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Potential Use of Waste in Electrocatalysis Using Foundry Sand as Electrocatalyst for the Hydrogen Evolution Reaction

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Approximately 13 million tons of foundry sand (FS), a waste from the metallurgic industry, are produced worldwide annually. Although several applications for this waste have been reported, there is a lack of research regarding its application in energy production, such as the hydrogen evolution reaction (HER). Due to several metal oxides commonly present in this waste, like iron oxides, FS may have great potential for HER. Simple carbon-paste electrodes comprised of graphite and FS were prepared and tested for HER. FS, after thermal treatment, showed an onset potential near +0.39 V vs Reversible Hydrogen Electrode and a current density of approximately 16 mA cm⁻² at -0.9 V. HER geometric rate, turnover number (TON), and faradaic efficiency were $1.77 \ \mu$ mol h⁻¹ cm⁻², 3126, and 43.4%, respectively. Those are reasonable values compared to the ones reported in the literature, showing the potential of this waste for the manufacturing of low-cost electrodes.

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The circular economy principle arises from the necessity of closing loops in production processes. Based on the natural cycles present in nature, this concept carries the idea of turning a waste of a process into a resource to another one. This principle also highlights reusing everything possible in a production process and recycling what cannot be used anymore.¹

Following the circular economy concept, Antunes et al.² emphasize the importance of cost minimization and sustainable manufacturing. Those authors also say that converting foundry sand (FS) into something else is a good example of it, as FS is a waste generated in aluminum production in Brazil, and it ends up reducing the lifespan of landfills. According to Bansal at al.,³ the annual generation of FS reaches 13 million tons worldwide, making clear the need to find applications for this waste. Furthermore, among the 12 principles of Green Chemistry, exists the idea of prevention of pollution and energy economy, from which reusing wastes become a strategic path to sustainability.⁴

Foundry Sand (FS) has been studied for environmental applications due to its iron content, varying from 2% to 23% in weight.^{2,5} Antunes et al.,² for example, demonstrated that FS can be used in the coating of aluminum alloys by plasma electrolytic oxidation. According to those authors, the hydrophobic ceramic coating generated by FS is highly adherent to the alloy and they are also chemically/thermally stable, according to the XRD signals indicating the formation of γ -alumina and iron of the formed coating.

Gürkan, Çoruh, and Elevli⁶ have shown that FS can be used for adsorbing Cu^{2+} and Pb^{2+} , with adsorption capacities greater than the ones of Na-bentonites at pH 7.0. Similarly, Saad et al.⁷ have shown that FS can be used to remove cadmium from an aqueous solution. Other applications given to this material are hydrogen production by hydrothermal heterogeneous catalysis and NO_x reduction assisted by plasma and ozone.⁸

FS has also been used for environmental remediation purposes. For example, Aggarwal et al.⁹ demonstrated that it is possible to degrade 2-chloro-4-nitrophenol by the photo-Fenton process, in a batch reactor, using foundry sand as the iron source, which was achieved in 105 min under solar light irradiation and 0.025% in

volume of H_2O_2 . Despite all these examples, no studies regarding electrochemical applications were found for this material, making this report probably the first to tap into the electrocatalytic properties of this specific waste onto HER.

Furthermore, there is an increasing demand for alternative, less carbon-consuming, energy sources. The production of clean energy from renewable sources and the use of electrolysis for H₂ production, as a green fuel, is a largely studied approach.^{10–15} Systems based on H₂-combustion generate water vapor instead of carbon-containing gases, minimizing impacts on the global carbon biogeo-chemical cycle.¹⁶ The water-splitting reaction is the main way of obtaining hydrogen and oxygen by the electrolysis of water molecules. This process may be performed in both acid or alkaline media, using hydronium cations and water as proton sources, respectively.¹⁷

The Hydrogen Evolution Reaction (HER) in water electrolysis is known to present near-to-ideal results when performed with Pt electrodes which, in real-life applications, is not feasible due to the low availability of this metal on Earth, making mass-scale processes quite expansive.¹⁸ The search for environmentally friendly and low-cost electrodes is currently quite active. Alternatives such as Pd electrodes were studied, showing that this kind of material is as efficient as Pt, but it is almost as expensive.¹⁹ Looking for low-cost electrocatalysts, carbon-supported electrodes, including glassy carbon or carbon paste, have been used.²⁰

The carbon-based electrodes are very versatile, allowing for the use of low-processed materials in powder form, metallic complexes such as Cu- and Co-porphyrins, ionic liquids, etc.^{21–23} Those systems are highly studied due to properties such as: large surface area, conductivity, stability, and the possibility of being obtained from renewable sources and/or being used with green solvents and materials.²⁴

Therefore, the goal of this work was to explore the application of FS in HER at mild conditions and using the simplest carbon paste electrode possible.

Experimental (Materials and Methods)

Chemicals and solutions-Graphite powder (Merck), K₃[Fe(CN)₆] (Merck), KNO₃ (Merck), KH₂PO₄ (TCL LTDA.), B₄Na₂O₇.10H₂O



Figure 1. Thermogravimetric analyses curves: (a) raw foundry sand; (b) purified foundry sand.

(Merck), citric acid (Merck), K₂HPO₄ (Biopack), NaOH (Panreac AppliChem), diethyl ether (Merck), and mineral oil (M8410, Sigma-Aldrich) were all purchased in Chile. Ultra-pure water was provided by a Millipore-Q system (18.2 M Ω cm), and Argon (99.99% purity) was obtained from AGA, Chile.

Foundry sand (FS) was obtained from a Tecumseh industrial plant (São Carlos, Brazil) and was used both as raw and purified material. Thermal purification was performed under atmospheric air in a porcelain crucible (model A-45 with cover) in a muffle furnace (EDG 7000 coupled to an EDG heater EDGCON 3 P). 3.00 g of FS were heated from room temperature to 50 °C at a rate of 10 °C min⁻¹ and held at that temperature for 30 min. Then the material was heated from 50 to 900 °C at a rate of 5 °C min⁻¹. The system remained at that temperature for 300 min. Then, the material was naturally cooled down to room temperature under atmospheric air.

Carbon paste electrodes-Carbon paste electrodes were prepared in an agate mortar, dispersing the mineral oil in the powder (graphite or graphite and FS) with approximately 20 ml of diethyl ether, homogenizing the blend until the solvent evaporated completely. That process was repeated three times. Blank electrodes were composed of 70% in weight of graphite and 30% of mineral oil, as proposed by Gidi et al.²⁵ 5, 10, and 20% in weight FS electrodes were composed of 72.5, 70, 65% in weight of graphite, respectively, and mineral oil q.s.p., keeping the same ratio between mineral oil and graphite.

The prepared paste was hand-packed in hollow Teflon tubes with a brass screw for electrical contact. This electrode was then heated to 90 °C for at least 2 h before being naturally cooled down and polished in weighing paper, for obtaining a smooth surface. These electrodes were measured by renewing their surfaces several times, keeping good reproducibility (variations less than 5% in current, for triplicates).

The geometrical area of these electrodes was 0.031 cm^2 , and its electroactive area was determined by a scan rate study, performed between 0.02 and 0.12 V s^{-1} , using $0.010 \text{ mol } \text{l}^{-1}$ of the Fe(CN)₆^{4–}/Fe(CN)₆^{3–} redox couple and $1.0 \text{ mol } \text{l}^{-1}$ KNO₃ as the support electrolyte. Figures S4 to S6 show the voltammetric profiles and necessary plots to apply the Randles-Sevcik (Eq. 1) for calculating the electrode areas, which are reported in Table S1.

Instrumentation-The electrochemical measures were performed in 0.1 mol l^{-1} phosphate buffer at pH 7.2, 0.1 mol l^{-1} citrate buffer at pH 4.4, and 0.05 mol l^{-1} di-sodium tetraborate buffer at pH 9.4, all under Ar atmosphere in a single-compartment cell, using the carbon paste electrodes as working electrodes, a great area Pt spiral wire as the counter electrode, and Ag/AgCl 3.0 mol l^{-1} as the reference electrode. A CHI1140B potentiostat was used.

For the electrolysis experiment, a greater area carbon paste electrode was used (0.54 cm^2) in a hermetic sealed two-compartment

cell (one for a graphite counter electrode, and one for the carbon paste and Ag/AgCl electrodes) kept in contact by a nafionTM membrane. The same electrolyte and atmosphere of the previous electrochemical measures were used. A CHI Instruments 750D potentiostat applying a fixed potential of -0.69 V vs RHE and magnetic stirring, aiming at transferring the H₂ bubbles to the headspace. To determine the amount of hydrogen produced, 50- μ L samples were withdrawn from the 31 ml headspace using a chromatographic syringe, being injected into a DANI-InstrumentsTM gas chromatography equipment.

During characterization, all measures were performed before any electrochemical experiment, to avoid modifications in the electrode surface by the electrolytes. X-ray diffractograms were obtained in a Brucker D8 advance 6000 using a Cu K α , with nickel filter, emission at 0.154 nm, angular step of 0.02°, integration time of 4 s, and scan from 5 to 90°. Raman spectroscopy was performed in an Espectrometer WITec Alpha 300-RA with a variable wavelength source (from 532 nm to 785 nm). Images were obtained by a field emission scanning electron microscope (FESEM) coupled to an energy dispersive X-ray (EDX) analysis equipment, FEI QuantaTM 250 FEG model. The thermogravimetric analyses were performed from 30 to 1000 °C in a Q50 V20.13 building 39 equipment from TA Instruments. The samples were kept under a nitrogen atmosphere up to 600 °C and a synthetic air one up to 1000 °C. The X-ray fluorescence spectroscopy (XRF) analyses were performed in a MiniPaI4 equipment from PANalytical.

Results and Discussion

Materials characterization.—The FS used was obtained from a cast iron and steel parts manufacturing plant (Tecumseh, São Carlos/ Brazil). This material contained amorphous carbon and clay as a binder. Figure 1 shows the thermogravimetric curves of the raw and thermally treated foundry sand. The raw material lost approximately 19% of its initial mass, which was attributed to the elimination of the non-ceramic components of the binding component.

To purify the ceramic components and assess the need for a previous treatment, the raw material was thermally treated at 900 °C for 6 h in atmospheric air. This temperature was chosen to guarantee the complete removal of the binder (Fig. 1). Both materials (raw and purified FS) were characterized. Figure 2 shows FESEM images and Table S1 contains the results of the X-ray fluorescence analysis (Fig. S1). The foundry sands were mainly composed, before/after the thermal treatment, 61.7/65.4% of SiO₂, 14.2/14.3% of Al₂O₃, and 8.0/8.7% of Fe₂O₃.

In Fig. 2, one could notice that the thermal treatment did decrease the particle size. This particle size reduction may modify the material electrochemical properties, increasing the availability of active sites for reactions. Table S1 results show that chlorinated and



Figure 2. FESEM images (20.0 kV, magnification 300×, copper support): (a) raw foundry sand; (b) purified foundry sand.



Figure 3. XRD obtained using a Cu K α source, with nickel filter, emission at 0.154 nm, an angular step of 0.02°, and integration time of 7 s, scan from 10 to 100° for: (a) raw foundry sand; (b) purified foundry sand.

sulfur species were eliminated, while the remaining elements were preserved.

The diffractogram profiles in Fig. 3 show the intense, characteristic signals of quartz (JCPDS 78–2315), the major component in those materials, as expected from the results of Table S1. It is also possible to observe less intense signals assigned to hematite (JCPDS 33–664) and corundum (JCPDS 46–1212). Although the intensity of the signals increased after the thermal treatment, which indicates greater crystallinity, no changes in the chemical identity of the components are suggested, meaning that changes in the catalytic activity of those materials could not be associated with changes in their crystalline phase.

Moreover, it is possible to observe the binder carbonaceous fraction of the raw material in Fig. 4, which shows the spectra from FTIR and Raman scattering analyses. The FTIR spectra showed the same signals for both materials (I = 3428 cm⁻¹, -OH stretching; II = 1083 cm⁻¹, Al-O stretching; III = 962 cm⁻¹, Si-OH bending; IV = 800 cm⁻¹, O-Si-O and O-Fe-Si symmetric linear stretching; V = 579 cm⁻¹, Fe-O vibrations; VI = 461 cm⁻¹, Si-O-Si bending), although the raw FS spectrum also presented a signal at VII = 1885 cm⁻¹, assigned to C=C and C=O stretchings.²⁶⁻²⁸ On the other hand, the Raman signals for the purified FS (225, 294, 413, and 1310 cm⁻¹) were associated with α -Fe₂O₃ which were not observed in the raw FS spectrum (the intense signals at 1370 and 1625 cm⁻¹ are associated to D and G-bands of amorphous carbon.^{29,30}

I = -OH stretching; II = Si-O un-symmetric linear stretching; III = Si-OH bending; IV = O-Si-O and Fe-O-Si symmetric linear stretching; V = Fe-O vibrations; VI = Si-O-Si bending; VII = C=Cand C=O stretchings.

By those analyses, it was possible to notice that the raw material is mainly composed of SiO_2 (quartz) impregnated aluminum and iron oxides, the last one the probable species responsible for the electrocatalytic properties of the material, as it is the only one found in this material that is reported to show any electrochemical properties towards HER, that despite has been reportedly low, it is increased by the presence of other metallic oxides presents in the medium.^{31–33} Moreover, the thermal treatment did not change the chemical identities of the compounds, although it indeed significantly reduced particle size and increased the characteristic signals of iron oxides in Raman spectroscopy.

Electrochemical characterization.—A The electrodes were prepared following a methodology developed in previous works,²⁵ aiming at preparing the simplest carbon paste electrode possible. Initially, electrodes with 70% graphite, 20% mineral oil, and 10% of one of the sands (weight percentages) were prepared. The blank electrode consisted of only graphite and mineral oil (70:30).²² The measures of Linear Sweep Voltammetry at a scan rate of 100 mV s⁻¹ (Fig. 5) showed that despite both electrodes had quite similar onset potentials (-0.69 and -0.68 V vs RHE for purified and raw FS, respectively), the



Figure 4. Spectra of raw and purified foundry sand: (a) FTIR; (b) Raman scattering.

Table I.	Comparison	of onset	potentials	(E ₀),	Tafel	slopes,	and
turnover	numbers (T	ON) in si	milar syst	ems.			

System	pH	E _O /V vs RHE	Tafel slope/mV dec ⁻¹	TON	References
Pt/C commercial	≈ 7	-0.04	120	_	38
Gr/Co-Fe	≈ 7	-0.65	184	7660	31
Gr/Co-Fe 560 nm	≈ 7	-0.62	145	8100	31
FeP	0.3	+0,11	55	-	32
[(2-AMP)Fe(NO) ₂] (homogeneous) ^{a)}	11	-	-	13456	33
MoS ₂ /N-doped GR	≈ 14	+0.21	79	-	36
NiFe-oxide	$\approx \! 14$	+0.18	114	-	39
iron-incorporated NiS/Ni(OH) ₂	≈7	+0.20	118	-	40
Purified foundry sand	7.2	+0.39	84.2	3126	This work

a) 2-AMP = 2-aminomethylpyridine

current density for the purified sand (approximately -16.2 mA cm^{-2} at -0.9 V vs RHE) was about 46% higher than the one for raw foundry sand (approximately -11.1 mA cm^{-2}).

To assess the effect of the amount of purified FS in the electrode, three mass fractions were tested: 5, 10, and 20%, maintaining the same graphite to mineral oil ratio. The results are shown in Fig. 5b. The electrode with 10% of purified FS showed the best results, followed by the one with 20% and, lastly, 5%. The reason why electrodes with 20% purified FS showed worse performances may be due to the resistivity increase caused by the silica matrix of the material.

The effect of pH was assessed for the electrode with 10% of purified FS as well. The results are shown in Fig. 5c. Despite the electrode reaching higher currents densities at more negative applied potentials in an acid medium (buffer citrate, pH 4.4), in mild conditions (phosphate buffer, pH 7.2), the onset potential was lower and current densities were higher at less negative applied potentials, even that more protons were expected to be available for reaction in the citrate buffer. The better results of the electrode at neutral pH may be associated with the solubility of the metal oxides, like iron oxide, in the foundry sand at an acid medium compromising the stability of the electrode.³⁴ The HER was quite diminished in all the range of potential studied at an alkaline medium (di-sodium

tetraborate buffer, pH 9.4) and it might be attributed to fewer protons being readily available for reaction.

The electrodes showed good reproducibility among replicates for HER (relative errors below 5%), as one can observe in the Linear Sweep Voltammetry at a scan rate of 100 mV s^{-1} in Fig. S2. This fact may be related to the relative homogeneity of the carbon paste (observable in the EDS mapping of the paste, Fig. S3). It is noticeable that the iron, silicon, and aluminum oxides are quite well distributed in the paste.

To determine the electroactive area of all electrodes, and calculate the current densities shown in Fig. 5, a scan rate (ν) study between 20 and 120 mV s⁻¹, using the redox couple Fe(CN)₆⁴⁻/Fe(CN)₆³⁻ was performed (Fig. S4). It is noticeable that as the FS content was increased, so was the capacitive current, being that took into account in the measure of peak current (I_p). Plotting log(I_p) vs log(ν) (Fig. S5) it is possible to observe that, for all electrodes, the angular coefficient was close to 0.5 (variations below 20%), which means that good diffusional control is established, and the Randles-Sevcik (Eq. 1) may be used to determine the electroactive area.³⁵

$$I_{p} = (2.69 \times 10^{5}) n^{3/2} C_{0} \quad A D^{1/2} \nu^{1/2}$$
[1]

In Eq. 1, I_p is the maximum peak current, n is the number of transferred electrons (for this reaction, 1); C₀ is the concentration of electroactive species (0.1 mol l⁻¹), D is the diffusion coefficient ($6.5 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$).³⁵ Figure S6 shows the I_p vs $\nu^{0.5}$ and Table S2 summarizes the areas and current densities (at -0.9 V vs RHE) for all electrodes.

In general, one can observe that increased contents of sand also generated increased electrochemical areas. Particularly, raw FS showed a relatively large electrochemical area (0.205 cm^2) , and it may be due to its large particle size, which makes carbon paste compression less effective. It is also noticeable that increased electrochemical areas do not necessarily mean increased electrochemical activity, as the raw FS electrode showed lower activity than 10 and 20% purified FS, although it was the electrode with the highest electroactive area.

To verify the mechanism of hydrogen evolution, a linear sweep voltammetry experiment was performed at a lower scan rate $(2 \text{ mV s}^{-1}, \text{ Fig. S7})$ for the 10% purified FS electrode. Figure 6 shows the obtained Tafel plot.

From the angular coefficient of the Tafel plot (Fig. 6), it was possible to determine the mechanism of hydrogen evolution.³⁶ As a multi-step process, the first one occurs when protons are discharged/ adsorbed on the surface of the electrode (Eq. 2), and then two paths



Figure 5. Voltammetric profiles at scan rate 0.1 V s⁻¹: (a) blank, 10% in weight of raw and purified foundry sand in 0.1 mol Γ^1 phosphate buffer at pH 7.2; (b) blank, 5, 10, 20% in weight of purified foundry sand in 0.1 mol Γ^1 phosphate buffer at pH 7.2, and; (c) 10% in weight of purified foundry sand in 0.1 mol Γ^1 phosphate buffer at pH 7.2, in 0.1 mol Γ^1 citrate buffer at pH 4.4, and in 0.05 mol Γ^1 di-sodium tetraborate buffer at pH 9.4.



Figure 6. The Tafel slope of the 10% in weight purified foundry sand system was obtained from the polarization curve at a scan rate of 2 mV s⁻¹ in 0.1 mol Γ^{-1} phosphate buffer at pH 7.2.

are possible: (i) addition of a proton to the hydrogen adsorbed in the first step (Eq. 3) or (ii) the combination of two adsorbed hydrogens (Eq. 4).³⁶

$$H^+ + e^- \rightarrow H_{ads}$$
 (Volmer step) [2]

$$H_{ads} + H^+ + e^- \rightarrow H_2$$
 (Heyrovsky step) [3]

$$H_{ads} + H_{ads} \rightarrow H_2$$
 (Tafel step) [4]

Being the most important kinetic parameter used in studying any electrocatalyst for HER, as lower the Tafel slope, the more efficient the catalyst. The Tafel slope may also be used to determine which path was taken in the mechanism13: in this case, the angular step is $(84.2 \pm 0.4) \text{ mV dec}^{-1}$, which is close to 85 mV dec⁻¹, one of the theoretical values of a Volmer-Heyrovsky mechanism when the calculated transfer coefficients are 0.70 and 0.30, as pointed out by Lasia.³⁷

Hydrogen quantification - To quantify hydrogen production by carbon paste electrodes with 10% purified FS, electrodes with higher electroactive areas were used (0.54 cm^{-2}) . This experiment was performed by applying a fixed potential of -0.69 V vs RHE to the working electrode for 4 h, as detailed in the experimental section. Figure 7 shows the current vs time behavior of the electrode during electrolysis, which could be taken as evidence of the electrode stability, while Fig. S8 shows the LSV profile of this electrode.



Figure 7. Stability study of the 10% in weight purified foundry sand system at fixed potential -0.69 V vs RHE during 4 h in 0.1 mol 1^{-1} phosphate buffer at pH 7.2.

The amount of hydrogen produced was quantified by taking 50 μ l samples of gas from the electrochemical cell headspace and analyzing them by gas chromatography (chromatograms shown in Fig. S8). As the headspace volume is known (31 ml), the samples hydrogen concentration may be used to calculate the total volume of hydrogen produced. The calibration curve used is shown in Eq. 5 (R² = 0.999), in which A is the relative chromatographic area and C_{H2} is the concentration of the extra pure hydrogen (99.999%) used in the calibration.

$$A = 6,04C_{H_2} - 0.326$$
 [5]

The amount of hydrogen produced in the cell, during 4 h of electrolysis was 3.81 μ mol. Then, knowing the electroactive area, it was possible to determine the geometric hydrogen production rate as 1.77 μ mol h⁻¹ cm⁻². Furthermore, the number of active sites could be determined by the charge, obtained by the relation between current and time (Eq. 6), and Faraday's Law of Electrolysis (Eq. 7).²³

$$i = \frac{Q}{t}$$
[6]

$$Q = NFn$$
 [7]

In Eqs. 6 and 7,²¹ Q is the charge in Coulombs, n is the number of electrons exchanged (in this case, 2 for HER), i is the faradaic current, obtained from the voltammogram shown in Fig. S8 (2.35 × 10^{-4} A), and t is the time, in seconds (taking from E = 0.3 V and $\nu = 0.1$ V s⁻¹, t = 3 s in Fig. S9). N represents the number of active sites, and finally, F is the Faraday constant (96,485 C mol⁻¹). Therefore, N was calculated as 1.22×10^{-9} mol.

The turnover number (TON) was calculated as the ratio between the amount of hydrogen produced (in mol) and the amount of active sites,²³ that is, TON = 3126. The obtained results, compared to the ones in Table I, are quite reasonable, as they were achieved with a very simple system using waste as a catalyst in a very mild pH. Specifically, the calculated Tafel slope should be highlighted, as the lower it is, the lower the energetic demand for HER.³⁷ In Table I, other papers with even lower Tafel slopes also presented higher onset potentials than the one obtained in this study. The only exception, achieves a lower onset potential at a highly alkaline medium.

Finally, the faradaic efficiency, f(%), was calculated using Eq. 8,²³ in which N_{H2} is the amount of hydrogen (in mol) produced, n is the number of electrons transferred in the process (2 for HER), F is the Faraday constant (96,485 C mol⁻¹) and q is the charge after 4 h of electrolysis obtained from Fig. S8. Therefore, f(%) = 43.4%. This result may be due to competitive reactions among the species in the sand, and further research is required to understand this value. Several

works of literature report that changing graphite with carbon nanotubes and adding ionic liquids to the carbon paste can be an approach for improving the results in HER,^{21–23} which opens a possibility of improvement for this system. Moreover, these results show this waste possible application in anionic membranes cells, given its electrochemical responses at mild pH conditions and the promisor results obtained for iron-based complexes in the literature to this kind of dispositive.⁴¹ Table S3 summarizes the faradaic efficiency and TON in other sampling times during the electrolysis.

$$f(\%) = \frac{N_{H_2} \ n F}{q} \times 100$$
[8]

Conclusions

In this work, an industrial waste, foundry sand, was assessed regarding its activity as an electrocatalyst for HER. The material, mainly composed of SiO₂, Al₂O₃, and Fe₂O₃, showed better activity after a thermal treatment to eliminate the carbonaceous binder. The best foundry sand content in the carbon paste electrodes was 10% in weight, and its activity for HER reaction was reasonable compared to other iron-based systems, showing a geometric rate of 1.77 μ mol h⁻¹ cm⁻², TON of 3126, and faradaic efficiency of 43.4%. Therefore, it is possible to use waste as a catalyst, in a simple and low-cost kind of electrode, which could be improved by modifications, opening a field of research.

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Associated Content

Supporting Information

The following files are available free of charge: Supplementary material containing additional materials characterizations, electrochemical surface area measures, hydrogen chromatographic measures, and geometric rate, TON, and Faradaic.

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