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Continuous electroconversion of CO₂ into formate using 2 nm tin oxide nanoparticles

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Abstract

Tin oxide nanoparticles (SnO₂ NPs) as electrocatalyst for the production of formate from CO₂ reduction reaction (CO₂RR). We synthesize, characterize and evaluate high surface area SnO₂ NPs (2.4 nm and 299 m² g⁻¹ in diameter size and surface area, respectively), for the continuous production of formate at high current density within a flow electrolyzer.

SnO₂ NPs under Ar and CO₂ reduction conditions were studied by cyclic voltammetry. SnO₂-based gas diffusion electrodes (SnO₂-GDEs) were manufactured to perform continuous CO₂RR. A maximum formate concentration value of 27 g L⁻¹ was achieved with a Faradaic efficiency (FE) of 44.9% at 300 mA cm⁻², which was significantly stable and reproducible when operated up to 10 h. Nevertheless, ohmic drop contribution due to the semiconducting properties of SnO₂ was not negligible. The low total FE (< 60%) of products pointed out a leakage of formate by crossover migration through the membrane from the catholyte towards the anolyte.

Keywords: CO₂ electroreduction, formate, SnO₂ nanoparticles, Continuous reactor, Gas diffusion electrodes.

1. Introduction

The concentration of CO₂ in the atmosphere is reaching unprecedented values (413 ppm in December 2020) [1] due to the increasing depletion of fossil fuels as world energy demand continues to increase. Thus, the conversion of captured CO₂ into useful chemicals is considered one of the most efficient technologies to tackle the challenge [2–4]. Although several CO₂ activation and conversion techniques are nowadays available such as chemical, photochemical

and photoelectrochemical methods [5–7], the catalytic process for the transformation of CO₂ into value-added products throughout electrochemical reactions is appealing due to the environmental and potential economic benefits. In particular, the possibility of closing the carbon cycle, as well as its strategic advantage in storing electrical energy in the form of chemical bonds, makes this technology one of the most sustainable methods currently available, in which the electrons can be derived from renewable energy sources such as wind or solar power [8]. For this reason, different approaches from both homogeneous [9–11] and heterogeneous catalysis [12,13] have been applied to the electrochemical CO₂ reduction reaction (CO₂RR).

Different commercially useful chemicals can be produced from the electrochemical conversion of CO₂ at room temperature as a function of the number of proton-coupled electron transfers required in each electrochemical reaction [14–17]. In addition to this, the selectivity of the reaction strongly depends on the catalytic material, as well as process conditions, such as the applied voltage, among others [18,19]. The main products obtained from CO₂ electroreduction can be classified in the following four categories: *i*) carbon monoxide (CO) [20,21]; *ii*) formic acid/formate (HCOOH/HCOO⁻) depending on the pH [22,23]; *iii*) alcohols such as methanol (CH₃OH) [24] and ethanol (C₂H₅OH) [25]; and *iv*) hydrocarbons including methane (CH₄) [26] and ethylene (C₂H₄) [27]. It is vital to stress the importance of controlling the hydrogen evolution reaction (HER) [28], since the production of hydrogen from water electrolysis competes with CO₂ electroconversion, reducing, therefore, the selectivity of the electrochemical process towards the desired useful reduction product.

In this work, we study the continuous production of formate from CO₂ single-pass electrochemical conversion, in which two electrons are exchanged, at high current density within a flow electrolyzer, which allows direct feed of gaseous CO₂ to the electrochemical interface by means of a gas diffusion cathode and avoids mass limitations associated with CO₂ solubility in solution. Formate is a widely used chemical commodity in different pharmaceutical or leather industries, among others [22]. Moreover, formate can be supplied as fuel (starting from 0.5 M in solution) for direct formic acid fuel cells (DFAFCs) to produce electricity [29] and is considered one of the highest value-added CO₂ electroreduction products in terms of market price since this chemical reaches a value of around \$1000 - \$1700 per ton of product [30]. The main targets pointed out in the literature for the CO₂RR-into-formate process to become industrially feasible are [31]: *i*) reaching a formate production higher than 45 g L⁻¹ (1 M); *ii*) using current densities higher than 100 mA cm⁻²; *iii*) keeping Faradaic efficiency (FE) higher than 50% and energy consumption lower than 500 kWh kmol⁻¹ product; and *iv*) using continuous-flow operation mode at mild-ambient temperature and pressure conditions. Moreover, the long-term stability and durability of the working electrodes have been recently reported to be crucial for this technology to be implemented in the short term [32] and further comprehensive durability tests are still needed in the literature.

Among the different available electrocatalysts mainly producing formate from CO₂RR, metallic tin (Sn) appears to be one of the best alternatives in terms of cost and selectivity, highlighting

also its low toxicity, even though other metals such as lead (Pb) and bismuth (Bi) have also been proposed as efficient electrocatalysts for formate production [23,33–37]. Nevertheless, not only the synthesis of small size capping agent free Sn nanoparticles (NPs) is tricky, but also the structural stability of Sn NPs during CO₂ electroreduction is under debate. Furthermore, the behavior of Sn NPs under industrial (high) cathode area and current density conditions represents a challenge that still needs to be solved [38]. As a consequence, either the use of oxide films on Sn electrodes or purely tin oxide (SnO₂) NPs has been recently considered in literature as suitable electrocatalytic material for the production of formate from CO₂RR [39–47], since SnO₂ presents much higher structural stability under electrochemical conditions. In particular, a lot of attention has been focused on identifying the role of the different species present on the surface of the electrode (Sn/SnO/SnO₂) during CO₂RR. This surface composition-reactivity relationship has been studied in detail by Raman and IR spectroscopy [48–50] and scanning electrochemical microscopy (SECM) [51], which have demonstrated that oxide films (SnO_x) on the surface of Sn electrodes play a key role by enhancing formate production and selectivity during CO₂RR.

Therefore, the present study aims at evaluating the application of crystalline and high specific surface area SnO₂ NPs (2.4 nm in average diameter size), synthesized by a template free and facile hydrothermal microwave-assisted method, as an alternative electrocatalyst for the continuous CO₂RR into formate at high current densities. As far as the authors know, this study represents one of the first approaches on evaluating the activity and selectivity performance of SnO₂ NPs smaller than 3 nm in a gas-phase flow electrolyzer using large size electrodes (10 cm² of geometrical area) operating at high current densities. This strategy has been recently proposed with the purpose of increasing the formate production rates using 100 nm SnO₂ nanoparticles [52,53] and alternative larger size tin oxide-based electrocatalysts such as SnO [54] or Sn₃O₄ [55]. Nevertheless, most of the work published so far has used SnO₂ catalyzed gas diffusion electrodes (GDEs) in a two compartments H-type cell, where poor current densities between 5 and 12.5 mA cm⁻² were reported [42,43,45,46,56]. Only highly porous SnO₂ nanosheets supported on carbon cloth reached 70 mA cm⁻² as current density in H-type cell [57]. Therefore, we would like to evaluate large size SnO₂-GDEs capable of operating at extreme current densities (*i.e.*, 500 mA cm⁻²) conditions in a gas-phase flow electrolyzer. Thus, the following objectives are addressed herein: *i*) synthesis and comprehensive physicochemical characterization of high surface area SnO₂ NPs; *ii*) electrochemical characterization of SnO₂ NPs deposited onto a glassy carbon electrode by cyclic voltammetry; *iii*) manufacturing of GDEs as cathodes containing SnO₂ NPs as catalyst; and *iv*) analysis of the synthesized SnO₂-GDE for the continuous CO₂RR into formate in aqueous solution, using a single-pass flow reactor configuration [58–60] to evaluate their performance operating at high current densities.

2. Experimental

2.1. Synthesis of SnO₂ nanoparticles

The synthesis of the SnO₂ NPs has been carried out by a hydrothermal microwave-assisted method [61,62]. In particular, a 0.1 mol L⁻¹ fresh aqueous solution of Sn (IV) was prepared by adding 3.506 g of SnCl₄·5H₂O to 100 ml (pH = 2). Subsequently, 50 ml of that solution were poured in a glass vial and transferred to a monomode microwave oven (Sairem Miniflox 200SS). The solution was then heated at 80 °C for 1 h under magnetic stirring (a maximum of 20 W was applied to maintain that temperature). The suspension was afterwards cooled to room temperature in few minutes. The obtained white powder was washed by centrifugation (three times with water and once with ethanol) for 20 min. Finally, a part of the powder was dried during 15 h at room temperature under vacuum to carry out the physicochemical characterization analyses. The remaining part of the powder was dispersed in isopropanol (1.33 g_{SnO₂} L⁻¹) to be used as the electrocatalyst in CO₂ electroreduction experiments.

2.2. Gas diffusion electrodes manufacturing

The preparation of SnO₂-GDEs was carried out according to the following procedure: initially, a carbon-based ink is prepared by mixing carbon powder (Vulcan XC-72R, Cabot, carbon black), and polytetrafluoroethylene (PTFE) (Sigma-Aldrich, 60 wt% dispersion in H₂O) in a mass ratio 40/60. The mixture was then diluted to 3% in isopropanol. The resulting dispersion was airbrushed onto a carbonaceous gas diffusion layer (TGP-H-60 with 40% (w/w) PTFE, Toray Inc.) supported on a Sn mesh current collector in order to obtain a partially hydrophobic carbon microporous layer (MPL), which was finally sintered at 623 K for 30 min, following a procedure previously described in recent contributions from some of the authors [63,64] (see Figure S3). Then, a catalytic ink containing the synthesized SnO₂ NPs dispersed in isopropanol and a Nafion solution (5 wt%, Alfa Aesar, copolymer polytetrafluoroethylene) with a (SnO₂+Nafion)/isopropanol mass ratio of 1.6/98.4 was finally airbrushed onto the MPL surface. The geometric surface area (A) of the catalytic layer was 10 cm² and the catalytic loading was 0.75 mg SnO₂ cm⁻², which were selected according to previous research studies using Sn-GDEs [65]. The final catalyst loading was 7.5 mg SnO₂ per electrode in all cases, which is controlled by continuous weighing of the electrode during the airbrushing process. Figure 1 shows a scheme of the as-prepared SnO₂-GDEs configuration.

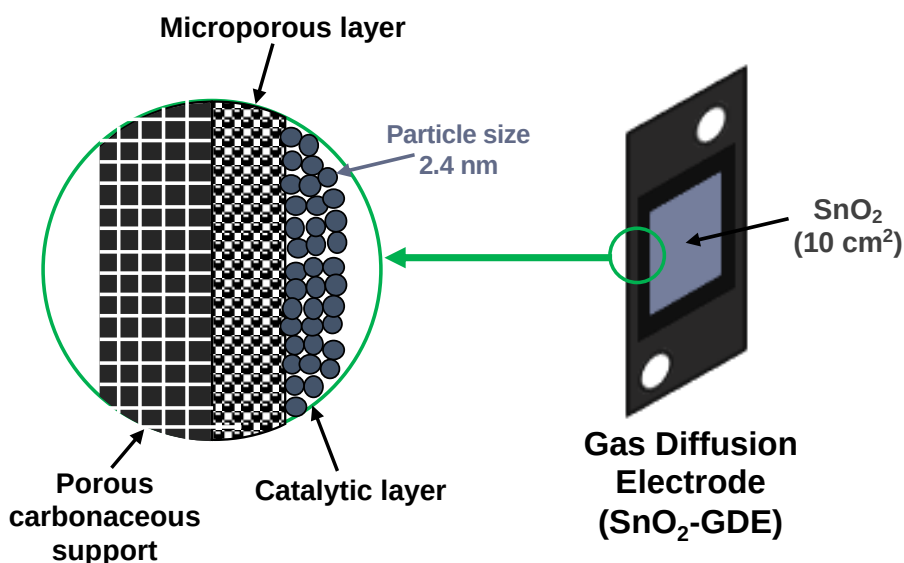


Fig. 1. Graphical representation of the SnO₂-GDE configuration.

2.3. Physicochemical and electrochemical characterization techniques.

The crystalline structure of the SnO₂ NPs was analyzed by powder X-ray diffraction (XRD) on a Bruker D8 Advance X-ray diffractometer in the 20-80° 2θ range using a Cu Kα X-ray irradiation source (λ = 0.1542 nm). Step time and step size were 1 s and 0.03°, respectively. The specific surface area analysis of the SnO₂ NPs was carried out by N₂ sorption at 77 K using a Belsorb Max (Belsorb Japan). Prior to measurements, SnO₂ NPs were degassed for 15 h under a primary vacuum at 150 °C. The BET method was applied to determine the specific surface area of the electrocatalyst.

The morphology and the average size of the SnO₂ NPs were analyzed by high resolution transmission electron microscopy (HR-TEM) using a JEOL 2100, which operates at 200 kV. The samples were prepared by evaporating diluted suspensions in ethanol onto carbon-coated copper grids. It is important to point out that more than 100 particles have been considered on several TEM pictures in order to evaluate the average size of the as-prepared SnO₂ NPs. Furthermore, the conductivity of the SnO₂ NPs was evaluated using impedance spectroscopy. In brief, the conductivity was measured on ~14% SnO₂ NPs pellet (thickness = 1.21 mm and diameter = 13 mm) at room temperature in air, with a frequency range varying between 0.1 and 10⁵ Hz and an amplitude of 200 mV_{rms} (4 repetitions). The spectra were then analyzed using Zview software for the determination of the electrical conductivity of the SnO₂ NPs (Impedance diagram shown in Figure S2).

Cyclic voltammetry (CV) analyses were performed using a CH Instruments 760E potentiostat in a three-electrode configuration electrochemical cell. A glassy carbon (GC) electrode (3 mm in diameter) was used as an inert current collector, at which different amounts of the prepared suspension (SnO₂ NPs in isopropanol) were deposited by drop casting, whereas a graphite rod

and an Ag/AgCl (saturated in KCl) were used as the counter and the reference electrodes, respectively. Either CO₂- or Ar-saturated 0.1 M KHCO₃ aqueous solutions were used as the electrolyte. The pH of the above-mentioned electrolytes was experimentally measured being 6.98 ± 0.07 (CO₂ saturation) and 9.03 ± 0.10 (Ar saturation), respectively. The GC electrode was mechanically polished with alumina, sonicated and rinsed with ultrapure water to ensure the complete removal of SnO₂ NPs from previous experiments. The applied potential ranged from 1 V to -1.75 V vs. Ag/AgCl at a scan rate of 100 mV s⁻¹. Potentials reported here were converted to reversible hydrogen electrode (RHE) using the equation: $E_{\text{RHE}} = E_{\text{Ag/AgCl}} + 0.197 + 0.059\text{pH}$.

2.4. CO₂ flow electrolyzer setup and experimental conditions

The manufactured SnO₂-GDEs were tested for CO₂RR in an electrochemical filter-press reactor configuration (Micro Flow Cell, Electrocell A/S) (see Figure S3), which operated at constant current in continuous mode controlled by a MSTAT4 system (Arbin Instruments). The electrochemical filter-press reactor was divided in two compartments (cathode and anode) by a cationic exchange membrane Nafion® 117. The filter-press configuration can be found elsewhere [63]. Figure 2 shows the CO₂RR continuous reactor scheme using a CO₂ single-pass flow configuration. (0.5 M KCl + 0.45 M KHCO₃) and 1 M KOH aqueous solutions were used as catholyte and anolyte, respectively. The effect on CO₂RR selectivity and performance of two experimental parameters was evaluated: the electrolyte flow per geometric electrode area (F/A) (0.57, 0.15 and 0.07 mL min⁻¹ cm⁻²) and the applied current density (from 200 to 500 mA cm⁻²). It is worth noting here that both the catholyte and the anolyte passed only once throughout the cell (single-pass configuration). The cathode side was also fed with a pure CO₂ gas stream at a flow of 200 mL min⁻¹. A Dimensionally Stable Anode [DSA/O₂ (Ir-MMO (mixed metal oxide) on Pt)] and a leak-free Ag/AgCl 3.4 mol L⁻¹ KCl electrodes were used as the anode and the reference, respectively. Reactor temperature was monitored along the experiment.

Liquid samples were analyzed by ion chromatography aiming at determining the formate concentration. A Dionex ICS 1100 equipped with an AS9-HC column was used as ion chromatograph, with a 4.5 mM Na₂CO₃ aqueous solution as the eluent (at a flow rate of 1 mL min⁻¹) and operated at approximately 13.8 MPa. Some liquid samples were selected to analyze the formation of alcohols by using a headspace gas chromatograph (GCMS-QP2010 Ultra Shimadzu) equipped with a flame ionization detector (FID). Additionally, a four-channel gas microchromatograph (490 Micro GC, Agilent Technologies) equipped with micro thermal conductivity detectors (Micro-TCD) was used for the detection and quantification of gaseous reduction products.

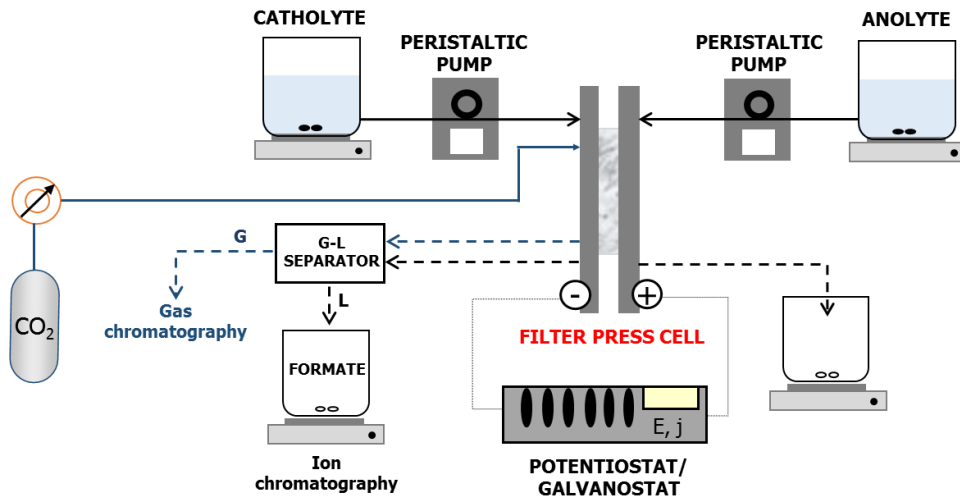


Fig. 2. CO₂RR continuous reactor setup scheme.

The manufactured SnO₂-GDEs were tested for continuous CO₂RR in a single-pass flow reactor at ambient conditions during 90 min electrolyses, where a pseudo-stable performance in time was observed (see Figure S4), as was previously described for Sn-GDEs [63]. Both liquid and gas samples were analyzed by duplicate every 30 min of electrolysis and an averaged concentration of each product (independent of electrolysis time) was calculated and reported herein. Some long-run electrolyses (5 h) were also performed to evaluate the stability of the developed electrocatalyst. Additionally, some figures of merit [66] to describe the CO₂RR were calculated, namely:

The Faradaic Efficiency (FE), which represents the percentage of the total charge applied to the system that is actually used to produce any target reduction product (*i.e.* formate), according to the following equation:

$$FE (\%) = \frac{z n F}{Q} \times 100 \quad (1)$$

where z represents the number of electrons exchanged to form the desired product (e.g. $z = 2$ for the electroconversion of CO₂ into formate), n corresponds to the number of moles produced, F is the Faraday constant ($F = 96,485 \text{ C mol}^{-1}$) and Q represents the total charge (C) circulated through the system, which is obtained by multiplying the current applied in amperes and the electrolysis time in seconds.

The Production Rate (r), which is defined as the productivity (moles) per unit of cathode area (geometric or electroactive area) and time ($\text{mmol m}^{-2} \text{ s}^{-1}$). r is essential to evaluate the technical feasibility of the process;

$$\text{Geometric rate} = r_G = F/A_G \cdot C_{\text{formate}} \quad (2)$$

$$\text{Real rate} = r_R = F/A_R \cdot C_{\text{formate}} \quad (3)$$

where (F/A) corresponds to the electrolyte flow per geometric (A_G) or real electrode area (A_R) in $L\ m^{-2}\ s^{-1}$ and C_{formate} is the concentration of product detected in $mmol\ L^{-1}$.

The Energy Consumption (EC), which represents the required amount of energy used to produce the target product (formate), according to:

$$\text{Energy Consumption} \left(\frac{kWh}{kmol} \right) = \frac{Q \cdot V}{n} \times 2.78 \cdot 10^{-4} \quad (4)$$

where V represents the absolute cell potential in volts.

The Energy Efficiency (reported in Table S3), which represents the total energy used towards the production of a specific desired product (e.g., formate), according to the following equation:

$$\text{Energy Efficiency (\%)} = (E_T/E) \cdot FE \quad (5)$$

where E_T is the theoretical potential in volts required for the electrocatalytic reduction of CO_2 to the product of interest (formate), whereas E and FE represent the real cathode potential applied in volts and the formate Faradaic Efficiency (%), respectively.

3. Results and Discussion

3.1. Physicochemical characterization of SnO_2 nanoparticles

The crystalline structure of the synthesized SnO_2 powder is firstly characterized using the X-ray diffraction technique. The obtained pattern presented in Figure 3 is indexed with the tetragonal phase of SnO_2 cassiterite (JCPDS 00-041-1445). The particle crystallite size is determined using Scherrer method on several very broad diffraction lines (see Table S1) obtaining a very small crystallite size, below 3 nm.

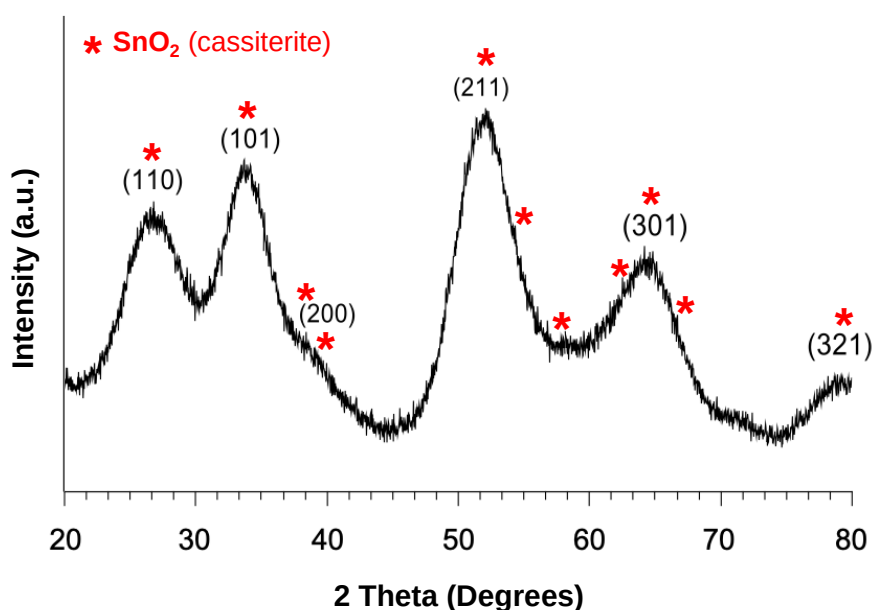


Fig. 3. X-ray diffraction pattern of the synthesized SnO₂ nanoparticles (the diffraction lines are indexed according to the cassiterite structure marked by red stars, JCPDS 00-041-1445).

This fact is further confirmed on the transmission electron micrographs of the synthesized SnO₂ NPs (Figure 4), where a mean size of (2.4 ± 0.6) nm can be measured. SnO₂ NPs are almost spherical and rather monodisperse in size. The surface area of the dried powder was also determined using the BET model and a specific surface area of (299 ± 10) m² g⁻¹ was determined for the synthesized SnO₂ NPs (see Figure S1), which is significantly larger than the value of commercially available equivalent nanomaterials.

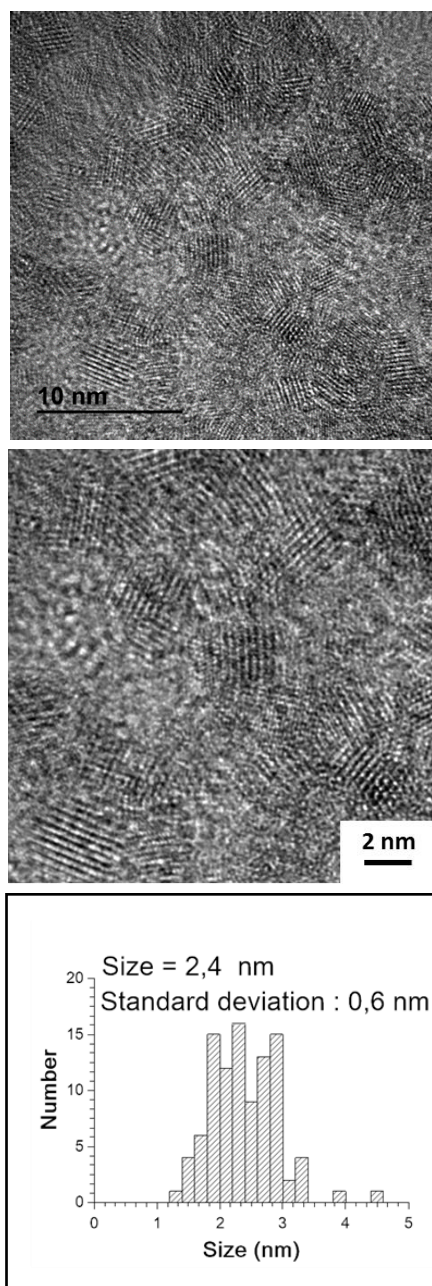


Fig. 4. HR-TEM image of synthesized SnO₂ nanoparticles including its size distribution.

3.2. Electrochemical characterization of SnO₂ nanoparticles

Different voltammetric analyses were carried out to study the electrochemical behavior of SnO₂ NPs in presence and absence of CO₂. In fact, some controversy is present in the literature nowadays regarding the mechanism of CO₂RR on SnO₂, since some reports pointed out SnO₂ and SnO as catalytically active sites for CO₂RR [39,42,45], but others suggested an initial electrochemical reduction step to form metallic Sn⁰, which was considered the actual catalytic site [67]. We studied small aliquots of SnO₂/isopropanol suspension deposited onto a GC electrode in presence and absence of CO₂. Figure 5a shows a clear and highly symmetrical reduction peak centered at -0.53 V vs RHE in a CO₂ free solution, which decreases rapidly in intensity with consecutive scans. This symmetrical peak shape denotes that the reduction process has taken place on the electrode surface and it is not linked to any electroactive species coming from the solution, which fits the reduction process from SnO₂ to metallic Sn⁰ previously reported by Zhang et al. [46]. Moreover, the backward scans show no reversibility in the reduction process observed, since a negligible oxidation current is collected in the anodic sweep. In addition to this, the effect of the amount of SnO₂ NPs deposited onto the electrode surface was also studied in the first CV scan, as shown in Figure 5b. The electrochemical response from the deposition of three different amounts of SnO₂ NPs (i.e. 1.88, 0.95 and 0.47 mg cm⁻²) was evaluated and lower peak currents were displayed as the amount of SnO₂ deposited decreases (8.5 10⁻⁵ A, 3.49 10⁻⁵ A and 2.20 10⁻⁵ A, respectively), which proves that the reduction current observed is proportional to the amount of SnO₂ NPs on the electrode. In contrast, Figure 6 shows a different electrochemical behavior displayed by SnO₂ NPs when CO₂ is present in solution. The reduction peak observed in figures 5a and 5b is not clearly shown, which suggests a different reduction mechanism. A clear hysteresis is observed in the cyclic voltammogram in the presence of CO₂ (blue plot in Figure 6), which denotes an electrode surface modification when cathodic potential is applied, which is subsequently confirmed by the presence of a symmetrical oxidation peak centered at -0.065 V in the anodic scan. This oxidation peak could be attributed to the reoxidation of some metallic Sn⁰ previously formed during the cathodic scan in agreement with Lee et al. [39] who have already demonstrated by XRD and XPS the stability of large sized SnO₂ NPs during CO₂RR with only a small fraction of metallic Sn⁰ formed at pH 8.4.

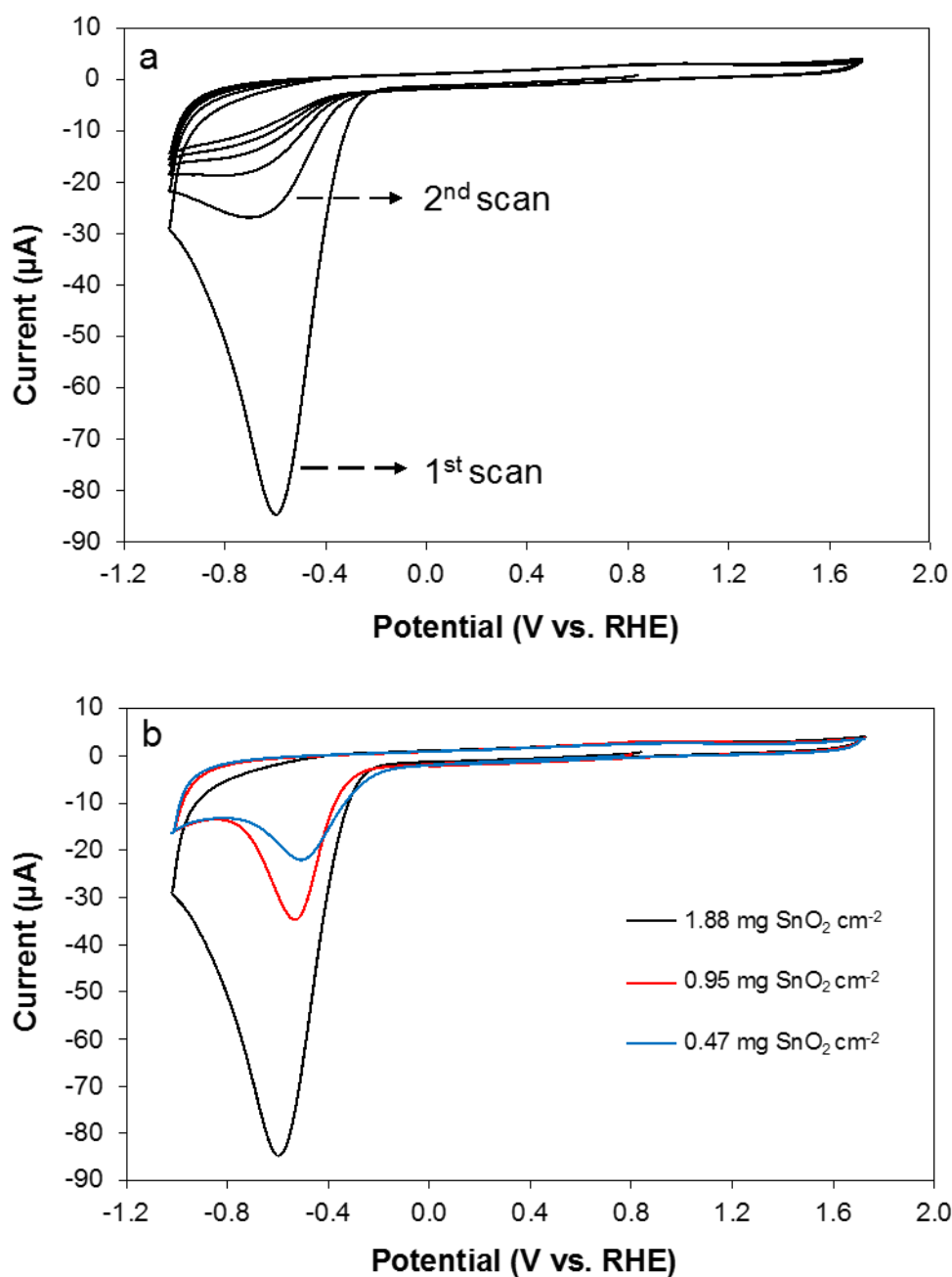


Fig. 5. Cyclic voltammetry of SnO_2 NPs deposited onto a GC electrode in an Ar saturated 0.1 M KHCO_3 aqueous solution: a) 1.88 mg SnO_2 NPs cm^{-2} are deposited and several consecutive scans are plotted, and b) effect of SnO_2 loading on the first CV scan to determine the peak currents. Scan rate 100 mV s^{-1} .

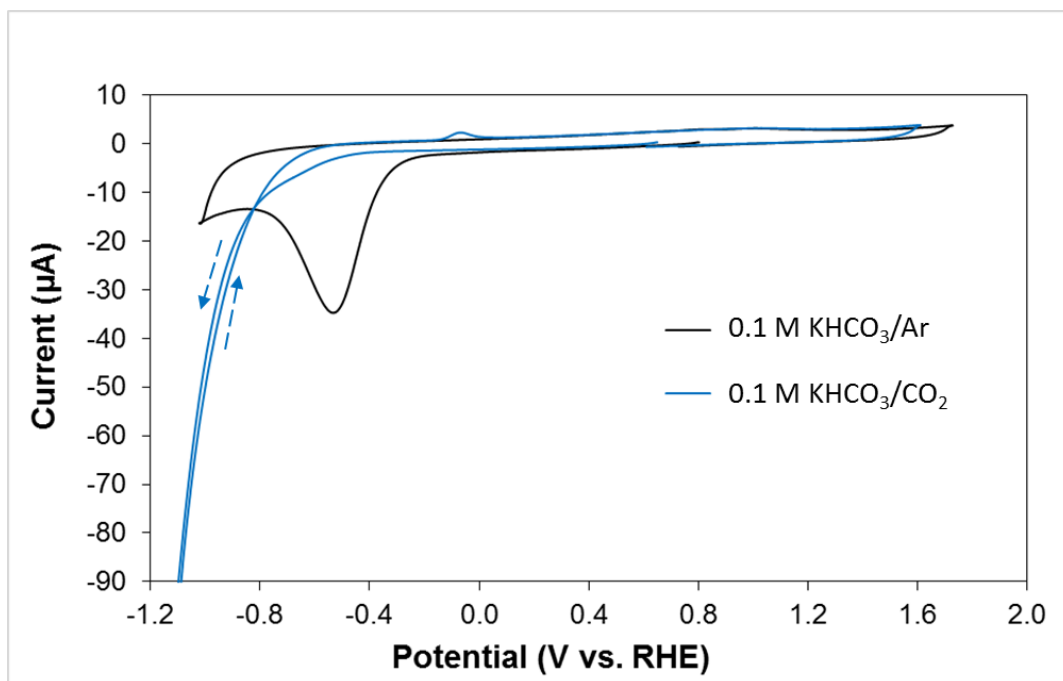


Fig. 6. Cyclic voltammetry of 0.95 mg SnO₂ NPs cm⁻² deposited onto a GC electrode in: (Black plot) an Ar saturated 0.1 M KHCO₃ aqueous solution and (Blue plot) a CO₂ saturated 0.1 M KHCO₃ aqueous solution. Scan rate 100 mV s⁻¹.

3.3. Continuous CO₂ electroreduction into formate

Two parameters were mainly evaluated on the performance of manufactured SnO₂-GDEs for CO₂RR in a flow electrolyzer: the catholyte flow per geometric electrode area (F/A) (0.57, 0.15 and 0.07 mL min⁻¹ cm⁻²) and the applied current density (from 200 to 500 mA cm⁻²), since those two operational variables were previously identified as key parameters in the production of formate from CO₂RR [22,63,68]. Figure 7 shows that the production of formate, which is a key figure of merit to evaluate the CO₂RR performance, is strongly dependent on both parameters: F/A and current density. Figure 7 exhibits much higher formate concentrations for lower catholyte flows per electrode area in all 3 current densities studied. This trend is in agreement with previously reported results obtained using Sn-GDEs (10-15 nm Sn NPs) for CO₂RR in a very similar flow electrolyzer at current densities between 90 and 200 mA cm⁻² [63]. Nevertheless, the comparison of formate concentration produced by equivalent experiments performed at 200 mA cm⁻² in SnO₂-GDEs (1.8 and 12.9 g HCOO⁻ L⁻¹ at 0.57 and 0.07 mL min⁻¹ cm⁻², respectively) and Sn-GDEs (2.6 and 16.9 g HCOO⁻ L⁻¹ at 0.57 and 0.07 mL min⁻¹ cm⁻², respectively [63]) highlights a poorer formate productivity in SnO₂-GDEs, in spite of the fact that SnO₂ NPs are significantly smaller in size than Sn NPs used in catalyzing the GDEs and SnO_x have been identified as responsible of enhancing formate production. Thus, the electrical conductivity of the synthesized SnO₂ NPs was evaluated by impedance spectroscopy (2 × 10⁻⁷ S cm⁻¹). This conductivity value is typical in semiconducting materials such as SnO₂, but provokes a significant electrical resistance in the electrode, which become more relevant at high current

densities. This fact was experimentally observed by heat generation in the reactor, which proved energy dissipation. This effect of the ohmic drop on electrode performance has been already addressed in flow electrolyzers for fuel cells [69]. Thus, an estimation of the impact in formate production by the electrical losses converted in heat by Joule effect during CO₂RR (*i.e.*, part of the charge supplied is used in generating heat instead of the reduction of CO₂ to the product of interest) was carried out and suggested that the difference in performance observed between SnO₂-GDEs and Sn-GDEs could be attributed to the moderate conductivity of SnO₂ NPs. Some additional calculations are described in the supplementary information.

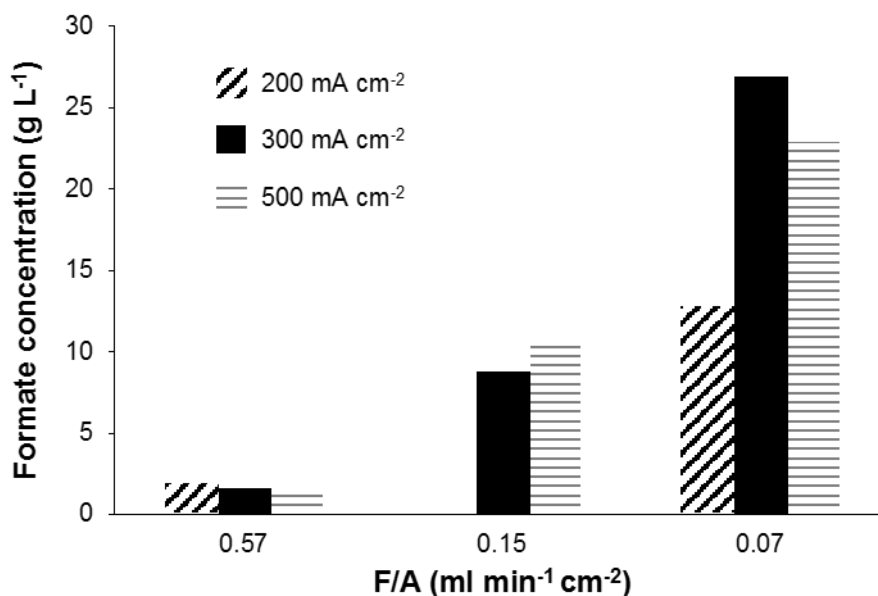


Fig. 7. Formate concentration produced on SnO₂-GDEs at different applied current densities and catholyte flows.

Table 1 presents the quantification of the main products in both liquid and gas-phases and the corresponding figures of merit obtained for CO₂RR performed on the manufactured SnO₂-GDEs in a flow electrolyzer at constant current. The most relevant result displayed in Table 1 corresponds to a formate production of 27 g L⁻¹ (entry 5). This is the highest formate concentration value reported on Sn based electrocatalysts using a flow electrolyzer and a catholyte solution in equivalent conditions. Only catholyte-free electrolyzers have been able to produce significantly higher formate concentrations [68,70]. Table 2 compares the best results obtained in the present study and those previously reported in the literature achieved for SnO_x-GDE, Sn-GDE and Sn-catalyst coated membrane electrode (CCME) configurations in flow electrolyzers.

Table 1. Formate production rates, concentration, Faradaic efficiencies and energy consumption results at SnO₂-GDEs (metal loading = 0.75 mg cm⁻²) as a function of the current density and the catholyte flow.

Entry	Geometric current density, j_G (mA cm ⁻²)	F/A (mL min ⁻¹ cm ⁻²)	Geometric rate, r_G (mmol m ⁻² s ⁻¹)	Real rate, r_R (mmol m ⁻² s ⁻¹)	Formate concentration (g L ⁻¹)	Formate FE (%)	Energy consumption (kWh kmol ⁻¹)	Gas-phase FE (%)			
								H ₂	CO	C ₂ H ₄	C ₃ H ₈
1	200	0.57	3.9 ± 0.2	1.73 10 ⁻³ ± 6 10 ⁻⁵	1.8 ± 0.1	37.3 ± 1.4	933 ± 36	9.9 ± 1.0	0.33 ± 0.01	---	1.9 ± 0.4
2		0.07	3.3 ± 0.4	1.48 10 ⁻³ ± 2 10 ⁻⁴	12.9 ± 1.5	32.1 ± 3.7	1251 ± 141	30.0 ± 4.3	0.33 ± 0.01	---	0.5 ± 0.3
3	300	0.57	3.5 ± 0.2	1.57 10 ⁻³ ± 7 10 ⁻⁵	1.7 ± 0.1	22.6 ± 1.0	2013 ± 93	11.4 ± 1.5	0.25 ± 0.07	---	1.5 ± 0.2
4		0.15	4.9 ± 0.5	2.20 10 ⁻³ ± 2 10 ⁻⁴	8.8 ± 0.9	31.7 ± 3.2	1350 ± 142	7.7 ± 0.9	0.27 ± 0.06	---	0.3 ± 0.1
5		0.07	7.0 ± 0.1	3.11 10 ⁻³ ± 2 10 ⁻⁵	27.0 ± 0.2	44.9 ± 0.3	752 ± 4	8.7 ± 1.5	0.22 ± 0.01	---	1.0 ± 0.3
6	500	0.57	3.0 ± 0.8	1.34 10 ⁻³ ± 3 10 ⁻⁴	1.4 ± 0.4	11.6 ± 3.0	4392 ± 610	16.1 ± 1.1	0.10 ± 0.02	0.79 ± 0.1	0.95 ± 0.2
7		0.15	6.0 ± 0.1	2.68 10 ⁻³ ± 6 10 ⁻⁵	10.8 ± 0.3	23.2 ± 0.5	2194 ± 50	16.5 ± 1.1	0.10 ± 0.04	0.69 ± 0.1	0.67 ± 0.1
8		0.07	6.0 ± 0.2	2.65 10 ⁻³ ± 1 10 ⁻⁴	22.9 ± 0.9	23.0 ± 0.9	2266 ± 93	12.8 ± 1.0	0.10 ± 0.01	0.57 ± 0.1	0.96 ± 0.2

Table 2. Comparison of our highest CO₂-into-formate result on SnO₂-GDE and some examples from the literature on tin oxide-based GDE, Sn-GDE and Sn-CCME configurations, in all cases using flow electrolyzers.

Catalyst	Reactor configuration	Pressure (bar)	Temperature (K)	Geometric current density, j_G (mA cm ⁻²)	Formate concentration (g L ⁻¹)	Formate FE (%)
SnO ₂ -GDE (this work)	Divided single-pass	1	293	300	27	44.9
SnO ₂ -GDE [52]	Divided single-pass	1	293	385	1	72
SnO _x -GDE [53]	Divided single-pass	1	293	150	8.1	77
SnO-GDE [54]	Divided single-pass	1	293	300	10.5	81
Sn ₃ O ₄ -GDE [55]	Divided single-pass	1	293	462	-	91.1
Sn-GDE [63]	Divided single-pass	1	293	200	16.9	42.3
Sn-CCME [22]	Divided single-pass	1	293	45	19.2	49.4
Sn sheet [71]	Undivided Recirculation	30	293	80	19.2	
Sn-CCME [70]	Divided single-pass	1	343	55.4	41.5	93.3
Sn-CCME [70]	Divided single-pass	1	323	38.5	116.2	77.7

The catholyte flow per geometric electrode area (F/A) and the applied current density were the two parameters evaluated on the results reported in Table 1. Looking first at the effect of current density, two different behaviors can be observed. On the one hand, at high catholyte flow (5.7 mL min^{-1}) formate concentration remained unaffected by the applied current density, 1.8, 1.7 and 1.4 g L^{-1} were detected at 200, 300 and 500 mA cm^{-2} , respectively (entries 1, 3 and 6 in Table 1). This fact provoked a relevant decrease in FE with increasing current density. On the other hand, at low catholyte flow (0.7 mL min^{-1}) formate concentration, rate and FE described a maximum at 300 mA cm^{-2} together with a minimum in EC of $752 \text{ kWh kmol}^{-1}$ (entry 5 in Table 1). Additionally, the increase of applied current density at constant catholyte flow provoked a significant diminution in the total FE of all quantified products, being 59.7% (entry 2) the maximum value achieved among all results reported in Table 1. Looking at the effect of F/A ratio in the results of Table 1, the formate concentration was significantly enhanced by reducing F/A from 0.57 to $0.07 \text{ mL min}^{-1} \text{ cm}^{-2}$ in all 3 current densities. Nevertheless, two different behaviors can be observed. On the one hand, at 200 mA cm^{-2} (entries 1 and 2 in Table 1) formate concentration increased almost linearly (from 1.8 to 12.9 g L^{-1}) by decreasing F/A ratio (from 0.57 to $0.07 \text{ mL min}^{-1} \text{ cm}^{-2}$) keeping FEs almost constant. On the other hand, at 300 (entries 3, 4 and 5 in Table 1) and 500 mA cm^{-2} (entries 6, 7 and 8 in Table 1) the increase observed in formate concentration (from 1.7 to 27 g L^{-1} and from 1.4 to 22.9 g L^{-1} , respectively) is twice the decrease in percentage of F/A ratio (from 0.57 to $0.07 \text{ mL min}^{-1} \text{ cm}^{-2}$). This fact together with the diminution in the total FE of all quantified products when higher current densities were applied and formate concentration independent of applied current density at high catholyte flow clearly demonstrated the existence of a leakage of formate by crossover from the catholyte towards the anolyte through the membrane, which was enhanced by increasing the catholyte flow. This phenomenon of formate anions migration towards the anode is usually negligible, working with a cationic exchange membrane like the one used in this work (Nafion 117), when the supporting electrolyte concentration (0.5 M) is significantly higher than the formate generated in the catholyte and the cell potential between the electrodes does not generate a strong electrical field. However, formate migration, which provokes the formate crossover to the anolyte through the membrane and limits the maximum formate concentration accumulated in the catholyte, becomes relevant when the concentration of formate generated ($27 \text{ g L}^{-1} = 0.6 \text{ M}$) in the catholyte becomes higher than the supporting electrolyte concentration (0.5 M), which happens when high current densities and low catholyte flow are applied. Then, formate migration current contribution to the total current becomes highly significant. Actually, a large drop in FE due to formate crossover through the Nafion 117 membrane was already described when reducing CO_2 on a metallic Sn^0 electrode in a single pass flow reactor at high applied current [38]. This effect together with the electrical resistance in the electrolyzer provoke a poor total FE in all entries shown in Table 1, being poorer at higher current densities.

The stability and durability of the SnO_2 NPs catalyzing the CO_2RR on SnO_2 -GDEs represent an important issue that needs to be addressed for evaluating the technical and economic feasibility of the CO_2 electroconversion process. Therefore, Figure 8 shows the evolution of absolute cell

potential and formate concentration with electrolysis time under optimal conditions selected from Table 1 (300 mA cm^{-2} and $0.07 \text{ mL min}^{-1} \text{ cm}^{-2}$). Figure 8 exhibits an almost constant cell potential and production of formate with time, which demonstrates the long-term stability of SnO_2 NPs during CO_2 electroreduction. In particular, this cathode operated up to 10 h, in two independent, but consecutive electrolysis of 5 h each. The maximum standard deviation comparing the formate concentration quantified in the duplicate 5 h electrolysis is $\pm 0.4 \text{ g L}^{-1}$ (see Table S2). Thus, the stability of the novel electrocatalyst proposed has been tested up to 10 h including a STOP and START point in the middle. It is therefore worth recalling the significant formate concentration achieved after 5 h of electrolysis ($27 \text{ g L}^{-1} = 0.6 \text{ M}$) in comparison with metallic Sn^0 based catalysts from the literature (see Table 2), denoting the possibility of using size-controlled SnO_2 NPs with high specific surface area for an enhanced CO_2 electroconversion into formate. Moreover, this formate concentration is higher than the required one for the use of formate as a fuel in DFAFC for the generation of electricity, which has been reported to be, at least, 0.5 M [72]. Therefore, the use of high surface area SnO_2 NPs in flow electrolyzers may open a novel promising perspective to develop more robust systems for CO_2 electroconversion into formate combined with DFAFCs for energy production.

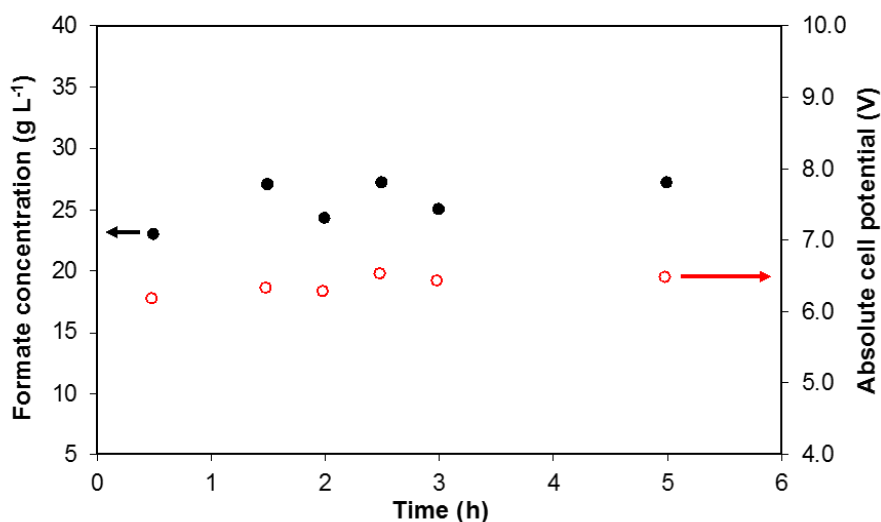


Fig. 8. Continuous formate production as a function of CO_2 electrolysis time on SnO_2 -GDE at 300 mA cm^{-2} and $F/A = 0.07 \text{ mL min}^{-1} \text{ cm}^{-2}$, including absolute cell potential evolution with time. Maximum formate concentration standard deviation: $\pm 0.4 \text{ g L}^{-1}$.

4. Conclusions

Crystalline and high specific surface area SnO_2 NPs (2.4 nm and $299 \text{ m}^2 \text{ g}^{-1}$ in average diameter size and surface area, respectively), synthesized by a facile hydrothermal microwave-assisted method, have been evaluated as an alternative electrocatalyst for the continuous production of formate from CO_2 single-pass electrochemical conversion, using large size electrodes operating at high current densities. So far, activity and selectivity performance of

SnO₂ NPs were reported either in a two compartments H-type cell displaying poor current densities or in continuous flow electrolyzers using large size SnO₂ catalytic particles and small size cathodes.

The electrochemical characterization by cyclic voltammetry of SnO₂ NPs has demonstrated a different mechanism under CO₂ and Ar reduction conditions, since the reduction peak associated with SnO₂ reduction to metallic Sn⁰ present in argon saturated solution is not clearly shown in the presence of CO₂.

The effect of catholyte flow per geometric electrode area (F/A) (0.57, 0.15 and 0.07 mL min⁻¹ cm⁻²) and applied current density (200, 300 and 500 mA cm⁻²) were evaluated on the performance of manufactured SnO₂-GDEs for continuous CO₂RR in a single-pass flow reactor at ambient conditions. At a constant current density of 300 mA cm⁻² and low catholyte flow per electrode area (0.07 mL min⁻¹ cm⁻²), a maximum formate concentration of 27 g L⁻¹ was achieved with a FE of 44.9%, a formate production rate of 6.98 mmol m⁻² s⁻¹ and an energy consumption of 752 kWh kmol⁻¹. This is the highest formate concentration value reported so far on Sn based electrocatalysts using a flow electrolyzer and a catholyte solution in equivalent conditions. This formate concentration result was only overcome by catholyte free flow electrolyzers, which benefits from a minimal amount of water vapor present as catholyte to carry out the CO₂RR. The FE towards formate using SnO₂ NPs was in the same range as those values reported for Sn-based electrodes (40-50%), even though higher energy consumption per kmol of formate produced was required at SnO₂-GDEs, which highlights the limited conductivity of SnO₂ NPs.

Poorer formate productivity in SnO₂-GDEs than in Sn-GDEs was observed at 200 mA cm⁻², in spite of the fact that SnO₂ NPs were significantly smaller in size than Sn NPs and SnO_x have been identified as responsible of enhancing formate production. This fact pointed out a non-negligible ohmic drop contribution on the SnO₂-GDEs due to the semiconducting properties of SnO₂, which provoked heat generation in the reactor by energy dissipation. However, the electrical losses by Joule effect associated with the ohmic drop during CO₂RR were not large enough to justify the low total FEs obtained (60 - 29 %), even though both liquid and gas-phase products were analyzed. This fact together with the too high increase observed in formate concentration linked to the decrease in F/A ratio at high current densities, as well as formate production independent of applied current density observed at high catholyte flow, demonstrated the existence of a leakage of formate by crossover migration from the catholyte towards the anolyte through the membrane, which was enhanced by increasing the catholyte flow. Formate migration limits the maximum formate concentration accumulated in the catholyte in this work and becomes relevant because the concentration of formate generated (27 g L⁻¹ = 0.6 M) in the catholyte becomes higher than the supporting electrolyte concentration (0.5 M). Then, formate migration current contribution to the total current becomes highly significant. For this reason, using a higher supporting electrolyte concentration in the catholyte is envisaged for the forthcoming experiments.

In conclusion, this study represents a step forward in the development of strategies based on SnO₂ nanomaterials for the continuous electrochemical conversion of CO₂ into formate since a formate concentration of 27 g L⁻¹ (0.6 M), which is superior to the limit for the use of formate as a fuel in DFAFCs, has been achieved during 10 h (by 2 consecutive electrolysis of 5 h each) in continuous galvanostatic mode at 300 mA cm⁻². Finally, these results suggest that interesting future research may involve developing SnO₂-based electrodes displaying higher electrical conductivity in order to reduce electrical losses and employing higher supporting electrolyte concentrations in the catholyte combined with new ionic membrane separators able to reduce the formate crossover from the catholyte to the anolyte where formate can be oxidized back to CO₂. This will allow to significantly increase the efficiency of formate production from CO₂RR on SnO₂ NPs at high current densities.

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References

- [1] National Oceanic & Atmospheric Administration (NOAA), Trends in Atmospheric Carbon Dioxide, Mauna Loa Observatory (MLO, Hawaii), Earth Syst. Res. Lab. (2020) <https://www.esrl.noaa.gov/gmd/ccgg/trends/monthly>.
- [2] X. Lu, D.Y.C. Leung, H. Wang, M.K.H. Leung, J. Xuan, Electrochemical Reduction of Carbon Dioxide to Formic Acid, *ChemElectroChem*. 1 (2014) 836–849. <https://doi.org/10.1002/celec.201300206>.
- [3] J.T. Song, H. Song, B. Kim, J. Oh, Towards higher rate electrochemical CO₂ conversion: From liquid-phase to gas-phase systems, *Catalysts*. 9 (2019) 224. <https://doi.org/10.3390/catal9030224>.
- [4] T. Sakakura, J.C. Choi, H. Yasuda, Transformation of carbon dioxide, *Chem. Rev.* 107 (2007) 2365–2387. <https://doi.org/10.1021/cr068357u>.
- [5] I. Merino-Garcia, E. Alvarez-Guerra, J. Albo, A. Irabien, Electrochemical membrane reactors for the utilisation of carbon dioxide, *Chem. Eng. J.* 305 (2016) 104–120.

<https://doi.org/10.1016/j.cej.2016.05.032>.

- [6] J. Albo, M. Alvarez-Guerra, A. Irabien, Electro-, photo- and photoelectro-chemical reduction of CO₂, in: *Heterog. Catal. Emerg. Tech. Des. Charact. Appl.*, Wiley-VCH, 2020.
- [7] J.L. White, M.F. Baruch, J.E. Pander, Y. Hu, I.C. Fortmeyer, J.E. Park, T. Zhang, K. Liao, J. Gu, Y. Yan, T.W. Shaw, E. Abelev, A.B. Bocarsly, Light-Driven Heterogeneous Reduction of Carbon Dioxide: Photocatalysts and Photoelectrodes, *Chem. Rev.* 115 (2015) 12888–12935. <https://doi.org/10.1021/acs.chemrev.5b00370>.
- [8] A. Taheri, L.A. Berben, Making C-H bonds with CO₂: production of formate by molecular electrocatalysts, *Chem. Commun.* 52 (2016) 1768–1777. <https://doi.org/10.1039/c5cc09041e>.
- [9] C. Costentin, M. Robert, J.M. Savéant, Catalysis of the electrochemical reduction of carbon dioxide, *Chem. Soc. Rev.* 42 (2013) 2423–2436. <https://doi.org/10.1039/c2cs35360a>.
- [10] E.E. Benson, C.P. Kubiak, A.J. Sathrum, J.M. Smieja, Electrocatalytic and homogeneous approaches to conversion of CO₂ to liquid fuels, *Chem. Soc. Rev.* 38 (2009) 89–99. <https://doi.org/10.1039/b804323j>.
- [11] E. Vichou, Y. Li, M. Gomez-Mingot, M. Fontecave, C.M. Sánchez-Sánchez, Imidazolium- And Pyrrolidinium-Based Ionic Liquids as Cocatalysts for CO₂ Electroreduction in Model Molecular Electrocatalysis, *J. Phys. Chem. C.* 124 (2020) 23764–23772. <https://doi.org/10.1021/acs.jpcc.0c07556>.
- [12] S. Nitopi, E. Bertheussen, S.B. Scott, X. Liu, A.K. Engstfeld, S. Horch, B. Seger, I.E.L. Stephens, K. Chan, C. Hahn, J.K. Nørskov, T.F. Jaramillo, I. Chorkendorff, Progress and Perspectives of Electrochemical CO₂ Reduction on Copper in Aqueous Electrolyte, *Chem. Rev.* 119 (2019) 7610–7672. <https://doi.org/10.1021/acs.chemrev.8b00705>.
- [13] C.M. Sánchez-Sánchez, J. Souza-Garcia, E. Herrero, A. Aldaz, Electrocatalytic reduction of carbon dioxide on platinum single crystal electrodes modified with adsorbed adatoms, *J. Electroanal. Chem.* 668 (2012) 51–59. <https://doi.org/10.1016/j.jelechem.2011.11.002>.
- [14] L. Zhang, I. Merino-Garcia, J. Albo, C.M. Sánchez-Sánchez, Electrochemical CO₂ reduction reaction on cost-effective oxide-derived copper and transition metal–nitrogen–carbon catalysts, *Curr. Opin. Electrochem.* 23 (2020) 65–73. <https://doi.org/10.1016/j.coelec.2020.04.005>.
- [15] H.K. Ju, G. Kaur, A.P. Kulkarni, S. Giddey, Challenges and trends in developing technology for electrochemically reducing CO₂ in solid polymer electrolyte membrane reactors, *J. CO₂ Util.* 32 (2019) 178–186. <https://doi.org/10.1016/j.jcou.2019.04.003>.

- 1 [16] R. Kortlever, J. Shen, K.J.P. Schouten, F. Calle-Vallejo, M.T.M. Koper, Catalysts and
2 Reaction Pathways for the Electrochemical Reduction of Carbon Dioxide, *J. Phys.*
3 *Chem. Lett.* 6 (2015) 4073–4082. <https://doi.org/10.1021/acs.jpcllett.5b01559>.
- 4 [17] C.M. Sánchez-Sánchez, V. Montiel, D.A. Tryk, A. Aldaz, A. Fujishima, Electrochemical
5 approaches to alleviation of the problem of carbon dioxide accumulation, *Pure Appl.*
6 *Chem.* 73 (2001) 1917–1927. <https://doi.org/10.1351/pac200173121917>.
- 7 [18] J. Wu, Y. Huang, W. Ye, Y. Li, CO₂ Reduction: From the Electrochemical to
8 Photochemical Approach, *Adv. Sci.* 4 (2017) 1700194.
9 <https://doi.org/10.1002/advs.201700194>.
- 10 [19] J. Qiao, Y. Liu, F. Hong, J. Zhang, A review of catalysts for the electroreduction of
11 carbon dioxide to produce low-carbon fuels, *Chem. Soc. Rev.* 43 (2014) 631–675.
12 <https://doi.org/10.1039/c3cs60323g>.
- 13 [20] C. Delacourt, P.L. Ridgway, J.B. Kerr, J. Newman, Design of an Electrochemical Cell
14 Making Syngas (CO +H₂) from CO₂ and H₂O Reduction at Room Temperature, *J.*
15 *Electrochem. Soc.* 155 (2007) B42–B49. <https://doi.org/10.1149/1.2801871>.
- 16 [21] I. Merino-Garcia, J. Albo, P. Krzywda, G. Mul, A. Irabien, Bimetallic Cu-based hollow
17 fibre electrodes for CO₂ electroreduction, *Catal. Today.* 346 (2020) 34–39.
18 <https://doi.org/10.1016/j.cattod.2019.03.025>.
- 19 [22] G. Díaz-Sainz, M. Alvarez-Guerra, J. Solla-Gullón, L. García-Cruz, V. Montiel, A. Irabien,
20 Catalyst coated membrane electrodes for the gas phase CO₂ electroreduction to
21 formate, *Catal. Today.* 346 (2020) 58–64. <https://doi.org/10.1016/j.cattod.2018.11.073>.
- 22 [23] J. García, C. Jiménez, F. Martínez, R. Camarillo, J. Rincón, Electrochemical reduction of
23 CO₂ using Pb catalysts synthesized in supercritical medium, *J. Catal.* 367 (2018) 72–80.
24 <https://doi.org/10.1016/j.jcat.2018.08.017>.
- 25 [24] J. Albo, A. Sáez, J. Solla-Gullón, V. Montiel, A. Irabien, Production of methanol from
26 CO₂ electroreduction at Cu₂O and Cu₂O/ZnO-based electrodes in aqueous solution,
27 *Appl. Catal. B Environ.* 176–177 (2015) 709–717.
28 <https://doi.org/10.1016/j.apcatb.2015.04.055>.
- 29 [25] D. Ren, Y. Deng, A.D. Handoko, C.S. Chen, S. Malkhandi, B.S. Yeo, Selective
30 Electrochemical Reduction of Carbon Dioxide to Ethylene and Ethanol on Copper(I)
31 oxide catalysts, *ACS Catal.* 5 (2015) 2814–2821. <https://doi.org/10.1021/cs502128q>.
- 32 [26] I. Merino-Garcia, J. Albo, A. Irabien, Productivity and Selectivity of Gas-Phase CO₂
33 Electroreduction to Methane at Copper Nanoparticle-Based Electrodes, *Energy Technol.*
34 5 (2017) 922–928. <https://doi.org/10.1002/ente.201600616>.
- 35 [27] I. Merino-Garcia, J. Albo, J. Solla-Gullón, V. Montiel, A. Irabien, Cu oxide/ZnO-based

- surfaces for a selective ethylene production from gas-phase CO₂ electroconversion, *J. CO₂ Util.* 31 (2019) 135–142. <https://doi.org/10.1016/j.jcou.2019.03.002>.
- [28] Z. Cai, Y. Wu, Z. Wu, L. Yin, Z. Weng, Y. Zhong, W. Xu, X. Sun, H. Wang, Unlocking bifunctional electrocatalytic activity for CO₂ reduction reaction by win-win metal-oxide cooperation, *ACS Energy Lett.* 3 (2018) 2816–2822. <https://doi.org/10.1021/acsenergylett.8b01767>.
- [29] X. Yu, P.G. Pickup, Recent advances in direct formic acid fuel cells (DFAFC), *J. Power Sources*. 182 (2008) 124–132. <https://doi.org/10.1016/j.jpowsour.2008.03.075>.
- [30] S. Ponnurangam, I. V. Chernyshova, P. Somasundaran, Nitrogen-containing polymers as a platform for CO₂ electroreduction, *Adv. Colloid Interface Sci.* 244 (2017) 184–198. <https://doi.org/10.1016/j.cis.2016.09.002>.
- [31] C. Oloman, H. Li, Electrochemical processing of carbon dioxide, *ChemSusChem*. 1 (2008) 385–391. <https://doi.org/10.1002/cssc.200800015>.
- [32] U.O. Nwabara, E.R. Cofell, S. Verma, E. Negro, P.J.A. Kenis, Durable Cathodes and Electrolyzers for the Efficient Aqueous Electrochemical Reduction of CO₂, *ChemSusChem*. 13 (2020) 855–875. <https://doi.org/10.1002/cssc.201902933>.
- [33] A. Irabien, M. Alvarez-Guerra, J. Albo, A. Dominguez-Ramos, Electrochemical conversion of CO₂ to value-added products, in: *Electrochem. Water Wastewater Treat.*, Elsevier, Amsterdam, 2018: pp. 29–59.
- [34] N. Han, P. Ding, L. He, Y. Li, Y. Li, Promises of Main Group Metal-Based Nanostructured Materials for Electrochemical CO₂ Reduction to Formate, *Adv. Energy Mater.* 10 (2020) 1902338. <https://doi.org/10.1002/aenm.202070046>.
- [35] G. Díaz-Sainz, M. Alvarez-Guerra, J. Solla-Gullón, L. García-Cruz, V. Montiel, A. Irabien, CO₂ electroreduction to formate: Continuous single-pass operation in a filter-press reactor at high current densities using Bi gas diffusion electrodes, *J. CO₂ Util.* 34 (2019) 12–19. <https://doi.org/10.1016/j.jcou.2019.05.035>.
- [36] D. Wu, G. Huo, W.Y. Chen, X.Z. Fu, J.L. Luo, Boosting formate production at high current density from CO₂ electroreduction on defect-rich hierarchical mesoporous Bi/Bi₂O₃ junction nanosheets, *Appl. Catal. B Environ.* 271 (2020) 118957. <https://doi.org/10.1016/j.apcatb.2020.118957>.
- [37] D. Pavesi, R.C.J. Van De Poll, J.L. Krasovic, M. Figueiredo, G.J.M. Gruter, M.T.M. Koper, K.J.P. Schouten, Cathodic Disintegration as an Easily Scalable Method for the Production of Sn-and Pb-Based Catalysts for CO₂Reduction, *ACS Sustain. Chem. Eng.* 8 (2020) 15603–15610. <https://doi.org/10.1021/acssuschemeng.0c04875>.
- [38] H. Li, C. Oloman, Development of a continuous reactor for the electro-reduction of

- 1 carbon dioxide to formate - Part 2: Scale-up, *J. Appl. Electrochem.* 37 (2007) 1107–
2 1117. <https://doi.org/10.1007/s10800-007-9371-8>.
- 3 [39] S. Lee, J.D. Ocon, Y. Il Son, J. Lee, Alkaline CO₂ electrolysis toward selective and
4 continuous HCOO⁻ production over SnO₂ nanocatalysts, *J. Phys. Chem. C* 119 (2015)
5 4884–4890. <https://doi.org/10.1021/jp512436w>.
- 6 [40] B. Kumar, V. Atla, J.P. Brian, S. Kumari, T.Q. Nguyen, M. Sunkara, J.M. Spurgeon,
7 Reduced SnO₂ Porous Nanowires with a High Density of Grain Boundaries as Catalysts
8 for Efficient Electrochemical CO₂-into-HCOOH Conversion, *Angew. Chemie - Int. Ed.* 56
9 (2017) 3645–3649. <https://doi.org/10.1002/anie.201612194>.
- 10 [41] Y. Chen, M.W. Kanan, Tin oxide dependence of the CO₂ reduction efficiency on tin
11 electrodes and enhanced activity for tin/tin oxide thin-film catalysts, *J. Am. Chem. Soc.*
12 134 (2012) 1986–1989. <https://doi.org/10.1021/ja2108799>.
- 13 [42] Yiliguma, Z. Wang, C. Yang, A. Guan, L. Shang, A.M. Al-Enizi, L. Zhang, G. Zheng, Sub-
14 5 nm SnO₂ chemically coupled hollow carbon spheres for efficient electrocatalytic CO₂
15 reduction, *J. Mater. Chem. A* 6 (2018) 20121–20127.
16 <https://doi.org/10.1039/c8ta08058e>.
- 17 [43] C. Zhao, J. Wang, J.B. Goodenough, Comparison of electrocatalytic reduction of CO₂ to
18 HCOOH with different tin oxides on carbon nanotubes, *Electrochem. Commun.* 65
19 (2016) 9–13. <https://doi.org/10.1016/j.elecom.2016.01.019>.
- 20 [44] R. Zhang, W. Lv, L. Lei, Role of the oxide layer on Sn electrode in electrochemical
21 reduction of CO₂ to formate, *Appl. Surf. Sci.* 356 (2015) 24–29.
22 <https://doi.org/10.1016/j.apsusc.2015.08.006>.
- 23 [45] Y. Fu, Y. Li, X. Zhang, Y. Liu, J. Qiao, J. Zhang, D.P. Wilkinson, Novel hierarchical SnO₂
24 microsphere catalyst coated on gas diffusion electrode for enhancing energy efficiency
25 of CO₂ reduction to formate fuel, *Appl. Energy* 175 (2016) 536–544.
26 <https://doi.org/10.1016/j.apenergy.2016.03.115>.
- 27 [46] S. Zhang, P. Kang, T.J. Meyer, Nanostructured tin catalysts for selective electrochemical
28 reduction of carbon dioxide to formate, *J. Am. Chem. Soc.* 136 (2014) 1734–1737.
29 <https://doi.org/10.1021/ja4113885>.
- 30 [47] J. Wu, F.G. Risalvato, S. Ma, X.D. Zhou, Electrochemical reduction of carbon dioxide III.
31 The role of oxide layer thickness on the performance of Sn electrode in a full
32 electrochemical cell, *J. Mater. Chem. A* 2 (2014) 1647–1651.
33 <https://doi.org/10.1039/c3ta13544f>.
- 34 [48] A. Kuzume, A. Dutta, S. Veszteg, P. Broekmann, Operando raman spectroscopy:
35 Studies on the Reactivity and Stability of SnO₂ Nanoparticles During Electrochemical
36 CO₂ Reduction Reaction, in: *Encycl. Interfacial Chem. Surf. Sci. Electrochem.*, Elsevier,

2018: pp. 217–226. <https://doi.org/10.1016/B978-0-12-409547-2.13300-1>.

- [49] M.F. Baruch, J.E. Pander, J.L. White, A.B. Bocarsly, Mechanistic Insights into the Reduction of CO₂ on Tin Electrodes using in Situ ATR-IR Spectroscopy, *ACS Catal.* 5 (2015) 3148–3156. <https://doi.org/10.1021/acscatal.5b00402>.
- [50] A. Dutta, A. Kuzume, M. Rahaman, S. Vesztergom, P. Broekmann, Monitoring the Chemical State of Catalysts for CO₂ Electroreduction: An In Operando Study, *ACS Catal.* 5 (2015) 7498–7502. <https://doi.org/10.1021/acscatal.5b02322>.
- [51] F.D. Mayer, P. Hosseini-Benhangi, C.M. Sánchez-Sánchez, E. Asselin, E.L. Gyenge, Scanning electrochemical microscopy screening of CO₂ electroreduction activities and product selectivities of catalyst arrays, *Commun. Chem.* 3 (2020) 155. <https://doi.org/10.1038/s42004-020-00399-6>.
- [52] S. Sen, S.M. Brown, M.L. Leonard, F.R. Brushett, Electroreduction of carbon dioxide to formate at high current densities using tin and tin oxide gas diffusion electrodes, *J. Appl. Electrochem.* 49 (2019) 917–928. <https://doi.org/10.1007/s10800-019-01332-z>.
- [53] M. Li, M.N. Idros, Y. Wu, S. Garg, S. Gao, R. Lin, H. Rabiee, Z. Li, L. Ge, T.E. Rufford, Z. Zhu, L. Li, G. Wang, Unveiling the effects of dimensionality of tin oxide-derived catalysts on CO₂ reduction by using gas-diffusion electrodes, *React. Chem. Eng.* 6 (2021) 345–352. <https://doi.org/10.1039/d0re00396d>.
- [54] Y. Qian, Y. Liu, H. Tang, B.L. Lin, Highly efficient electroreduction of CO₂ to formate by nanorod@2D nanosheets SnO, *J. CO₂ Util.* 42 (2020) 101287. <https://doi.org/10.1016/j.jcou.2020.101287>.
- [55] L.X. Liu, Y. Zhou, Y.C. Chang, J.R. Zhang, L.P. Jiang, W. Zhu, Y. Lin, Tuning Sn₃O₄ for CO₂ reduction to formate with ultra-high current density, *Nano Energy.* 77 (2020) 105296. <https://doi.org/10.1016/j.nanoen.2020.105296>.
- [56] G. Liu, Z. Li, J. Shi, K. Sun, Y. Ji, Z. Wang, Y. Qiu, Y. Liu, Z. Wang, P.A. Hu, Black reduced porous SnO₂ nanosheets for CO₂ electroreduction with high formate selectivity and low overpotential, *Appl. Catal. B Environ.* 260 (2020) 118134. <https://doi.org/10.1016/j.apcatb.2019.118134>.
- [57] F. Li, L. Chen, G.P. Knowles, D.R. MacFarlane, J. Zhang, Hierarchical Mesoporous SnO₂ Nanosheets on Carbon Cloth: A Robust and Flexible Electrocatalyst for CO₂ Reduction with High Efficiency and Selectivity, *Angew. Chemie.* 56 (2017) 505–509. <https://doi.org/10.1002/ange.201608279>.
- [58] E. Jeng, F. Jiao, Investigation of CO₂ single-pass conversion in a flow electrolyzer, *React. Chem. Eng.* 5 (2020) 1768–1775. <https://doi.org/10.1039/d0re00261e>.
- [59] S. Malkhandi, B.S. Yeo, Electrochemical conversion of carbon dioxide to high value

chemicals using gas-diffusion electrodes, *Curr. Opin. Chem. Eng.* 26 (2019) 112–121.
<https://doi.org/10.1016/j.coche.2019.09.008>.

[60] P. Jeanty, C. Scherer, E. Magori, K. Wiesner-Fleischer, O. Hinrichsen, M. Fleischer, Upscaling and continuous operation of electrochemical CO₂ to CO conversion in aqueous solutions on silver gas diffusion electrodes, *J. CO₂ Util.* 24 (2018) 454–462.
<https://doi.org/10.1016/j.jcou.2018.01.011>.

[61] B.L. Caetano, F. Meneau, C. V. Santilli, S.H. Pulcinelli, M. Magnani, V. Briois, Mechanisms of SnO₂ nanoparticles formation and growth in acid ethanol solution derived from SAXS and combined raman-XAS time-resolved studies, *Chem. Mater.* 26 (2014) 6777–6785. <https://doi.org/10.1021/cm5032688>.

[62] M. Krishna, S. Komarneni, Conventional- vs microwave-hydrothermal synthesis of tin oxide, SnO₂ nanoparticles, *Ceram. Int.* 35 (2009) 3375–3379.
<https://doi.org/10.1016/j.ceramint.2009.06.010>.

[63] A. Del Castillo, M. Alvarez-Guerra, J. Solla-Gullón, A. Sáez, V. Montiel, A. Irabien, Sn nanoparticles on gas diffusion electrodes: Synthesis, characterization and use for continuous CO₂ electroreduction to formate, *J. CO₂ Util.* 18 (2017) 222–228.
<https://doi.org/10.1016/j.jcou.2017.01.021>.

[64] G. Díaz-Sainz, M. Alvarez-Guerra, B. Ávila-Bolívar, J. Solla-Gullón, V. Montiel, A. Irabien, Improving trade-offs in the figures of merit of gas-phase single-pass continuous CO₂ electrocatalytic reduction to formate, *Chem. Eng. J.* 405 (2021) 126965.
<https://doi.org/10.1016/j.cej.2020.126965>.

[65] A. Del Castillo, M. Alvarez-Guerra, J. Solla-Gullón, A. Sáez, V. Montiel, A. Irabien, Electrocatalytic reduction of CO₂ to formate using particulate Sn electrodes: Effect of metal loading and particle size, *Appl. Energy.* 157 (2015) 165–173.
<https://doi.org/10.1016/j.apenergy.2015.08.012>.

[66] C.M. Sánchez-Sánchez, E. Expósito, J. Solla-Gullón, V. García-García, V. Montiel, A. Aldaz, Calculation of the characteristic performance indicators in an electrochemical process, *J. Chem. Educ.* 80 (2003) 529. <https://doi.org/10.1021/ed080p529>.

[67] J. Gu, F. Héroguel, J. Luterbacher, X. Hu, Densely Packed, Ultra Small SnO Nanoparticles for Enhanced Activity and Selectivity in Electrochemical CO₂ Reduction, *Angew. Chemie - Int. Ed.* 57 (2018) 2943–2947. <https://doi.org/10.1002/anie.201713003>.

[68] G. Díaz-Sainz, M. Alvarez-Guerra, A. Irabien, Continuous electrochemical reduction of CO₂ to formate: Comparative study of the influence of the electrode configuration with Sn and Bi-based electrocatalysts, *Molecules.* 25 (2020) 4457.
<https://doi.org/10.3390/molecules25194457>.

[69] Y. Bultel, P. Ozil, R. Durand, Modelling the mode of operation of PEMFC electrodes at

the particle level: Influence of ohmic drop within the active layer on electrode performance, *J. Appl. Electrochem.* 28 (1998) 269–276.
<https://doi.org/10.1023/A:1003207514936>.

[70] W. Lee, Y.E. Kim, M.H. Youn, S.K. Jeong, K.T. Park, Catholyte-Free Electrocatalytic CO₂ Reduction to Formate, *Angew. Chemie - Int. Ed.* 57 (2018) 6883–6887.
<https://doi.org/10.1002/anie.201803501>.

[71] F. Proietto, B. Schiavo, A. Galia, O. Scialdone, Electrochemical conversion of CO₂ to HCOOH at tin cathode in a pressurized undivided filter-press cell, *Electrochim. Acta.* 277 (2018) 30–40. <https://doi.org/10.1016/j.electacta.2018.04.159>.

[72] L. An, R. Chen, Direct formate fuel cells: A review, *J. Power Sources.* 320 (2016) 127–139. <https://doi.org/10.1016/j.jpowsour.2016.04.082>.