocatalyst. An electrical wire was attached to the carbon paste and the electrode was subsequently sealed using a L_{bp} or hemin- L_{bp} sheets ($\varnothing = 30 \text{ mm}$). After the deposition of enzyme powder in the microcavity, the hollow bioelectrodes were left to dry in air for 4h. Laser intensity image of the electrode cavities were carried out by a 3D Laser Scanning Microscope (Keyence VK-X200).

2.4. Electrochemical Measurements

Electrochemical measurements were performed using a PGSTAT 100 potentiostat operated by Nova software. All bioelectrocatalytic tests were performed in aqueous solution (0.1 M phosphate buffer) at controlled temperature, agitation (500 rpm) and O_2 -saturated condition, using a platinum wire as counter electrode, Ag/AgCl (KCl saturated) as a reference electrode and the hollow electrodes as working electrode in a conventional three-electrode electrochemical cell. All potentials are given with respect to RHE ($E_{\text{RHE}} = E_{\text{Ag}/\text{AgCl}} + 0.197 \text{ V}$).

3. Results and discussions

The hollow electrode was created by assembling a disk (diameter 30 mm) of a commercial buckypaper (C_{bp}) with a similar disk of buckypaper (L_{bp}) made by filtration of an organic dispersion of multiwalled carbon nanotubes (MWCNTs) by sticking the periphery of the discs with carbon paste. C_{bp} presents a more porous structure than L_{bp} which facilitates the penetration of water and substrates inside the inner cavity. In contrast, L_{bp} exhibits a denser and compact structure composed of significantly smaller

148 nanotubes (diameters 10–20 nm) which allow a direct electron transfer (DET) with redox
149 enzymes [9]. The electrical connection of the two glued disks was carried out by insertion
150 of a metallic wire into the carbon paste, the thickness of which defines the volume of the
151 microcavity. Figure 1A shows an image of the resulting hollow electrode as well as a
152 section of the inner cavity that corresponds to about $28 \pm 4 \mu\text{L}$.

153 With the aim to illustrate the concept of entrapment and electrical wiring of an en-
154 zyme within a hollow bioelectrode, bilirubin oxidase (BOx) was chosen as a model en-
155 zyme. BOx is a multicopper oxidase typically employed as the biocatalyst for the
156 four-electron reduction of O_2 to H_2O and widely used for the production of biofuel cells
157 [10–13]. Thus, 2 mg of BOx powder was deposited on one disk before the formation of the
158 cavity (diameter 12 mm). The resulting bioelectrode was then immersed into a in 0.1 mol
159 L^{-1} phosphate buffer (pH 6.5) and the potential electroactivity of BOx towards the reduc-
160 tion of O_2 was investigated by cyclic voltammetry. Figure 1B shows the cyclic
161 voltammograms recorded at 1 mV s^{-1} under argon and O_2 -saturated conditions. In pres-
162 ence of O_2 , a catalytic current clearly appears with onset potential *ca.* 0.55 V which cor-
163 responds to the conventional catalytic phenomena observed for bioelectrodes based on a
164 DET with immobilized BOx [14]. This catalytic current confirms the penetration of water
165 and substrate, the solubilization of the enzyme powder in the inner microcavity and the
166 ability of the hollow electrode to establish an electrical communication with BOx.

167 As previously reported, the presence of different types of porphyrins adsorbed on
168 MWCNTs coatings or buckypapers generally induces a BOx orientation favorable to a
169 DET between its T1 Cu centre and carbon nanotubes and thus enhances the intensity of
170 the catalytic current for O_2 reduction [14]. The improvement of the electrocatalytic ac-
171 tivity of the hollow bioelectrode was therefore studied via the modification of the L_{bp} by
172 an iron-protoporphyrin. For this purpose, hemin was solubilized in the MWCNTs dis-
173 persion and firmly adsorbed on MWCNTs walls, by strong π - π interactions before the
174 filtration step. The resulting bioelectrode based on hemin- L_{bp} glued with C_{bp} was tested
175 towards O_2 reduction. As expected, a marked increase in current intensity (+52 % at 0.5V)
176 and an improved onset potential (*ca.* 0.77 V) were recorded corroborating the efficient
177 orientation of BOx induced by the adsorbed hemin (Figure 1B).

178 In addition to the orientation of the BOx by electrostatic interactions beneficial to the
179 DET, the presence of carboxylic groups on the hemin confers a less hydrophobic charac-
180 ter to the MWCNTs and therefore to the buckypaper thus facilitating its wettability. This
181 hypothesis has been corroborated by contact angle measurements made with the differ-
182 ent buckypapers. The water contact angles of L_{bp} and C_{bp} were $128 \pm 7^\circ$ and $131 \pm 3^\circ$, re-
183 spective. In contrast, the contact angle of hemin- L_{bp} could not be measured, confirming
184 that modification of MWCNTs by hemin rendered the surface hydrophilic (Figure S1).
185 Moreover, top-down SEM images of buckypapers (Figure S1) showed a subtle morpho-
186 logic change of hemin- L_{bp} compared to L_{bp} due to the presence of hemin layers. Fur-
187 thermore, the amount of immobilized hemin on L_{bp} was estimated via the charge re-
188 corded under the $\text{Fe}^{2+/3+}$ redox couple of hemin at $E_{1/2} = -0.140 \text{ V vs RHE}$. A resulting sur-
189 face coverage with hemin of $2.66 \times 10^{-8} \text{ mol cm}^{-2}$ (Figure S2) theoretically corresponds to
190 the formation of 380 compact monolayers on flat surface illustrating the 3D functionali-
191 zation of L_{BP} [15].

192 The storage stability of two hollow bioelectrodes maintained in an aqueous solution
193 and containing 2 mg of BOx, was investigated by recording periodically their faradaic
194 catalytic current for O_2 reduction at 0.5V as a function of time (Figure 1C). After an initial
195 drastic decrease in catalytic current for approximately 20 days for both bioelectrodes, a
196 near stabilization of the catalytic process occurs, exhibiting a small continuous decrease
197 in catalytic current of 1.9 ± 0.3 and $2.2 \pm 0.1 \mu\text{A cm}^{-2} \text{ day}^{-1}$ for bioelectrode based on L_{bp}
198 and hemin- L_{bp} , respectively. It should be noted that the bioelectrode without hemin loses
199 almost totally its electroactivity after 75 days whereas the bioelectrode based on
200 hemin- L_{bp} retains 30 % and 11 % of its initial activity after 3 and 6 months respectively.

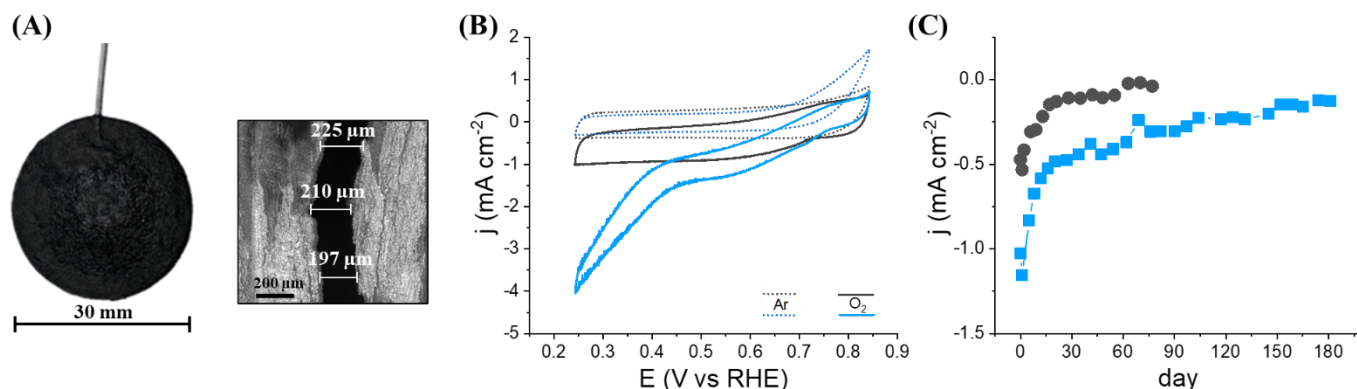


Figure 1. (A) Face view photography of the hollow MWCNT-based buckypaper electrode and laser intensity image of vertical cross section of a hollow electrode. (B) Cyclic voltammograms recorded in phosphate buffer (pH 6.5; 1 mV s⁻¹) at hollow electrodes based on L_{bp} (black) or hemin-L_{bp} (blue) glued with C_{bp} and containing BO_x (2.0 mg) trapped inside the electrode cavity. Buffer under argon (dashes) or O₂ (solid lines). (C) Evolution of the faradaic catalytic current at 0.5V for the reduction of O₂ as a function of time recorded periodically on hollow electrodes based on L_{bp} (black) or hemin-L_{bp} (blue) and containing 2 mg of BO_x. Both bioelectrodes are stored in 0.1 M phosphate buffer (pH 6.5).

The manufacturing process of the hollow electrode makes it possible to easily modulate the quantity of enzyme trapped inside the hollow electrode. Thus, the influence of immobilized amount of BO_x (0.16–4 mg) on the electrocatalytic properties of the resulting bioelectrodes based on hemin-L_{bp} was studied (Figure 2A). As expected, the catalytic current increases with increasing amount of BO_x up to 1 mg and reaches a plateau for higher amounts. Above 1 mg of trapped enzyme, the electroenzymatic reaction could be limited by the electroactive surface or the diffusion of oxygen inside the cavity. In this context, the experiments were continued with 2 mg of BO_x in the microcavity in order to have a reserve of catalyst.

The effect of temperature and pH on the functioning of the trapped enzyme has been studied. The current response of the hollow bioelectrode was measured in the temperature range of 15 to 60°C. The catalytic current increases to a maximum at 25–37°C and then decreases sharply reflecting enzyme deactivation (Figure 2B). Regarding the pH dependence in the range 4–8.5, it appears that the bioelectrocatalytic response is good at pH values ranging from 6 to 7 (83% of activity), the maximum current being recorded at pH 6.0. Taking into account that a strong decrease in activity is observed between pH 5 and 6, the experiments were carried out at pH 6.5 to avoid pH effects (Figure 2C). With the aim to estimate the turnover frequency for BO_x in solution within the microcavity, the charge related to the chronoamperometric response of the bioelectrode based on hemin-L_{bp} at 0.5V for 15 min was recorded (Figure 2D). By the integration of the anodic current area to give the transferred charges from the chronoamperometric measurement and taking into account 4 e⁻ for O₂ reduction, a TOF of 0.3 s⁻¹ was calculated which represents 14 % of the specific activity of the enzyme (1.96 U mg⁻¹ BO_x).

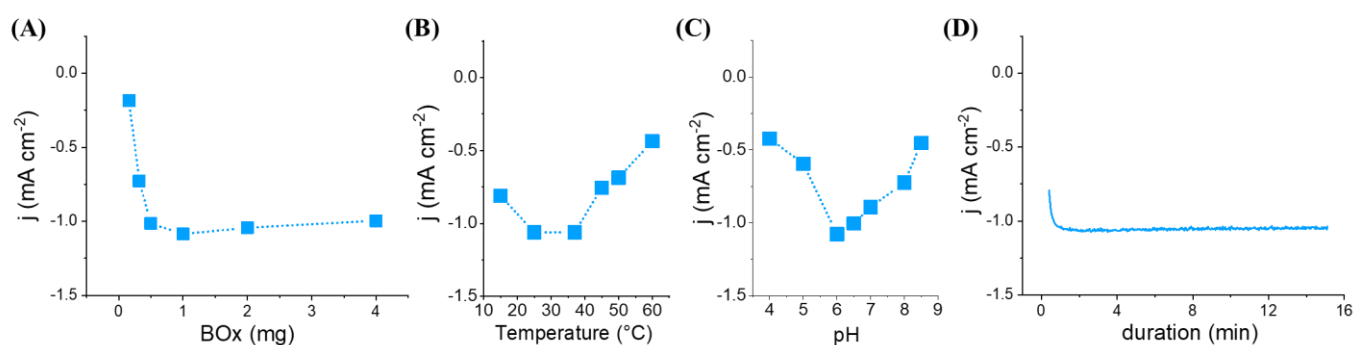


Figure 2. (A) Influence of various amounts of BOx entrapped inside the hollow electrode based on hemin-L_{bp} on the electrocatalytic reduction of O₂. Applied potential 0.5V vs RHE. Faradaic catalytic current recorded at 0.5V on a hollow electrode based on hemin-L_{bp} in oxygen-purged 0.1 M phosphate buffer and containing 2 mg of BOx; (B) Plot of the current as a function of temperature at pH 6.5; (C) Plot of the current as a function of pH at 25 °C. (D) Chronoamperometric measurement at 0.5V in oxygen-purged 0.1 M phosphate buffer (pH 6.5) at 25 °C.

If the electroenzymatic reaction is limited by the need to have contact between enzyme and buckypaper surface (DET), one possibility to improve the catalytic current would be to introduce a freely diffusing redox mediator into the confined solution to electrically connect BOx in solution via mediated electron transfer (MET). As ABTS has already been successfully used for MET with BOx [16], 0.5 mg of ABTS and 2.0 mg of BOx were trapped in the cavity of the hollow electrode based on hemin-L_{bp}. Figure 3A shows a clear increase (+40%) in the value of the faradaic catalytic current from -1.35 mA cm⁻² to -1.9 mA cm⁻² at 0.5 V, corroborating the electrical wiring of BOx by two phenomena: DET and MET by ABTS.

In addition, the long-term operational stability of the bioelectrode containing BOx and ABTS was studied by chronoamperometry at 0.5 V. A remarkable stability of the cathodic current (loss of 2% after 8 h) seems to indicate the absence of ABTS release (Figure 3B). After 23 h of intermittent operation over 7 days, 218.6 C were recorded corresponding to the reduction of 5.66×10⁻⁴ mol of O₂ and leading to a turnover number of 19245, the loss of catalytic current being only 54% after 7 days.

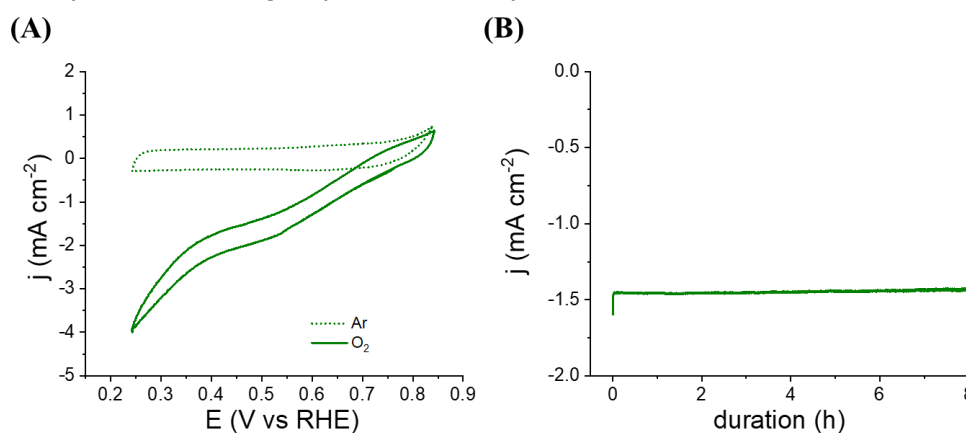


Figure 3. (A) Cyclic voltammograms recorded in phosphate buffer (pH 6.5; 1 mV s⁻¹) at a hollow electrode based on hemin-L_{bp} containing 0.5 mg of ABTS and 2.0 mg of BOx under argon (dashes) or O₂ (solid line). (B) Chronoamperometric measurement at 0.5V under oxygen-purged phosphate buffer.

4. Conclusions

264 This work reports on the easy elaboration of hollow planar electrodes based on
265 buckypapers and their successful application to the trapping of an enzyme powder in a
266 microcavity. The resulting bioelectrodes are permeable to water but do not allow enzyme
267 permeation. The entrapment of BOx as electrocatalyst model leads to a bioelectrode ex-
268 hibiting efficient electroenzymatic reduction of O₂ by direct electron transfer with BOx
269 molecules in solution. The bioelectrocatalysis process was improved using hemin and
270 ABTS for orientation and electrical wiring of BOx, respectively. In addition to long oper-
271 ating and storage stability of the hollow bioelectrode, this design allows to co-immobilize
272 enzymes and redox mediators in the microcavity and to modulate the amount of en-
273 trapped enzyme. This concept paves the way for the development of a new generation of
274 enzyme electrodes as biosensors or biofuel cells.

275 **Supplementary Materials:** Additional results containing the Figures S1 and S2 are available online
276 at www.mdpi.com/xxx/s1,

277 **Author Contributions:** The manuscript was written through contributions of all authors. Concep-
278 tualization, Paulo H. Buzzetti, Anastasiia Berezovska, Yannig Nedellec, and Serge Cosnier; formal
279 analysis, Paulo H. Buzzetti, Anastasiia Berezovska, and Yannig Nedellec; investigation, Paulo H.
280 Buzzetti, Anastasiia Berezovska, Yannig Nedellec, and Serge Cosnier; data curation, Paulo H.
281 Buzzetti, Anastasiia Berezovska, and Yannig Nedellec; validation, Paulo H. Buzzetti, Anastasiia
282 Berezovska, Yannig Nedellec, and Serge Cosnier; writing - original draft preparation, Paulo H.
283 Buzzetti, and Serge Cosnier; writing - review and editing, Paulo H. Buzzetti and Serge Cosnier;
284 supervision, Serge Cosnier; funding acquisition, Serge Cosnier. All authors have given approval to
285 the final version of the manuscript.

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294 **Conflicts of Interest:** The authors declare no conflict of interest.

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