

This is the final peer-reviewed accepted manuscript of:

Andrea Cingolani, Diego Olivieri, Alessandro Messori, Cristiana Cesari, Valerio Zanotti, Stefano Zacchini, Isacco Gualandi, Erika Scavetta, Federica Mariani, Domenica Tonelli and Rita Mazzoni: "Electrochemical polymerisation of newly synthesised 3,4-ethylene dioxothiophene-N-heterocyclic carbene iron complexes and application as redox mediators" *Inorganica Chimica Acta* 542 (2022) 121138

The final published version is available online at:

<https://doi.org/10.1016/j.ica.2022.121138>

Rights / License:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>)

When citing, please refer to the published version.

Electrochemical Polymerisation of Newly Synthesised 3,4-Ethylene Dioxythiophene-N-Heterocyclic Carbene Iron Complexes and Application as Redox Mediators

Andrea Cingolani,^a Diego Olivieri,^b Alessandro Messori,^{a,c} Cristiana Cesari,^{a,c} Valerio Zanotti,^a Stefano Zacchini,^{a,c} Isacco Gualandi,^{a,c*} Erika Scavetta,^{a,c} Federica Mariani,^{a,c} Domenica Tonelli^a and Rita Mazzoni^{a,c*}

^a Department of Industrial Chemistry “Toso Montanari”, University of Bologna, Viale Risorgimento 4, 40136 Bologna, Italy; ^b Department of Biomolecular Sciences, University of Urbino “Carlo Bo”, Piazza Rinascimento 6, 61029 Urbino (PU), Italy; ^c Center for Chemical Catalysis – C3, University of Bologna, viale Risorgimento 4 40136 Bologna, Italy.

Corresponding authors:

Rita Mazzoni: rita.mazzoni@unibo.it;

Isacco Gualandi: isacco.gualandi@unibo.it.

This work is a contribution for the special issue honouring Professor Claudio Pettinari.

Keywords

Iron complexes, N-heterocyclic carbene, NHC, Cyclopentadienone, EDOT, PEDOT:PSS, glucose sensor, functionalization, electropolymerization

Abstract

Immobilization of redox active complexes as electrodes modifier is appealing for a large set of applications such as sensing, electrolyzers or fuel cell. In this work iron based N-heterocyclic carbene complexes bearing an 3,4-Ethylene dioxythiophene (EDOT) moiety in the side chain have been prepared following two different synthetic approaches determined by the length of the lateral chain. The approaches exploit carbonyldiimidazole (CDI) as the coupling agent between the $-\text{CH}_2\text{OH}$ moiety of the hydroxymethyl-EDOT and the $-\text{OH}$ functionalized N-heterocyclic carbene iron complex or the imidazolium salt precursor. In both cases, the syntheses allow to obtain functional monomers suitable for electrochemical polymerization in the form of thin films on conducting substrates. The modified electrodes have been characterized by ATR-IR, showing successful copolymerisation to functionalized poly(3,4-ethylene dioxythiophene) (PEDOT), by cyclic voltammetry (CV), demonstrating the dominant and reversible redox response of NHC-iron complexes, and by SEM-EDS, which provides the average copolymerisation ratio. The capability of the NHC-iron complex to act as a redox mediator has been assessed by using the functionalized device for glucose detection.

1. Introduction

Iron is the most abundant transition metal in the Earth's crust, which means low cost and wide availability, it is biocompatible and plays a crucial role in biological mechanisms. Furthermore, the environmental impact concerning its wider use is quite reassuring.¹ Iron redox properties can be finely tuned by the design of suitable ligands in molecular complexes, which are thus emerging as a promising alternative to precious metals in several applications, such as catalysis²⁻⁴ and electrocatalysis for energy production. Emerging technologies exploit, for example, iron molecular complexes on both sides of water splitting, namely water oxidation⁵⁻⁷ or hydrogen evolution.⁸⁻¹¹

Immobilization through ionic or covalent bond is a good tool to exploit the high activity and specific properties of transition metal molecular complexes.^{2, 12-16} While this approach has been studied in the last two decades in order to obtain single site iron based molecular catalysts for olefin

polymerization¹⁷⁻²¹ alkenes and alkanes oxidation,^{22,23} hydrogenation²⁴ and Michael addition reactions,²⁵ it has recently become an innovative approach for the development of more efficient electrochemical devices.

Indeed, chemically modified electrodes are widely employed in electrochemistry and an important goal in this field is to find a way to strongly anchor redox mediators on the electrode surface (e.g. covalent bonding). A competitive redox mediator requires good electrochemical reversibility, regeneration at low potential, and generation of stable redox forms in order to be able to shuttle the electrons between the electrode and a substrate or an active redox site, such as a redox enzyme. Among others, ferrocene represents the first organometallic complex widely employed in this field.²⁶⁻³⁴ To improve its attachment to the electrode surface, many immobilization methods, including cross-linking gels or polymers, have been developed.^{35,36} Beyond the kind of immobilization, the presence and the length of spacers between the polymer and the redox mediator play a key role in defining the performance of chemically modified electrodes by affecting the stability,³⁷ charge transport³⁸ and even the redox response.³⁷

Conductive polymers are receiving increasing attention in electrochemistry due to their low cost, their relatively high conductivity, and their lightweight and flexibility. These peculiar characteristics allow their use in highly innovative devices in which conventional electrode materials fail. Examples of these applications are the fabrication and development of wearable sensors, supercapacitors and batteries³⁹ or to be used in paper electronics. Among conductive polymers, poly(3,4-ethylenedioxythiophene) (PEDOT) has received great attention due to its mixed ionic-electronic conduction, high chemical and thermal stability, biocompatibility and low-energy band gap⁴⁰ which makes it suitable for electro-optical applications. Moreover, the presence of ethylenedioxy substituents in the 3 and 4 positions of the polythiophenic ring makes it regiochemically better defined than the unsubstituted polythiophene. PEDOT can be prepared by several chemical or electrochemical routes, both in aqueous and organic media; electrochemical polymerization methods allow obtaining PEDOT coated electrodes by employing a small amount of monomer and short polymerization

times.⁴¹ The EDOT electropolymerization in aqueous media can be achieved using suitable water-soluble polyelectrolytes as emulsifiers and doping agents. In particular, when the polymerization is carried out in the presence of a typical polyelectrolyte, such as poly(styrene-4-sulfonate) ((PSS)ⁿ⁻), stable and conducting films of PEDOT:PSS can be synthesized. The electrosynthesis relies on an oxidative polymerization stimulated by an anodic potential that induces the oxidation of EDOT. However, the applied potential can also oxidize PEDOT that acquires a positive charge and incorporates the (PSS)ⁿ⁻ polyanion in its structure. Since PEDOT is a p-type semiconductor, the role of PSS coincides with the function of a dopant that stabilises the charge-carrier form PEDOT⁺. PEDOT:PSS has been proven to produce films and micro-structured systems with facile electrochemistry, high-ionic conductivities, good electrochemical stability and a capacitance suitable for practical use in electrochemical supercapacitors.⁴²⁻⁴⁶ Moreover, thanks to its unique features, PEDOT:PSS has been recently employed for the fabrication of all-plastic electrochemical transistors (OECTs).^{47,48} For these reasons, PEDOT:PSS has been chosen as a polymeric matrix to covalently bind ferrocene, towards the development of amperometric sensors combining the ferrocene redox mediator properties and the high conductivity of PEDOT:PSS. Within this field, our research groups have recently described the synthesis and application of a ferrocene clicked PEDOT:PSS coated electrode employed in dopamine amperometric detection.⁴⁹ Indium tin oxide (ITO) electrodes were coated with PEDOT:PSS that was ferrocene-functionalized by a two-step procedure consisting of the electrodeposition of PEDOT-N₃ followed by copper-catalysed azide-alkyne cycloaddition of ethynylferrocene. The coated electrodes were characterized by XPS, AFM, and cyclic voltammetry (CV). The electrocatalytic performance of the device was assessed in the detection of 3,4-dihydroxyphenyl ethylamine, also commonly known as dopamine (DA). Therefore, the successful anchoring of short Fc functionalised chains to PEDOT:PSS was demonstrated, suggesting that covalent binding is a promising strategy to design modified films with superior electrocatalytic activity.

Despite the excellent properties of ferrocene, electrochemists are constantly looking for new active redox compounds able to selectively and efficiently mediate the charge transfer between specific molecules in solution and the electrode surface, for mainly exploiting an electrocatalytic pathway. The growing expectations placed on innovative electrochemical devices in the field of sensing and energy storage and production is making these demands increasingly urgent. Following in these footsteps, bis-carbonyl cyclopentadienone N-heterocyclic carbene (NHC) iron complexes were developed by the group,^{50, 51, 5} showing a reversible redox Fe(0)-Fe(I) that closely resembles the one of ferrocene Fe(II)-Fe(III) anodic couple (located at potentials of +0.53 V and +0.63V (vs. SCE)). Moreover, these complexes electrocatalyze the oxygen evolution reaction in a 4:1 THF:water mixture.⁵ This peculiar redox behaviour arises from the combination of highly versatile ligands such as N-heterocyclic carbenes⁵²⁻⁵⁶ and cyclopentadienones.⁵⁷⁻⁶⁴ Both these classes of ligands can play a role in the steric and electronic properties of the corresponding complexes. Furthermore, they give stability making them suitable single site systems upon immobilization.

In this work, we describe a new procedure to anchor NHC iron complexes to a PEDOT:PSS film in view of advanced electrochemical applications. The new procedure takes advantage of the easy functionalization of NHC ligands.⁶⁵⁻⁶⁸ Indeed hydroxyl functionalization is exploited for a coupling reaction with hydroxymethyl EDOT moiety by -CH₂OH. The coupling agent carbonyldiimidazole (CDI) allowed the formation of a stable carbonate-EDOT functionalized monomeric iron complex. Pristine spin-coated PEDOT:PSS electrodes have been functionalised by electrochemical copolymerization of EDOT with two different iron-EDOT monomers. The monomers syntheses have been optimized for different length (C₃ and C₁₁) of the spacers between the EDOT unit and the metal-organic complex. The coated electrodes have been characterised by XPS, SEM-EDS and cyclic voltammetry and their electrochemical performances have been assessed by using the NHC-iron functionalized electrode to mediate glucose oxidase oxidation in the presence of oxygen.

2. Experimental Section

2.1 Materials and methods All reactions were routinely carried out under a nitrogen atmosphere, using standard Schlenk techniques. Glassware was oven dried before use. Solvents: dichloromethane (CH_2Cl_2), diethyl ether (Et_2O) and acetonitrile (CH_3CN) were dried and distilled prior to use. Other solvents such as ethylacetate (EtOAc), ethanol (EtOH), methanol (MeOH), hexane, toluene, CDCl_3 , C_7D_8 , (Eurisotop) have been employed without further purification. Reagents: $\text{Fe}_2(\text{CO})_9$ (Strem), silver oxide, trimethylamine-N-oxide, 1-N-methylimidazole, potassium tert-butoxide, magnesium sulphate, lithium perchlorate, 1,1'-carbonyldimidazole, and 11-bromo-1-undecanol, (2,3-Dihydrothieno[3,4-b][1,4]dioxin-2-yl)methanol (hydroxymethyl-EDOT) (Merck) have been employed as purchased. Triscarbonyl-(2,4-bis(trimethylsilyl)bicyclo[3.3.0]nona-1,4-dien-3-one),⁵⁰ Dicarboxyl-(2,4-bis(trimethylsilyl)bicyclo[3.3.0]nona-1,4-dien-3-one)[1-(3-hydroxypropyl)-3-methylilidene]iron⁵ have been prepared following procedures reported in the literature. The prepared derivatives were characterized by spectroscopic methods. The NMR spectra were recorded using Varian Inova 300 (^1H , 300.1; ^{13}C , 75.5 MHz), Varian Mercury Plus VX 400 (^1H , 399.9; ^{13}C , 100.6 MHz), Varian Inova 600 (^1H , 599.7; ^{13}C , 150.8 MHz) spectrometers at 298 K; chemical shifts were referenced internally to residual solvent peaks. Full ^1H - and ^{13}C -NMR assignments were done, when necessary, by gHSQC and gHMBC NMR experiments using standard Varian pulse sequences. Infrared spectra were recorded at 298 K on a Perkin-Elmer Spectrum 2000 FT-IR spectrophotometer. ESI-MS spectra were recorded on Waters Micromass ZQ 4000 with samples dissolved in MeOH or CH_3CN . Elemental analyses were performed on a Thermo-Quest Flash 1112 Series EA instrument. UV irradiation was performed by using a commercial Hg lamp.

2.2 Synthesis of EDOT functionalized complexes 2-C₃ and 2-C₁₁

2.2.1 Dicarboxyl-(2,4-bis(trimethylsilyl)bicyclo[3.3.0]nona-1,4-dien-3-one)[1-(3-((1H-imidazol-1-carbonyl)oxy)propyl)-3-methyl-ilidene]iron (2-C₃-COIm). In a 50mL Schlenk 1,1'-carbonyldimidazole 0.039 g (0.24 mmol) and 2-C₃-OH 0.040 g (0.08 mmol) were dissolved in 10 mL of CH_2Cl_2 and left under stirring for 4h. The reaction mixture was washed with water (2x20 mL)

and organic layer dried over MgSO₄, filtered and concentrated. The yellow oil was washed several times with hexane to leave a yellow solid. Quantitative yield (50 mg).

2-C₃-COIm has been analyzed by IR, ¹H-NMR, ¹³C-NMR, ESI-MS. ¹H-NMR (399.9 C₇D₈) δ (ppm): 8.00 (s, 1H, CH_{im}), 7.57 (s, 1H, CH_{im}), 7.23 (s, 1H, CH_{im}), 6.45 (s, 1H, CH_{im}), 6.30 (s, 1H, CH_{im}), 4.23 (m, 2H, CH₂), 4.10 (m, 2H, CH₂), 3.49 (s, 3H, CH₃N), 2.36 (m, 4H, CH_{2ex}), 1.74-1.56 (m, 4H+2H, CH_{2ex} + CH₂), 0.26 (s, 18H, CH₃TMS). ¹³C-NMR (150.8 MHz, C₇D₈) δ (ppm): 219.0 (CO), 186.1 (C_{carb}), 178.5 (C=O_{Cp}), 167.8 (OCN), 133.8 (CH_{im}), 131.1 (CH_{im}), 104.7 (C_{3,4q}), 67.9 (C_{2,5q}), 39.2 (CH₂O), 31.3 (CH₂N), 30.7 (NCH₃), 29.8 (CH₂), 24.6 (CH_{2ex}), 23.8 (CH_{2ex}), 0.9 (CH₃TMS). IR (CH₂Cl₂, cm⁻¹): (ν_{CO}) 1981, 1921, 1765. ESI-MS (m/z): 625 [M+H]⁺, 648 [M+Na]⁺. Anal. Calcd (%) for C₂₈H₄₀N₄O₅Si₂Fe: C, 53.84%; H, 6.45%; N, 8.97%. Found: C, 54.01%; H, 6.34%; N, 9.07%.

2.2.2 Dicarboxyl-(2,4-bis(trimethylsilyl)bicyclo[3.3.0]nona-1,4-dien-3-one[1-(3-(((2,3-dihydrothieno[3,4-b][1,4]dioxin-2-yl)methoxy)carbonyloxy)propyl)-3-methylidene]iron (2-C₃). In a 50 mL Schlenk potassium tert-butoxide 0.011 g (0.10 mmol) was suspended in 10 mL CH₃CN. EDOT-OH 0.017 g (0.10 mmol) was added to the solution and left under reflux for 2h. Solution was cool down to room temperature and 5 mL of CH₃CN solution containing **2-C₃-COIm** 0.053 g (0.08 mmol) was added dropwise. The reaction mixture was left under stirring at room temperature overnight. Upon removal of the solvent, the crude was purified by neutral alumina column chromatography using ethyl acetate/methanol (50/1). Yield = 53% (31 mg).

2-C₃ has been analyzed by IR, ¹H-NMR, ¹³C-NMR, ESI-MS. ¹H-NMR (399.9 C₇D₈) δ (ppm): 6.49 (s, 1H, CH_{im}), 6.14 (s, 1H, CH_{im}), 6.07 (s, 2H, CHS), 4.25 (t, 2H, CH₂), 3.69 (m, 4H, CH₂EDOT), 3.64 (t, 2H, CH₂OCO), 3.59 (t, 2H, CH₂), 3.49 (s, 3H, CH₃N), 3.34 (s, 1H, CH_{EDOT}), 2.38 (m, 4H, CH_{2ex}), 1.77 (m, 2H, CH₂), 1.77-1.68 (m, 4H, CH_{2ex}), 0.27 (s, 18H, CH₃TMS). ¹³C-NMR (150.8 MHz, C₇D₈) δ (ppm): 218.7 (CO), 183.9 (C_{carb}), 174.3 (C=O_{Cp}), 154.9 (OCOO), 143.4 (C_qEDOT), 123.7 (CH_{im}), 121.9 (CH_{im}), 104.1 (C_{3,4q}), 98.6 (CHS), 74.2 (CH_{EDOT}), 73.3 (C_{2,5q}), 66.5 (CH₂EDOT-OCO₂), 59.0 (CH₂-OCO₂), 49.4 (CH₂N), 40.5 (NCH₃), 33.7 (CH₂), 26.0 (CH_{2ex}), 23.2 (CH_{2ex}), 0.9 (CH₃TMS). IR

(CH₂Cl₂, cm⁻¹): (ν_{CO}) 1981, 1921, 1748. ESI-MS (m/z): 729 [M+H]⁺, 751 [M+Na]⁺. Anal. Calcd (%) for C₃₂H₄₄N₂O₈SSi₂Fe: C, 52.74%; H, 6.09%; N, 3.84%. Found: C, 51.82%; H, 6.32%; N, 3.92%.

2.2.3 1-(11-idrossiundecil)-3-metil-1H-imidazolium bromide (1-C₁₁-OH). In a round-bottom flask 1-N-methylimidazole 0.3mL (3.76mmol) and 11-bromo-1-undecanol 0.3mL (3.76 mmol) were dissolved in 15 mL of ethyl acetate and left under stirring at 65°C for 24h. The mixture is filtered and the solid washed several time with ethyl acetate. Quantitative yield (1,25 g).

Suitable crystals of **1-C₁₁-OH** for X-Ray diffraction were obtained by double layer (Dichloromethane/Hexane). **1-C₁₁-OH** has been analysed by ¹H-NMR, ¹³C-NMR, ESI-MS and X-Ray Crystallography (Figure S13). ¹H NMR (399.9 MHz, CDCl₃): δ(ppm): 10.78 (s, 1H, NCHN), 7.23 (s, 1H, CH_{im}), 7.19 (s, 1H, CH_{im}), 4.36 – 4.29 (m, 2H, CH₂N), 4.14 (s, 3H, CH₃N), 3.64 (t, *J* = 6.6 Hz, 2H, CH₂O), 1.98 – 1.88 (m, 2H, CH₂CH₂N), 1.64 – 1.50 (m, 2H, CH₂CH₂O), 1.40 – 1.19 (m, 14H, -CH₂-). ¹³C-NMR (150.8 MHz, CDCl₃): δ(ppm): 138.1 (NCHN), 124.0 (CH_{im}), 121.5 (CH_{im}), 62.8 (CH₂O), 50.2 (NCH₂), 36.8 (CH₃N), 32.8-25.6 (-CH₂-). ESI-MS (m/z): (+) 253 [M⁺]; (-) 79/81 [Br⁻]. Anal. Calcd (%) for C₁₅H₂₉N₂O: C, 71.10%; H, 11.54%; N, 11.05%. Found: C, 70.93%; H, 11.42%, N, 10.91%.

2.2.4 1-(11-((1H-imidazol-1-carbonyl)oxy)undecil)-3-methyl-1H-imidazolium bromide (1-C₁₁-COIm). In a 50mL Schlenk 1,1'-carbonyldimidazole 0.438 g (2.70 mmol) and **1-C₁₁-OH** 0.299 g (0.90 mmol) were dissolved in 10 mL of CH₂Cl₂ and left under stirring for 4h. The reaction mixture was washed with water (2x20 mL) and organic layer dried over MgSO₄, filtered and concentrated. The white oil was washed several time with Et₂O to leave a white solid. Quantitative yield (384 mg). **1-C₁₁-COIm** has been analyzed by IR, ¹H-NMR and ¹³C-NMR. ¹H-NMR (399.9 MHz, CDCl₃): δ(ppm): 10.50 (s, 1H, NCHN), 8.11 (s, 1H, CH_{im}), 7.41 (s, 1H, CH_{im}), 7.31 (s, 1H, CH_{im}), 7.30 (s, 1H, CH_{im}), 7.05 (s, 1H, CH_{im}) 4.41 (t, *J*_{H,H} = 8 Hz, 2H, CH₂O), 4.32 (t, *J*_{H,H} = 8 Hz, 2H, CH₂N), 4.11 (s, 3H, CH₃N), 1.90 (m, 4H, CH₂CH₂N), 1.79 (m, 4H, CH₂CH₂O), 1.39-1.25 (m, 14H, -CH₂-). ¹³C-NMR (150.8 MHz, CDCl₃): δ(ppm): 148.7 (OCN), 137.8 (CH_{im}), 137.0 (CH_{im}), 130.5 (CH_{im}), 123.3 (CH_{im}), 121.6 (CH_{im}), 117.1 (CH_{im}), 68.5 (CH₂O), 50.1 (NCH₂), 36.7 (CH₃N), 30.2-25.6 (-CH₂-). IR

(CH₂Cl₂, cm⁻¹): ν 1760, 1732 cm⁻¹. ESI-MS (m/z): (+) 347 [M]⁺, (-) 79/81 [Br⁻]. Anal. Calcd (%) for C₁₉H₃₁N₄O₂: C, 65.67%; H, 8.99%, N, 16.12%. Found: C, 65.34%; H, 8.87%; N, 16.35%.

2.2.5 1-(11-(((2,3-dihydrothieno[3,4-b][1,4]dioxyn-2-yl)methoxy)carbonyloxy)-undecyl)-3-methyl-1H-imidazolium bromide (1-C₁₁). In a 50 mL Schlenk potassium tert-butoxide 0.099 g (0.88 mmol) was suspended in 10 mL CH₃CN. EDOT-OH 0.152 g (0.88 mmol) was added to the solution and left under reflux for 2h. Solution was cool down to room temperature and 5 mL of CH₃CN solution containing 1-C₁₁ 0.377 g (0.88 mmol) was added dropwise. The reaction mixture was left under stirring at room temperature overnight. Solvent was removed under vacuum. The residue was dissolved in CH₂Cl₂ and washed with water (2x). Organic layers were dried over MgSO₄, filtered and concentrated. The oil was washed with Et₂O to leave a white solid. Yield = 42% (196 mg).

1-C₁₁ has been analyzed by IR, ¹H-NMR and ¹³C-NMR. ¹H-NMR (399.9 MHz, CDCl₃): ¹H-NMR (599.7 MHz, CDCl₃): δ (ppm): 10.61 (s, 1H, CH_{im}), 7.30 (s, 1H, CH_{im}), 7.23 (s, 1H, CH_{im}), 6.35 (q, 2H, HCS), 4.40 (m, 1H, CHO_{EDOT}), 4.34 (m, 2H, OC(O)OCH_{2,EDOT}), 4.31 (t, J_{H,H} = 8 Hz, 2H, CH₂N), 4.25 (m, 1H, CH₂O_{EDOT}), 4.15 (t, J_{H,H} = 8 Hz, 2H, CH₂O), 4.12 (s, 3H, CH₃N), 4.06 (m, 1H, CH_{2,EDOT}), 1.91 (m, 2H, CH₂CH₂N), 1.66 (m, 2H, CH₂CH₂O), 1.32-1.22 (m, 14H, -CH₂-). ¹³C-NMR (150.8 MHz, CDCl₃): δ (ppm): 154.9 (OC(O)O), 141.1 (C_{q,EDOT}), 140.9 (C_{q,EDOT}), 138.8 (NCN), 122.8 (CH_{im}), 121.3 (CH_{im}), 100.2 (SC_{EDOT}), 100.0 (SC_{EDOT}), 71.2 (CHO_{EDOT}), 68.7 (CH₂OC(O)O), 65.4 (OC(O)OCH_{2,EDOT}), 65.3 (CH₂O_{EDOT}), 50.4 (CH₂N), 36.9 (NCH₃), 30.3-25.6 (-CH₂-). IR (CH₂Cl₂): ν 1749cm⁻¹. ESI-MS (m/z): (+) 451 [M]⁺; (-) 79/81 [Br⁻]. Anal. Calcd (%) for C₂₃H₃₅N₂O₅S: C, 61.17%; H, 7.81%; N, 6.20%. Found: C, 61.25%; H, 7.65%; N, 6.32%.

2.2.6 Dicarboxyl-(2,4-bis(trimethylsilyl)bicyclo[3.3.0]nona-1,4-dien-3-one)[(1-(11-(((2,3-dihydrothieno[3,4-b][1,4]dioxin-2-yl)methoxy)carbonyloxy)undecyl)-3-methyl-imidene)]iron (2-C₁₁). Imidazolium salt 1-C₁₁ 0.380 g (0.71 mmol), silver oxide 0.207 g (0.89 mmol), triscarbonyl-(2,4-bis(trimethylsilyl)bicyclo[3.3.0]nona-1,4-dien-3-one)iron **I** 0.299g (0.71 mmol) and trimethylamine-N-oxide 0.080 g (1.07 mmol) were reacted in CH₃CN under inert atmosphere and

with protection from light. After stirring the reaction for 1h at room temperature, the solvent was removed under vacuo, then the solid dissolved in toluene. The reaction mixture was stirred under reflux for 1 h. Upon removal of the solvent, the crude was purified by neutral alumina column chromatography using ethyl acetate/methanol (40/1). Yield: 50 % (298 mg).

2-C₁₁ has been analyzed by IR, ¹H-NMR, ¹³C-NMR, ESI-MS. ¹H-NMR (399.9 CDCl₃) δ (ppm): 7.01 (s, 2H, CH_{im}), 6.34 (q, 2H, SCH), 4.39 (m, 1H, CHO_{EDOT}), 4.34 (m, 2H, OC(O)OCH_{2,EDOT}), 4.23 (m, 1H, CH₂O_{EDOT}), 4.16 (t, 2H, CH₂N), 4.11 (t, 2H, CH₂O), 4.07 (m, 1H, CH₂O_{EDOT}), 3.91 (s, 3H, CH₃N), 2.41 (m, 4H, CH₂ex), 1.88 (m, 2H, CH₂ex), 1.77 (m, 2H, CH₂CH₂N), 1.70 (m, 2H, CH₂ex), 1.66 (m, 2H CH₂CH₂O), 1.43 (m, 2H, CH₂(CH₂)₂N), 1.4-1.28 (m, 12H, -CH₂-), 0.164 (s, 18H, CH₃TMS). ¹³C-NMR (150.8 MHz, CDCl₃, g-HSQC, g-HMBC) δ (ppm): 217.0 (CO), 183.8 (C_{carbene}), 175.9 (C=O_{Cp}), 154.9 (OCOO), 141.1 (C_{q,EDOT}), 140.9 (C_{q,EDOT}), 124.2 (CH_{im}), 121.7 (CH_{im}), 104.0 (C_{3,4q}), 100.2 (SC_{EDOT}), 99.9 (SC_{EDOT}), 71.2 (CHO_{EDOT}), 71.1 (C_{2,5q}), 68.7 (CH₂OC(O)O), 65.4 (OC(O)OCH_{2,EDOT}), 65.3 (CH₂O_{EDOT}), 52.0 (CH₂N), 40.3 (NCH₃), 31.8 (CH₂CH₂N) 29.7-25.6 (-CH₂-), 24.4 (CH₂ex), 22.5 (CH₂ex), 0.2 (CH₃TMS). IR (CH₂Cl₂, cm⁻¹): (ν_{CO}) 1982, 1921, 1747. ESI-MS (m/z): 841 [M+H]⁺, 863 [M+Na]⁺, 879 [M+K]⁺. Anal. Calcd (%) for C₄₀H₆₀N₂O₈SSi₂Fe: C, 57.13%; H, 7.19%; N, 3.33% Found: C, 57.05; H, 7.08; N, 3.27.

2.3 Electrochemical Studies. Cyclic voltammograms and chronoamperometric measurements were performed on a CH1660C (CH Instruments) electrochemical analyser using a three-electrode cell: depending on the working conditions, a spin-coated PEDOT:PSS electrodes (1 cm²) or a glassy-carbon disk (0.071 cm²) or a graphite sheet (2 cm²) was used as the working electrode, a Ag/AgNO₃ (0.1 M) as the reference electrode, and a platinum-wire as the counter electrode. All experiments were performed under a nitrogen atmosphere and solutions were degassed for 10 minutes. All potentials are referred to the saturated calomel electrode (SCE).

2.4 Electrochemical polymerisation of 2-C_x. The electrochemical polymerization was carried out on the spin-coated PEDOT:PSS films. The electrosynthesis of **2-C_x** was carried out, under a N₂ atmosphere, potentiodynamically, by cyclic voltammetry, cycling one time in the potential range

between 0.0 V and 1.5 V at a scan rate of 0.05 V s⁻¹, in a 0.1 M LiClO₄ CH₃CN solution containing 10 mM 2-C_x/EDOT (1:1) monomers. Prior to the application of the potential pulse, the CH₃CN suspension was vigorously stirred for 20 min. After the electrodeposition, the film was repeatedly washed with deionized water to remove both the supporting electrolyte and the excess monomer and finally allowed to dry in air.

2.5 SEM-EDS analysis preparation. The electrochemical polymerisation was carried out on a platinum slide of 2 cm² by cyclic voltammetry. The platinum slide was previously cleaned by cyclic voltammetry in a 0.1 M H₂SO₄ aqueous solution and then rinsed with ethanol in order to remove any acidic residue. A blank measurement (i.e. platinum slide without polymer) showed no traces of sulphur derived from the treatment with H₂SO₄.

2.6 Glucose Oxidase device preparation. A layer of glucose oxidase (GOx) was deposited over the 2-C_x/PEDOT film: 30 μL of 0.1 M phosphate buffer (pH 7.00) containing 10 mg GOx/mL was spread over the copolymer films and dried at room temperature. A layer of chitosan was then applied in order to avoid dissolution of the enzyme during analysis: 40 μL of 1% v/v acetic acid solution containing 4 mg chitosan/mL were drop-cast on the electrode surface and dried at room temperature. The following scheme is a representation of the GOx device (Figure 1).

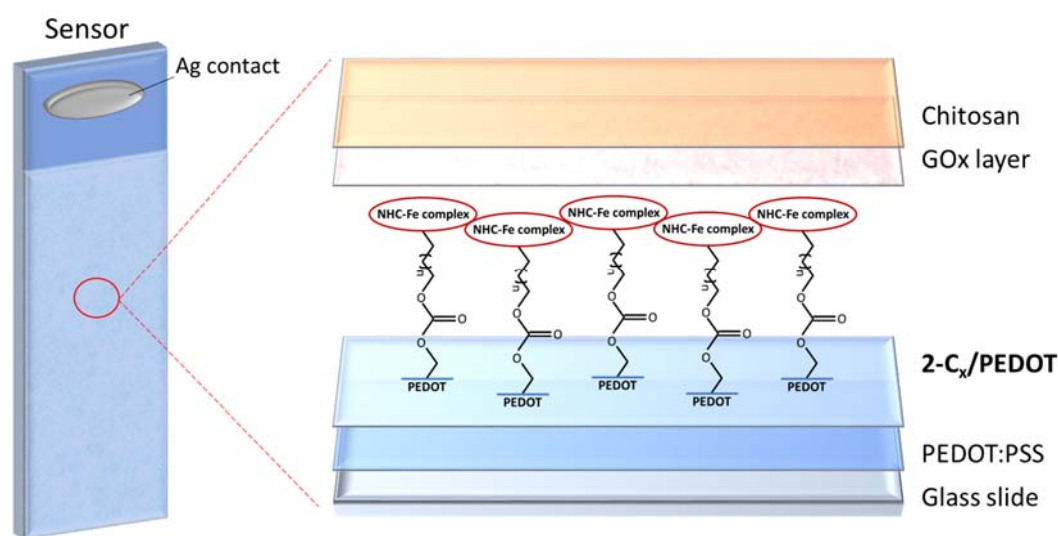


Figure 1. Scheme of the functionalized biosensor.

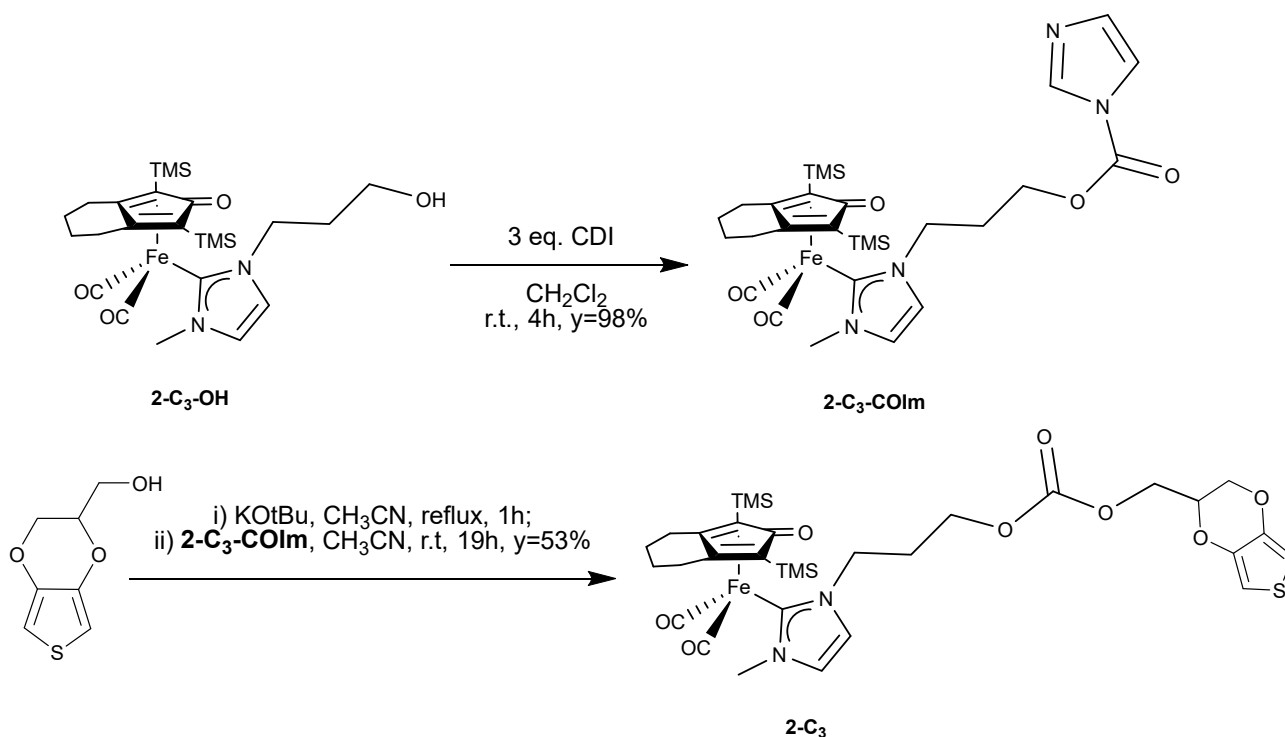
3. Results and Discussion

Two synthetic approaches have been developed in order to obtain EDOT-functionalized N-heterocyclic carbene bis-carbonyl cyclopentadienone iron complexes with different side chain lengths (C_3 and C_{11}) suitable as monomers for immobilization on electrodes via electrochemical polymerization. Variable linker length may in fact influence electrodeposition yield or activity towards substrates. The order of reaction steps showed a high influence of the length of the lateral chain (C_3 or C_{11}). Both the approaches exploit carbonyldiimidazole (CDI) as the coupling agent between a $-CH_2OH$ moiety of the hydroxymethyl-EDOT (EDOT-OH) and a primary alcohol moiety. However, the functionalization with the shorter side chain (C_3) better occurs with the direct coupling between the hydroxyl-functionalized N-heterocyclic carbene iron complex and EDOT-OH, while the longer chain (C_{11}) first required the functionalization of the imidazolium salt with EDOT, to be lately employed as a precursor for the synthesis of the N-heterocyclic carbene iron monomer. Nevertheless, both the approaches, better described in the following, allow to obtain functional monomers that can be electrochemically polymerised in the form of thin films on conducting substrates.

3.1 Synthesis of EDOT functionalized iron N-heterocyclic carbene complexes **2-C₃** and **2-C₁₁**

Compound **2-C₃**, bearing an hydroxypropyl substituent on a $-(CH_2)_3-$ side chain, has been synthesised following the route showed in Scheme 1. Iron complex **2-C₃-OH**, prepared as previously described⁶ was coupled to an hydroxymethyl-EDOT (EDOT-OH) molecule exploiting CDI, leading to the EDOT-iron monomer **2-C₃**. The synthesis of **2-C₃** has been followed by IR spectroscopy observing similar terminal CO stretching frequencies if compared with the **2-C₃-OH** precursor as expected. Nevertheless, a new band appeared in the region of the carbonate moiety at 1748 cm^{-1} (**2-C₃**: $\nu(\text{CO}) = 1981, 1921, 1748\text{ cm}^{-1}$ vs. **2-C₃-OH**: $\nu(\text{CO}) = 1981, 1921\text{ cm}^{-1}$). ¹H-NMR analysis shows signals assigned to CHs of imidazole ring at 6.48 ppm, to CHs linked to S atom of EDOT at 6.07 ppm and to the alkyl chain from 1.77 to 1.68 ppm. ¹³C-NMR spectra shows the diagnostic signals for the Fe- C_{carbene} at 183 ppm, the carbonate carbon at 155 ppm, the pattern from the iron complex skeleton and from the EDOT group (see Experimental for details). ESI-MS analysis confirmed the molecular

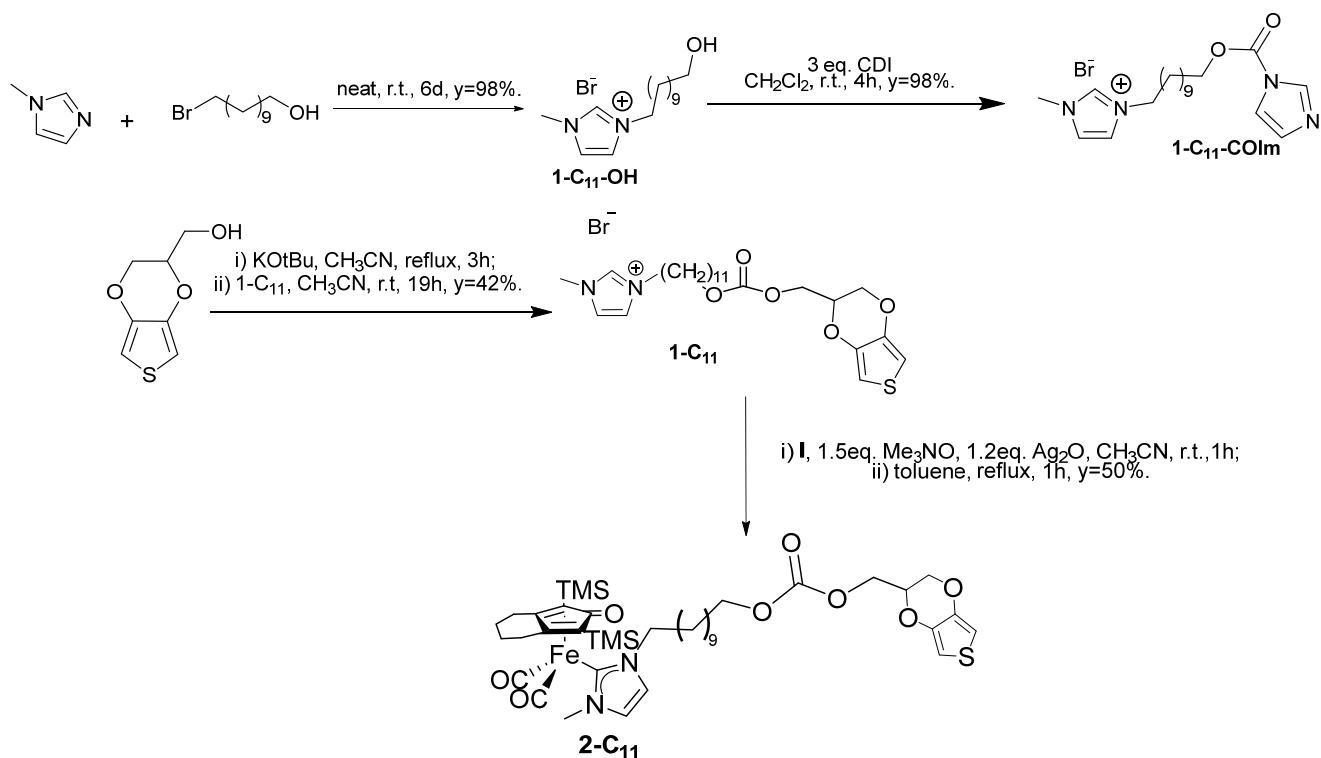
weight of the compound allowing the identification of **2-C₃** molecular ion at (m/z): 729 [M+H]⁺, 751 [M+Na]⁺.



Scheme 1. Multistep synthesis of **2-C₃**.

Complex **2-C₁₁** has been prepared following a different approach, as described in the multi-step route depicted in Scheme 2. This methodology foresees the initial coupling of the imidazolium salt with EDOT-OH, followed by synthesis of the correspondent NHC-iron complex **2-C₁₁**.

New imidazolium salt **1-C₁₁-OH** was characterized by ¹H-NMR, ¹³C-NMR and ESI-MS; moreover, its structure, showing eleven CH₂ in the lateral chain, was confirmed by single crystal X-Ray Diffraction (see Experimental Section). 1,1'-Carbonyldimidazolole (CDI) was exploited as coupling reagent between the -OH groups of **1-C₁₁-OH** and **EDOT-OH** through the formation of the intermediate **1-C₁₁-COIm** in order to get the corresponding imidazolium salt **1-C₁₁** bearing an EDOT functionality on the side chain. **2-C₁₁** was then prepared following a procedure similar to that previously reported by the group,⁵⁰ consisting of a transmetallation reaction from a silver-NHC intermediate to the iron complex precursor FeCpO(CO)₂(NCCH₃) **I**, employing the **1-C₁₁** as carbene precursor (Scheme 2).



Scheme 2. Multistep synthesis of **2-C₁₁**.

The synthesis of **2-C₁₁** has been followed by IR spectroscopy observing a lowering in the CO stretching frequencies (**2-C₁₁**: $\nu(\text{CO}) = 1982, 1921 \text{ cm}^{-1}$ vs. **I**: $\nu(\text{CO}) = 1999, 1938 \text{ cm}^{-1}$) due to the strong NHC σ -donor properties, and the presence of the C=O stretching of carbonyl group at 1747 cm^{-1} typical of a carbonate moiety. ¹H-NMR spectrum shows signals assigned to CHs of imidazolium ring at 7.01 ppm, to CHs linked to S atom of EDOT at 6.35 ppm and to the alkyl chain at 1.25 ppm. ¹³C-NMR analysis shows the diagnostic signals for the Fe-C_{carbene} at 184 ppm, the carbonate carbon at 155 ppm and the pattern from the iron complex skeleton and from the EDOT group (See Experimental for details). ESI-MS analysis confirmed the molecular weight of the compound allowing the identification of **2-C₁₁** molecular ion at (m/z): 841 [M+H]⁺, 863 [M+Na]⁺, 879 [M+K]⁺. In general characterization of **2-C₁₁** have been found comparable to the analogue **2-C₃**.

2.2 Electrochemical copolymerisation

Both iron compounds were copolymerised with EDOT on PEDOT:PSS electrodes (see Experimental). The use of co-monomer EDOT is necessary to obtain a regular film, since the steric hindrance of the large iron-NHC tail is located in close proximity to the EDOT propagation centre.

2-C₃ and **2-C₁₁** were electrocopolymerized by cyclic voltammetry (one cycle in the potential range between 0.0 and +1.5 V at a scan rate of 0.05 V s⁻¹) from a 10 mM solution of **2-C₃** or **2-C₁₁** and EDOT containing 0.1 M LiClO₄ as the supporting electrolyte. The immobilization strategies benefit from the well-known oxidative polymerization of conductive polymers involving the thiophenic moiety of the two monomers. Figure 2 shows the CVs obtained during the deposition of **2-C₁₁** (red line) and **2-C₃** (black line) copolymers on PEDOT electrodes and exhibits two waves for both monomers labelled. The wave I takes place at about 0.60 V for both monomers and is ascribed to the redox process involving the iron complexes as suggested by the potential values of free complexes.⁵ The peak current takes a value of 5x10⁻⁵A, that can be ascribed to only the oxidation Fe centres. Therefore, no additional electron transfer occurs with the electrode surface suggesting this oxidation is not involved in the polymerization processes. The waves II take place at potential higher than 1.1 V and the onset values are dependent on the spacer length. The oxidation of **2-C₁₁** monomer occurs at the highest value highlighting the oxidation is more difficult for longer spacer. The waves II can be ascribed to the oxidation of thiophenic moieties as suggested by the potentials that are close to the values of similar EDOT monomers.⁴⁹ The peak current are higher than the wave I indicating: i) all the monomers are involved in the reaction; II) the transfer of more than one electron occurs during the reaction. Therefore, the oxidation of thiophenic units is the starting step of the polymerization. The following steps are the coupling of just formed radical cations and the eliminations of 2 hydrogen ions to form species with a higher molecular mass. Since the oligomers oxidation is easier than monomer oxidation, the polymerization continues and the PEDOT chains are partially oxidized. Electropolymerisation with more than one cycle (e.g. 4 and 10) resulted in poor stability of the iron

complex on the film. In order to obtain a homogeneous layer of copolymer over the surface, the best ratio between the two monomers was identified as **2-C_x/EDOT 1:1**.

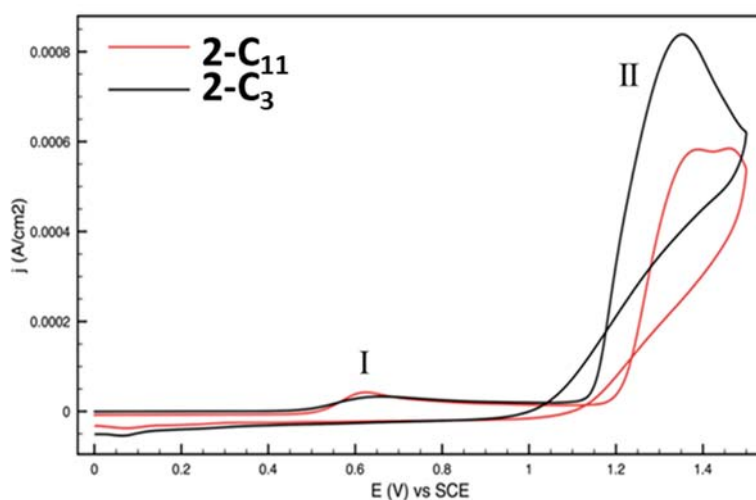


Figure 2. CVs obtained during electrochemical co-polymerization in a 0.1 M LiClO₄ in CH₃CN solution containing 10 mM **2-C₁₁/EDOT(1:1)** (red line) and **2-C₃/EDOT(1:1)** (black line). Scan rate: 0.1 V s⁻¹.

2.3 Characterisation of the **2-C₃/PEDOT** and **2-C₁₁/PEDOT** coated electrodes

Both coated electrodes were characterised by CV in 0.1 M LiClO₄ aqueous solution and the resulting voltammograms are compared in Figure 3.

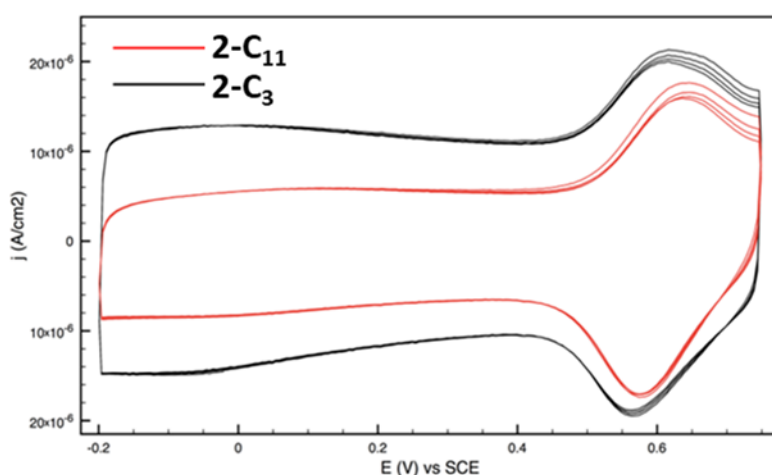


Figure 3. CV curves recorded at the modified electrodes coated with **2-C₁₁/EDOT(1:1)** (red line) and **2-C₃/EDOT(1:1)** (black line) in 0.1 M LiClO₄ aqueous solution. Scan rate: 0.05 V s⁻¹.

In this potential window, the bare PEDOT:PSS electrode exhibits a pseudo-capacitive behavior that is suggested by the typically rectangular-shape CV.⁴⁹ The redox processes are ascribed to the oxidation/reduction of conductive polymer that are associated to the formation/disappearing of polaron and bipolaron species. After the polymerization of the NHC-iron PEDOT films a new reversible redox peak system appears in the voltammograms and the CV curve of both **2-C_x**/PEDOT coated electrodes is dominated by the faradaic and reversible signal of the NHC-iron complexes. The two redox peaks are located at potentials of 0.64 V and 0.57 V for **2-C₁₁** and at potentials of 0.61 V and 0.57 V for **2-C₃**, values that are typical of cyclopentadienone N-heterocyclic carbene complexes.⁵ The stability of the functionalised polymer films was assessed by CV in aqueous and organic environments containing 0.1 M LiClO₄. While a dramatic 50% peak current decrease was recorded in CH₃CN after 25 cycles at 0.02 V s⁻¹, the films showed good stability in aqueous solution (< 10 % peak current decrease).

The polymeric films were also characterized by SEM-EDS. **2-C_x**/PEDOTs were coated on a platinum layer of 2 cm², previously treated with acid as described in the Experimental Section. Figure 4 shows SEM images of **2-C₁₁** and **2-C₃**. Differently from spin-coated films prepared from commercial PEDOT:PSS suspensions, which typically exhibit a flat morphology, the electrodeposited films are characterised by globular domains and higher roughness in accordance with the literature.⁶⁹

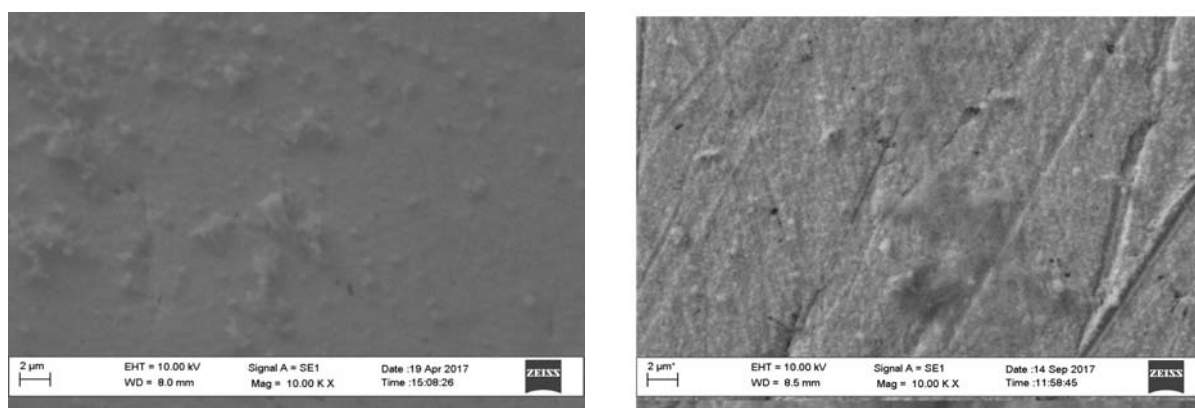


Figure 4. SEM maps of **2-C₁₁** (left) and **2-C₃** (right) at 10.00 K X magnitude.

Furthermore, the EDS analysis allowed to measure atomic percentages of elements in a specific region of the surface. Therefore, in our case, iron and sulfur were exploited in order to evaluate an average ratio between **2-C_x**/PEDOT. Sulphur value represents the sum of all 3,4 ethylen dioxy thiophenic repeating units present in polymer, while iron value can be correlated to the number of EDOT monomers bearing iron-NHC complexes. The values are reported in Table 1 and confirmed the CVs observations. Indeed, a lower **2-C₃**/PEDOT ratio compared to **2-C₁₁**/PEDOT was found, likely due to the shorter chain linker of **2-C₃**, hence a more steric influence on the electropolymerisation mechanism.

Table 1. SEM-EDS analysis. S and Fe values of two copolymers coated on a platinum layer.

	S value (%)	Fe value (%)	2-C_x /PEDOT (%)	2-C_x /EDOT ratio
2-C₁₁	1.60±0.17	0.25±0.10	16	1/6
2-C₃	2.8±0.5	0.35±0.10	13	1/7

Finally, polymeric films were coated over a graphite layer of 2 cm² and characterised by ATR-IR spectroscopy. The CO stretching frequencies were in accordance with a NHC-iron species covalently bonded to the polymer ($\nu(\text{CO})\text{Fe-C}_{11}$: 2010, 1960 cm⁻¹; $\nu(\text{CO})\text{Fe-C}_3$: 2017, 1974 cm⁻¹). Stretching frequencies experiences a shift to higher value compared to the same neutral complexes as monomer ($\nu(\text{CO})\text{Fe-C}_{11}$: 1982, 1921 cm⁻¹; $\nu(\text{CO})\text{Fe-C}_3$: 1981, 1921 cm⁻¹), that could be probably ascribed to interaction between the PSS of the polymer PEDOT chain. Indeed, sulfonic group might engage a hydrogen bond with cyclopentadienone, resulting in the observed shift.

Summarizing, the IR, SEM and EDS characterizations show the success of electrochemical polymerization of PEDOT film modified by NHC complex. The presence of the characteristics iron peak system in the CV curves confirms that the Fe complex maintains its redox activity after the immobilization highlighting its use as redox mediator. To prove a possible utilization as redox

mediators the **2-C_x**/PEDOT coated electrodes were tested in a widespread application, consisting in glucose biosensing. To this aim, the **2-C_x**/PEDOT film was further modified with a membrane containing of the enzyme glucose oxidase (GOx) according to the procedure reported in the experimental part.

Glucose determination was therefore realized under hydrodynamic conditions, by chronoamperometry under magnetic stirring, at $E_{app} = 0.65$ V with successive additions of glucose to a phosphate buffer solution at pH 7.00. As an example, Figure 5 shows the current vs time graph recorded by the biosensor obtained with the **2-C₃**/PEDOT device during seven successive glucose additions, which have been carried out to increase its concentration of 3 mM in the solution under investigation. Following each addition the current sharply increases, demonstrating that **2-C_x**/PEDOT can act as redox mediator in glucose biosensor. The current values are linearly correlated with the glucose concentration.

Calibration curves were obtained by plotting the steady state current, measured after subtraction of the base line current, vs. glucose concentration (see the inset in Figure 5). Two different **2-C_x**/PEDOT electrodes were prepared and the reproducibility and repeatability of the sensors were examined. For a given **2-C₃**/PEDOT electrode, the relative standard deviation (RSD) was 3% for seventeen additions of 3 mM glucose. These sensors presented a linear range between 3 mM and 51 mM and a mean sensitivity of $7.5 \mu\text{A M}^{-1} \text{cm}^{-2}$. For a given **2-C₁₁**/PEDOT electrode, the relative standard deviation (RSD) was 8% for seventeen additions of 3 mM glucose. These sensors presented a linear range between 6 mM and 47 mM and a mean sensitivity of $6 \mu\text{A M}^{-1} \text{cm}^{-2}$.

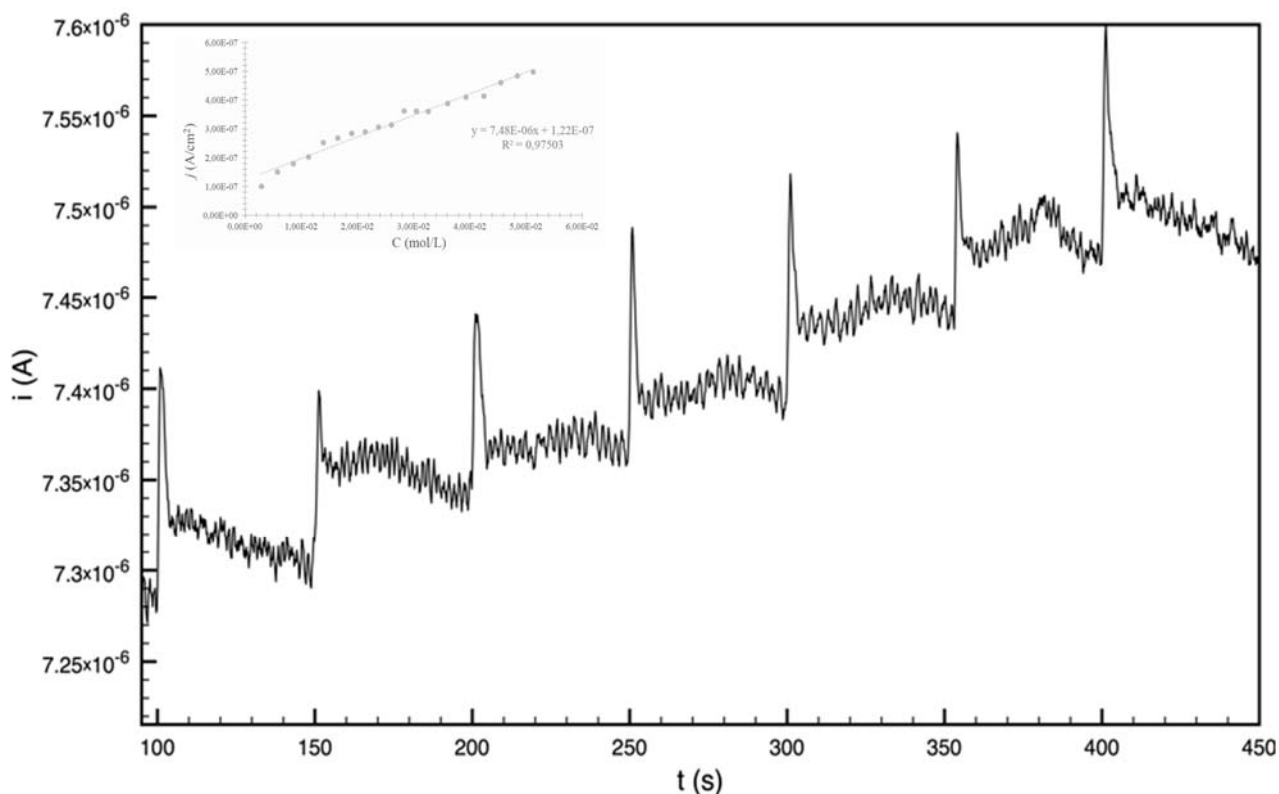


Figure 5. Chronoamperometric response at 0.65 V vs. SCE of PEDOT:PSS electrode coated with a 2-C₃/PEDOT film, in 0.1 M LiClO₄ solution, and a layer of GOx/chitosan to increasing glucose additions. The inset shows the relevant calibration curve.

3. Conclusions

Low cost PEDOT:PSS electrodes were functionalised with 2-C_x/PEDOT, by electrodeposition of comonomer 2-C_x and EDOT. Monomers 2-C₁₁ and 2-C₃ have been synthesised following a clean and easy reaction pathway that involve transmetallation from silver-NHC complexes to iron, employing the appropriate imidazolium salt as carbene precursor. The NHC-iron complexes have been coupled to a EDOT monomer exploiting the 1,1'-dicarbonylimidazole (CDI) as coupling reagent following two different approach for different linkers length. The modified electrodes have been characterized by CV, showing that the response of 2-C_x/PEDOT is dominated by the reversible faradaic signal of the corresponding iron complex with the presence of two redox peaks located at 0.64 V and 0.57 V for 2-C₁₁ and at 0.61 V and 0.57 V for 2-C₃, values typical of homogeneous iron cyclopentadienone, N-heterocyclic carbene redox couple. Remarkably, the coatings are stable in aqueous solution.

To demonstrate the successful immobilization, and to make sure that iron complexes are covalently bonded to the polymer chain, the coated electrodes have been characterized by ATR-IR and SEM-EDS, the average copolymerisation ratio between **2-C_x**/PEDOT found are: 1/6 for **2-C₁₁** and 1/7 for **2-C₃**.

After deposition of Glucose Oxidase enzyme (GOx) over the **2-C_x**/PEDOT film, the device has been assessed by analysing glucose in solution. Both sensors present comparable activity, among which **2-C₃** is the best with a linear range between 3 and 51 mM and a mean sensitivity of 7.5 $\mu\text{A M}^{-1} \text{cm}^{-2}$.

Although the sensor needs to be further developed for practical application, the possibility of immobilisation with various linkers and of fine-tuning of NHC-iron complexes both on cyclopentadienone substituents and on N atoms of carbene, paves the way for new developments on chemically modified electrodes.

Acknowledgments

Authors wish to thank the University of Bologna for financial support.

Conflict of Interest

There are no conflict of interest to declare.

5. References

- ¹ M. Bystrzanowska, P. Petkov, M. Tobiszewski, Ranking of Heterogeneous Catalysts Metals by Their Greenness, *ACS Sustain. Chem. Eng.* 7 (2019) 18434–18443.
- ² F. Moccia, L. Rigamonti, A. Messori, V. Zanotti, R. Mazzoni, Bringing Homogeneous Iron Catalysts on the Heterogeneous Side: Solutions for Immobilization, *Molecules* 26 (2021) 2728.
- ³ I. Bauer, H.-J. Knölker, Iron Catalysis in Organic Synthesis. *Chem. Rev.* 115 (2015) 3170–3387
- ⁴ A. Fürstner, Iron Catalysis in Organic Synthesis: A Critical Assessment of What It Takes to Make This Base Metal a Multitasking Champion, *ACS Cent. Sci.* 2 (2016) 778–789.

- ⁵ A. Cingolani, I. Gualandi, E. Scavetta, C. Cesari, S. Zacchini, D. Tonelli, V. Zanotti, P. Franchi, M. Lucarini, E. Sicilia, G. Mazzone, D. Nanni, R. Mazzoni, Cyclopentadienone–NHC Iron(0) Complexes as Low Valent Electrocatalysts for Water Oxidation, *Catal. Sci. Technol.* 11 (2021) 1407–1418.
- ⁶ M. K. Coggins, M.-T. Zhang, A. K. Vannucci, C. J. Dares, T. J. Meyer, Electrocatalytic Water Oxidation by a Monomeric Amidate Ligated Fe(III)—Aqua Complex, *J. Am. Chem. Soc.* 136 (2014) 5531–5534.
- ⁷ K. G. Kottrup, S. D’Agostini, S., P. H. van Langevelde, M. A. Siegler, D. G. H. Hetterscheid, Catalytic Activity of an Iron-Based Water Oxidation Catalyst: Substrate Effects of Graphitic Electrodes, *ACS Catal.* 8 (2018) 1052–1061.
- ⁸ R. Mazzoni, A. Gabiccini, C. Cesari, V. Zanotti, I. Gualandi, D. Tonelli, Diiron Complexes Bearing Bridging Hydrocarbyl Ligands as Electrocatalysts for Proton Reduction, *Organometallics* 34 (2015) 3228–3235.
- ⁹ F. Gloaguen, Electrochemistry of simple organometallic models of iron–iron hydrogenases in organic solvent and water, *Inorg. Chem.* 55 (2016) 390–398.
- ¹⁰ F. Arrigoni, L. Bertini, L. De Gioia, A. Cingolani, R. Mazzoni, V. Zanotti, G. Zampella, Mechanistic Insight into Electrocatalytic H₂ Production by [Fe₂(CN){μ-CN(Me)₂}(μ-CO)(CO)(Cp)₂]: Effects of Dithiolate Replacement in [FeFe] Hydrogenase Models, *Inorg. Chem.* 56 (2017) 13852–13864.
- ¹¹ F. Arrigoni, L. Bertini, L. De Gioia, G. Zampella, R. Mazzoni, A. Cingolani, I. Gualandi, D. Tonelli, V. Zanotti, On the Importance of Cyanide in Diiron Bridging Carbyne Complexes, Unconventional [FeFe]-Hydrogenase Mimics without Dithiolate: An Electrochemical and DFT Investigation, *Inorg. Chim. Acta* 510 (2020) 119745.
- ¹² A. Cingolani, V. Zanotti, C. Cesari, M. Ferri, L. Mazzocchetti, T. Benelli, S. Merighi, L. Giorgini, R. Mazzoni, Synthesis of Functionalized Iron N-Heterocyclic Carbene Complexes and Their

Potential Application as Flame Behavior Modifier in Cross Linked Epoxy Resins, *Inorg. Chim. Acta* 519 (2021) 120273.

¹³ C. Cesari, R. Conti, A. Cingolani, V. Zanotti, M. C. Cassani, L. Rigamonti, R. Mazzoni, Synthesis and Reactivity of Poly(Propyleneimine) Dendrimers Functionalized with Cyclopentadienone N-Heterocyclic-Carbene Ruthenium(0) Complexes, *Catalysts* 10 (2020) 264.

¹⁴ C. Copéret, A. Comas-Vives, M. P. Conley, D. P. Estes, A. Fedorov, V. Mougel, H. Nagae, F. Nunez-Zarur, P. A. Zhizhko, Surface Organometallic and Coordination Chemistry toward Single-Site Heterogeneous Catalysts: Strategies, Methods, Structures, and Activities, *Chem. Rev.* 116 (2016) 323–421.

¹⁵ L. Busetto, M. C. Cassani, P. W. N. M. van Leeuwen, R. Mazzoni, Synthesis of New Poly(Propyleneimine) Dendrimers DAB-Dendr- [NH(O)COCH₂CH₂OC(O)C₅H₄Rh(NBD)]_n {n = 4, 8, 16, 32, 64} Functionalized with Alkoxy carbonylcyclopentadienyl Complexes of Rhodium(I), *Dalton Trans.* (2004) 2767–2770.

¹⁶ D. Zuccaccia, L. Busetto, M. C. Cassani, A. Macchioni, R. Mazzoni, PGSE NMR Studies on DAB-Organorhodium Dendrimers: Evaluation of the Molecular Size, Self-Aggregation Tendency, and Surface Metal Density, *Organometallics* 25 (2006) 2201–2208.

¹⁷ F. A. R. Kaul, G. T. Puchta, H. Schneider, F. Bielert, D. Mihalios, W. A. Herrmann, Immobilization of Bis(Imino)Pyridyliron(II) Complexes on Silica, *Organometallics* 21 (2002) 74–82.

¹⁸ M. Pirouzmand, M. M. Amini, N. Safari, Immobilization of Iron Tetrasulfophthalocyanine on Functionalized MCM-48 and MCM-41 Mesoporous Silicas: Catalysts for Oxidation of Styrene, *J. Colloid Interface Sci.* 319 (2008) 199–205.

¹⁹ I. Kim, B. H. Han, C.-S. Ha, J.-K. Kim, H. Suh, Preparation of Silica-Supported Bis(Imino)Pyridyl Iron(II) and Cobalt(II) Catalysts for Ethylene Polymerization, *Macromolecules* 36 (2003) 6689–6691.

²⁰ Z. Zheng, J. Liu, Y. Li, Ethylene Polymerization with Silica-Supported Bis(Imino)Pyridyl Iron(II) Catalysts, *J. Catal.* 234 (2005) 101–110.

- ²¹ C. Liu, G. Jin, Polymer-Incorporated Iron Catalysts for Ethylene Polymerization—A New Approach to Immobilize Iron Olefin Catalysts on Polystyrene Chains, *New J. Chem.* 26 (2002) 1485–1489.
- ²² A. A. Costa, G. F. Ghesti, J. L. de Macedo, V. S. Braga, M. M. Santos, J. A. Dias, S. C. L. Dias, Immobilization of Fe, Mn and Co Tetraphenylporphyrin Complexes in MCM-41 and Their Catalytic Activity in Cyclohexene Oxidation Reaction by Hydrogen Peroxide, *J. Mol. Catal. A Chem.* 282 (2008) 149–157.
- ²³ B. Fan, H. Li, W. Fan, C. Jin, R. Li, Oxidation of Cyclohexane over Iron and Copper Salen Complexes Simultaneously Encapsulated in Zeolite Y, *Appl. Catal. A Gen.* 340 (2008) 67–75.
- ²⁴ J. Brünig, Z. Csendes, S. Weber, N. Gorgas, R. W. Bittner, A. Limbeck, K. Bica, H. Hoffmann, K. Kirchner, Chemoselective Supported Ionic-Liquid-Phase (SILP) Aldehyde Hydrogenation Catalyzed by an Fe(II) PNP Pincer Complex, *ACS Catal.* 8 (2018) 1048–1051.
- ²⁵ K. D. Khalil, E. I. Ibrahim, F. A. Al-Sagheer, A Novel, Efficient, and Recyclable Biocatalyst for Michael Addition Reactions and Its Iron(III) Complex as Promoter for Alkyl Oxidation Reactions, *Catal. Sci. Technol.* 6 (2016) 1410–1416.
- ²⁶ P. Marianne, Electrocatalytic oxidation of ascorbic acid and voltammetric determination with a ferrocene-modified platinum electrode, *Anal. Chim. Acta* 187 (1986) 333-338.
- ²⁷ J. Kulys, E. J. D'Costa, Printed electrochemical sensor for ascorbic acid determination, *Anal. Chim. Acta* 243 (1991) 173-178.
- ²⁸ A. Escorcia, A.-A. Dhirani, Electrochemical properties of ferrocenylalkane dithiol-gold nanoparticle films prepared by layer-by-layer self-assembly, *J. Electroanal. Chem.* 601 (2007) 260-268.
- ²⁹ J. Qiu, H. Peng, R. Liang, Ferrocene-modified Fe₃O₄@SiO₂ magnetic nanoparticles as building blocks for construction of reagentless enzyme-based biosensors, *Electrochem. Commun.* 9 (2007) 2734-2738.

- ³⁰ J. D. Qiu, J. Guo, R. P. Liang, M. Xiong, A Nanocomposite Chitosan Based on Ferrocene-Modified Silica Nanoparticles and Carbon Nanotubes for Biosensor Application, *Electroanalysis* 19 (2007) 2335-2341.
- ³¹ L. Fernandez, H. Carrero, Electrochemical evaluation of ferrocene carboxylic acids confined on surfactant–clay modified glassy carbon electrodes: oxidation of ascorbic acid and uric acid, *Electrochim. Acta* 50 (2005) 1233-1240.
- ³² M. A. Rampi, O. J. A. Schueller, G. M. Whitesides, Alkanethiol self-assembled monolayers as the dielectric of capacitors with nanoscale thickness, *Appl. Phys. Lett.* 72 (1998) 1781-1783.
- ³³ D. J. Wold, R. Haag, M. A. Rampi, C. D. Frisbie, Distance Dependence of Electron Tunneling through Self-Assembled Monolayers Measured by Conducting Probe Atomic Force Microscopy: Unsaturated versus Saturated Molecular Junctions, *J. Phys. Chem. B* 106 (2002) 106, 2813.
- ³⁴ A. Callegari, M. Marcaccio, D. Paolucci, F. Paolucci, N. Tagmatarchis, D. Tasis, E. Vazquez, M. Prato, Anion recognition by functionalized single wall carbon nanotubes, *Chem. Commun.* (2003) 2576-2577.
- ³⁵ L. Su, X. P. Qiu, L. H. Guo, F. S. Zhang, C. H. Tung, Amperometric glucose sensor based on enzyme-modified boron-doped diamond electrode by cross-linking method *Sens. Actuators, B* 99 (2004) 499-504.
- ³⁶ B. Ballarin, M. C. Cassani, R. Mazzoni, E. Scavetta, D. Tonelli, Enzyme electrodes based on sonogel containing ferrocenyl compounds, *Biosensors and Bioelectronics* 22 (2007) 1317–1322.
- ³⁷ S. A. Merchant, M. T. Meredith, T. O. Tran, D. B. Brunski, M. B. Johnson, D. T. Glatzhofer, D. W. Schmidtke, Effect of Mediator Spacing on Electrochemical and Enzymatic Response of Ferrocene Redox Polymers *J. Phys. Chem. C* 114 (2010) 11627–11634.
- ³⁸ F. Mao, N. Mano, A. Heller Long Tethers Binding Redox Centers to Polymer Backbones Enhance Electron Transport in Enzyme “Wiring” Hydrogels, *J. Am. Chem. Soc.* 125 (2003) 4951-4957.
- ³⁹ I. Gualandi, M. Tessarolo, F. Mariani, L. Possanzini, E. Scavetta, B. Fraboni, Textile Chemical Sensors Based on Conductive Polymers for the Analysis of Sweat, *Polymers* 13 (2021) 894.

- ⁴⁰ M. Dletrich, J. Hemze, G. Heywang, F. Jonas, Electrochemical and spectroscopic characterization of polyalkylenedioxythiophenes, *J. Electroanal. Chem.* 369 (1994) 87-92.
- ⁴¹ L. B. Groenendaal, F. Jonas, D. Freitag, H. Pielartzik, J. R. Reynolds, Poly(3,4-ethylenedioxythiophene) and Its Derivatives: Past, Present, and Future, *Adv. Mater.* 12 (2000) 481-494.
- ⁴² G. Li, P. G. Pickup, Ion transport in poly(3,4-ethylenedioxythiophene)–poly(styrene-4-sulfonate) composites, *Phys. Chem. Chem. Phys.* 2 (2000) 1255-1260.
- ⁴³ J. Bobacka, A. Lewenstam, A. Ivaska, Electrochemical impedance spectroscopy of oxidized poly(3,4-ethylenedioxythiophene) film electrodes in aqueous solutions, *J. Electroanal. Chem.* 489 (2000) 17-27.
- ⁴⁴ X. Cui and D. Martin, Electrochemical deposition and characterization of poly(3,4-ethylenedioxythiophene) on neural microelectrode arrays *Sens. Actuators, B* 89 (2003) 92-102.
- ⁴⁵ A. Lisowska-Oleksiak, A. Kupniewska, Transport of alkali metal cations in poly(3,4-ethylenethiophene) films, *Solid State Ionics* 157 (2003) 241-248.
- ⁴⁶ D. Han, G. Yang, J. Song, L. Niu, A. Ivaska, Morphology of electrodeposited poly(3,4-ethylenedioxythiophene)/poly(4-styrene sulfonate) films, *J. Electroanal. Chem.* 602 (2007) 24.
- ⁴⁷ L. Basiricò, P. Cosseddu, B. Fraboni, A. Bonfiglio, inkjet printing of transparent, flexible, organic transistors, *Thin Solid Films* 520 (2011) 1291-1294.
- ⁴⁸ M. Demelas, E. Scavetta, L. Basirico, R. Rogani, A. Bonfiglio, A deeper insight into the operation regime of all-polymeric electrochemical transistors, *Appl. Phys. Lett.* 102 (2013) 193301.
- ⁴⁹ E. Scavetta, R. Mazzoni, F. Mariani, R. G. Margutta, A. Bonfiglio, M. Demelas, S. Fiorilli, M. Marzocchi, B. Fraboni, Dopamine Amperometric Detection at a Ferrocene Clicked PEDOT:PSS Coated Electrode, *J. Mater. Chem. B* 2 (2014) 2861–2867.
- ⁵⁰ A. Cingolani, C. Cesari, S. Zacchini, V. Zanotti, M. C. Cassani, R. Mazzoni, Straightforward Synthesis of Iron Cyclopentadienone N-Heterocyclic Carbene Complexes, *Dalton Trans.* 44 (2015) 19063–19067.

- ⁵¹ A. Cingolani, V. Zanotti, S. Zacchini, M. Massi, P. V. Simpson, N. Maheshkumar Desai, I. Casari, M. Falasca, L. Rigamonti, R. Mazzoni, Synthesis, Reactivity and Preliminary Biological Activity of Iron(0) Complexes with Cyclopentadienone and Amino-Appended N-Heterocyclic Carbene Ligands: Reactivity and Bio-Activity of Amino-Appended NHC Iron(0) Complexes, *Appl. Organomet. Chem.* 33 (2019) e4779.
- ⁵² M.N. Hopkinson, C. Richter, M. Schedler, F. Glorius, An overview of N-heterocyclic carbenes, *Nature* 510 (2014) 485–496.
- ⁵³ S.P. Nolan, *N-Heterocyclic Carbenes: Effective Tools for Organometallic Synthesis*, Wiley VCH, 2014.
- ⁵⁴ E. Peris, Smart N-Heterocyclic Carbene Ligands in Catalysis, *Chem. Rev.* 118 (2018) 9988–10031.
- ⁵⁵ C.A. Smith, M.R. Narouz, P.A. Lummis, I. Singh, A. Nazemi, C.-H. Li, C.M. Crudden, N-Heterocyclic Carbenes in Materials Chemistry, *Chem. Rev.* 119 (2019) 4986–5056.
- ⁵⁶ Q. Liang, D. Song, Iron N-heterocyclic carbene complexes in homogeneous catalysis, *Chem. Soc. Rev.* 49 (2020) 1209–1232
- ⁵⁷ B.L. Conley, M.K. Pennington-Boggio, E. Boz, T.J. Williams, Discovery, Applications, and Catalytic Mechanisms of Shvo's Catalyst, *Chem. Rev.* 110 (2010) 2294–2312.
- ⁵⁸ T. Pasini, G. Solinas, V. Zanotti, S. Albonetti, F. Cavani, A. Vaccari, A. Mazzanti, S. Ranieri, R. Mazzoni, Substrate and product role in the Shvo's catalyzed selective hydrogenation of the platform bio-based chemical 5-hydroxymethylfurfural, *Dalton Trans.* 43 (2014) 10224–10234.
- ⁵⁹ C. Cesari, L. Sambri, S. Zacchini, V. Zanotti, R. Mazzoni, Microwave-Assisted Synthesis of Functionalized Shvo-Type Complexes, *Organometallics* 33 (2014) 2814–2819.
- ⁶⁰ R. Mazzoni, C. Cesari, V. Zanotti, C. Lucarelli, T. Tabanelli, F. Puzzo, F. Passarini, E. Neri, G. Marani, R. Prati, F. Viganò, A. Conversano, F. Cavani, Catalytic Biorefining of Ethanol from Wine Waste to Butanol and Higher Alcohols: Modeling the Life Cycle Assessment and Process Design, *ACS Sustainable Chem. Eng.* 7 (2019) 224–237.

- ⁶¹ C. Cesari, A. Cingolani, M. Teti, A. Messori, S. Zacchini, V. Zanotti, R. Mazzoni, Imidazolium Salts of Ruthenium Anionic Cyclopentadienone Complexes: Ion Pair for Bifunctional Catalysis in Ionic Liquids, *Eur. J. Inorg. Chem.* (2020) 1114–1122.
- ⁶² Cesari, C.; Gagliardi, A.; Messori, A.; Monti, N.; Zanotti, V.; Zacchini, S.; Rivalta, I.; Calcagno, F.; Lucarelli, C.; Tabanelli, T.; Cavani, F.; Mazzoni, R., Boosting the guerbet reaction: A cooperative catalytic system for the efficient bio-ethanol refinery to second-generation biofuels, *J. Catal.* 405 (2022) 47–59.
- ⁶³ T.C. Johnson, G.J. Clarkson, M. Wills, (Cyclopentadienone)iron Shvo Complexes: Synthesis and Applications to Hydrogen Transfer Reactions, *Organometallics* 30 (2011) 1859–1868.
- ⁶⁴ L. Pignataro, C. Gennari, Recent Catalytic Applications of (Cyclopentadienone)iron Complexes, *Eur. J. Org. Chem.* (2020) 3192–3205.
- ⁶⁵ C. Cesari, R. Mazzoni, H. Müller-Bunz, M. Albrecht, Ruthenium(0) complexes with triazolylidene spectator ligands: Oxidative activation for (de)hydrogenation catalysis, *J. Organomet. Chem.* 739 (2015) 256–262.
- ⁶⁶ C. Cesari, A. Cingolani, C. Parise, S. Zacchini, V. Zanotti, M.C. Cassani, R. Mazzoni, Ruthenium hydroxycyclopentadienyl N-heterocyclic carbene complexes as transfer hydrogenation catalysts, *RSC Adv.* 5 (2015) 94707–94718.
- ⁶⁷ C. Cesari, S. Conti, S. Zacchini, V. Zanotti, M.C. Cassani, R. Mazzoni, Sterically driven synthesis of ruthenium and ruthenium–silver N-heterocyclic carbene complexes, *Dalton Trans.* 43 (2014) 17240–17243.
- ⁶⁸ Cristiana Cesari, Rita Mazzoni, Elia Matteucci, Andrea Baschieri, Letizia Sambri, Massimo Mella, Andrea Tagliabue, Francesco Luca Basile, Carlo Lucarelli Hydrogen Transfer Activation via Stabilization of Coordinatively Vacant Sites: Tuning Long-Range π -System Electronic Interaction between Ru(0) and NHC Pendants, *Organometallics* 38 (2019) 1041–1051.

⁶⁹ M. Marzocchi, I. Gualandi, M. Calienni, I. Zironi, E. Scavetta, G. Castellani, B. Fraboni, Physical and Electrochemical Properties of PEDOT:PSS as a Tool for Controlling Cell Growth, ACS Appl. Mater. Interfaces 7 (2015) 17993–18003.