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Alkynes as Building Blocks, Intermediates and Products in the Electrochemical Procedures Since 2000

Martina Bortolami, Rita Petrucci, Daniele Rocco, Vincenzo Scarano, and Isabella Chiarotto*^[a]*The present work is dedicated to the memory of Professor Jean-Michel Savéant*

Electrochemical procedures present a selective and environmentally friendly approach for fine chemicals preparation. The use of electricity instead of classical chemical reagents is economical and ecologically attractive. In fact, electricity from renewable resources can be used for electrochemical transformations with highly sustainable and desirable electrochem-

ical applications. Alkynes triple C–C bond has a key role in many chemical transformations, and a growing attention has been recently paid to its electrochemical reactivity. The use of alkynes as building blocks or intermediates or products in electrochemical synthesis is presented in this minireview.

1. Introduction

Electrochemistry represents a wide interdisciplinary field, which has applications in many areas of physics, chemistry, metallurgy, and biology. Electrochemistry in the 20th century has seen the Jean-Michel Savéant's scientific contribution in the foundation and development of a new discipline, the molecular electrochemistry,^[1] and this review is in honour of his meaningful work needful for all the electrochemists.

Alkynes may be described as terminal and internal. Both the C–C and the terminal C–H bond represent reaction sites capable of undergoing numerous transformations. Herein, we want to report an overview of the papers published since 2000 concerning the electrochemical transformations involving alkynes, either as reagents or products. Generally, internal alkynes are more stable than terminal ones and both can be considered an important source of raw material. Nevertheless, due to the significant triple bond strength (839 kJ mol^{−1}), all alkynes are characterized by a moderate thermodynamic reactivity.^[2] Typically, alkynes undergo addition reactions with halogens, hydrogen and water, C–C coupling, dimerization, cyclisation and oxidation reactions. Moreover, they can undergo C–C chain extension by nucleophilic substitution and addition reactions.^[3]

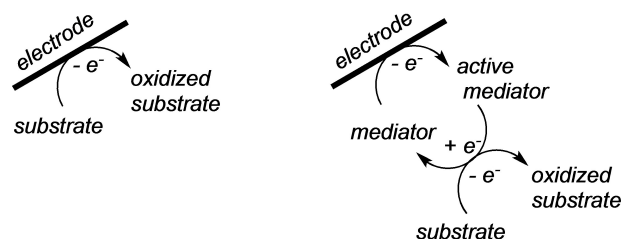
The electrochemical process of C–C triple bond reduction or oxidation involves high potential values. Although appropriate substitutions (e.g. the substitution of the terminal H with a metal) may lower the reduction or oxidation potential values, the obtained product may be further reduced or oxidized.

Generally, functionalization is used to achieve higher reactivity but, commonly, the alkynes functionalization is not easy to obtain, and it requires the use of mediators, such as transition metals. As an alternative, the use of electrolytic generation of intermediates able to react with the triple C–C bond can be chosen over the direct charge transfer.

In all cases, the electrochemical procedures offer possibility of using systems with a lower environmental impact and mild reaction conditions.^[4]

Although the alkyne functional group has long been neglected by the electrochemical landscape, a recent growing interest for this class of organic compounds led to several papers mainly concerning the strategy to accomplish their chemical transformations, such as functionalization and difunctionalization by electrochemical methodologies.^[5]

Unlike other aliphatic hydrocarbons, i.e. alkanes and alkenes, no value of standard potential of alkynes was present in literature until 1978, as reported in the Encyclopedia of Electrochemistry of the Elements: Organic Section (Edited by M. Dekker)^[6] and afterwards the electrochemical reduction of alkynes was mostly investigated.^[7] Currently, papers on the oxidation processes involving alkynes are more numerous. As a rule, electrochemical reactions involving alkynes can be classified basically in direct or indirect actions on substrate, depending to whether the electron transfer occurs between the working electrode and the organic substrate or if a mediator is present, respectively (Scheme 1).



Scheme 1. Unspecific examples in the direct (left) and indirect (right) anodic transformation.^[8]

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An invited contribution to a joint Special Collection in memory of Prof. Jean-Michel Savéant

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In this minireview, we will provide an overview of the last 20 years literature related to the role of alkynes as reactants or reaction products in the electrochemical procedures, distinguishing between cathodic and anodic reactions. We sincerely apologize if some important contributions have been unintentionally omitted.

2. Cathodic Reactions

The electrochemical processes leading to the synthesis of alkynes as final products are currently very few. In 2018, Feroci and co-workers reported that 2-(bromoethynyl)naphthalene can be cathodically converted to 2-ethynynaphthalene.^[9] In a previous work, the same authors, reported the electrosynthesis of vinyl bromides starting from 1,1-dibromo-1-alkenes: 2-ethynynaphthalene was obtained as main product (65 %) when the electrolysis was carried out at Au cathode in the absence of acetic acid as protonating agent.^[10]

The Corey-Fuchs reaction is a two steps reaction in which an aldehyde is first converted into a 1,1-dibromoalkene, with chain extension by one carbon atom, by reaction with carbon tetrabromide and triphenylphosphine. The second step requires the cleavage of the C–Br bond by reaction with BuLi at -78°C in THF. In the electrochemically modified Corey-Fuchs reaction the chemical reduction of alkyl halides was achieved by a selective cathodic cleavage of the C–Br bond. The 2-(2,2-dibromovinyl) naphthalene was chosen as model substrate, that

in a DMF solution (Pt cathode) provided selectively 2-ethynynaphthalene **2** or 2-(bromoethynyl)naphthalene **3** in high yields, depending on the electrolysis conditions. In fact, a high yield of the terminal alkyne **2** or the brominated product **3** was possible by the choice of the opportune supporting electrolyte, reported in the Scheme 2.

The synthetic electrochemical procedure was extended with success to other substrates, demonstrating that the electrochemical method can be a valid alternative to traditional synthetic procedures.

The first electrochemical hydrogenation of alkynes, using gaseous ammonia as the proton source, was reported by Cheng and co-workers in 2019.^[11] With a view to sustainable chemistry, the direct utilization of ammonia in organic synthesis as hydrogen source, with nitrogen as the only side product, resulted a great choice.^[12] Liquid ammonia solution is employed in the Birch reduction, under cryogenic and pressurized conditions, to convert aromatic compounds to not aromatized products.^[13] In the electrochemical procedure reported by Cheng, the reaction was carried out at atmospheric pressure and room temperature, using carbon both as the anode and cathode.

A variety of functional groups are well tolerated in the electrochemical hydrogenation with gaseous ammonia, including phenyl groups and heterocycles, that results conversely incompatible with transition-metal-catalysed hydrogenation reaction. The optimized conditions were evaluated on a few compounds with C–C triple bonds. Starting from alkyne



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Isabella Chiarotto graduated in Chemistry and Pharmaceutical Technology at Sapienza University. Researcher at the Chemistry Department of Sigma Tau Pharmaceutical Industry Spa-Pomezia (1989–91). In 1996 she attended research training at Ecole Normale Supérieure in Paris. She is currently associate professor of Chemistry for Engineering at Sapienza University. Her research interests are mainly focussed on electrochemical studies and applications in organic syntheses.



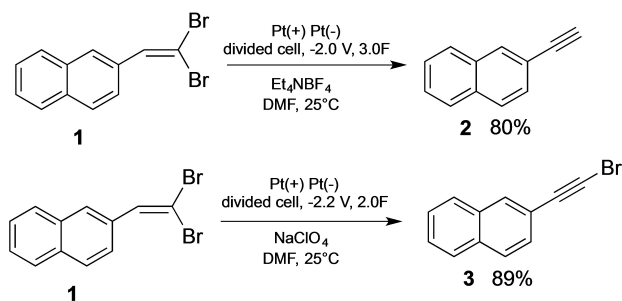
Daniele Rocco graduated in Organic Chemistry, Ph.D. in "Engineering and Applied Science for Energy and Industry, is currently postDoc at Sapienza University. His research activity is focused on the design, synthesis and characterization of new molecules in the field of organic electronics and electrochemistry.



Vincenzo Scarano graduated in Organic Chemistry in 2020 (Sapienza University). He is now a Ph.D. student (Engineering and Applied Science for Energy and Industry). His research interest is in the fields of electroorganic and classical organic chemistry.



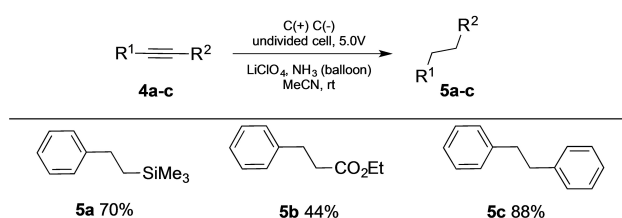
Rita Petrucci graduated in Organic Chemistry in 1988 (Sapienza University of Rome). She is an assistant professor of Chemistry for Engineering at Sapienza University. Her research interests are in the fields of molecular electrochemistry, spectroelectrochemistry, and mass spectrometry, applied to natural antioxidants, in particular to polyphenols in food and beverages.



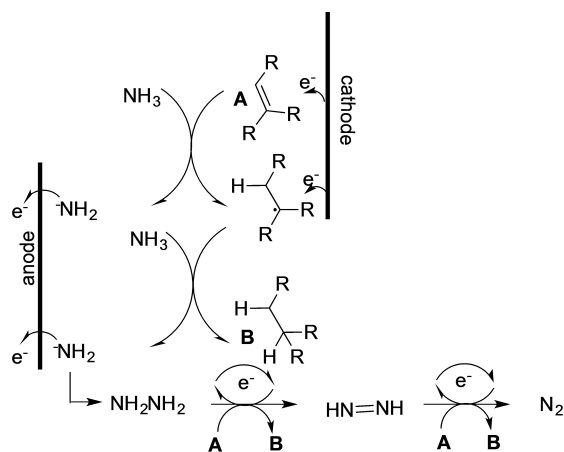
Scheme 2. Electrochemical synthesis of 2-ethynynaphthalene **2** and 2-(bromoethynyl) naphthalene **3**.^[9]

precursors **4a–c**, trimethyl(phenylethynyl)silane **5a**, ethyl 3-phenylpropanoate **5b** or 1,2-diphenylethane **5c** were obtained as completely hydrogenated products in 70 %, 44 % and 88 % yield, respectively (Scheme 3).

A mechanism for the electrochemical hydrogenation of an unspecific unsaturated carbon was proposed, according to which the cathodic reduction of the substrate (**A**, Scheme 4) coupled with the proton transfer from ammonia led to the hydrogenated product (**B**, Scheme 4) and the amide anion. During the process, the amide anion is anodically oxidized to hydrazine, which can act as H donor leading to the chemically hydrogenated product as well (Scheme 4). Hydrazine is an important industrial chemical and fuel, which recently has attracted notable attention due to its employ in liquid fuel cells.



Scheme 3. Electrochemical hydrogenation of alkynes by ammonia as the hydrogen source.^[11]



Scheme 4. Proposed mechanism for the electrochemical hydrogenation of unsaturated carbons with gaseous ammonia as the hydrogen source.^[11]

This interest is underlined in a recent work on the electrochemical synthesis of hydrazine from ammonia.^[14]

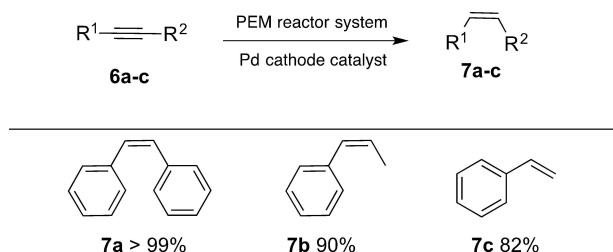
In the same year 2019, Atobe and co-workers employed diphenylacetylene as a model substrate in the stereo selective electrocatalytic semi-hydrogenation of alkynes to *Z*-alkenes in a process with a proton-exchange membrane reactor (PEM).^[15] This procedure results are more efficient and eco-friendlier than Lindlar's catalyst still used in this kind of hydrogenation.

Starting from alkyne precursors **6a–c**, *Z*-alkenes **7a–c** were obtained using a Pd catalyst with excellent current efficiencies at low electrolysis potentials (Scheme 5). The hydrogenated products were obtained without hydrogen gas in the chamber of reaction, providing a safer system compared to traditional hydrogenation reactions.

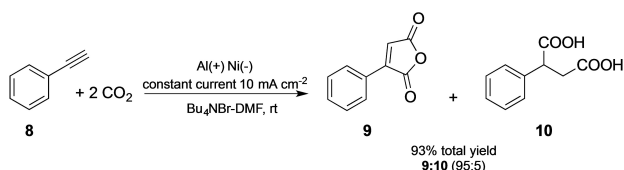
The protons produced during the anodic reaction are transported through the proton conductive polymer and reduced at the cathode to atomic hydrogen adsorbed on the membrane electrode containing Pd catalyst.^[16] The over-hydrogenated product can be also formed with not optimized conditions. A very interesting application of this method was the electro catalytic hydrogenation of 3-hexyne-1-ol to give *Z*-3-hexene-1-ol, in 97 % yield, commonly known as leaf alcohol, being a scent compound utilized as flavour and perfume.

Among the cathodic processes, Jiang and co-workers reported in 2008 the electrochemical carboxylation of phenylacetylene **8** with carbon dioxide.^[17] The constant current electrolysis carried out in the presence of CO₂ (3 MPa) and in the absence of additional catalysts led to the phenyl maleic anhydride **9** and the 2-phenylsuccinic acid **10**. The anhydrous conditions promoted the formation of **9** as main product, which was obtained in excellent yields. Conversely, the formation of the saturated **10** resulted prevalent in presence of H₂O. Cyclic voltammograms showed that a nickel cathode appears to be more effective than a Pt or Ag one, playing a catalytic role in the reduction reaction of aryl-acetylenes with CO₂. Many other factors, as the presence of water as protons source, type of solvents and conducting salts, amount of electricity and temperature as well as carbon dioxide pressure, were studied to obtain the optimal conditions in the electro-carboxylation, reported in Scheme 6.

The mechanism proposed by the authors provides for different reaction paths. At the beginning phenylacetylene **8** and CO₂ seem to undergo a single electron transfer on the surface of the nickel cathode to form two radical anions, at the same moment. Then, the radical anions can react in different



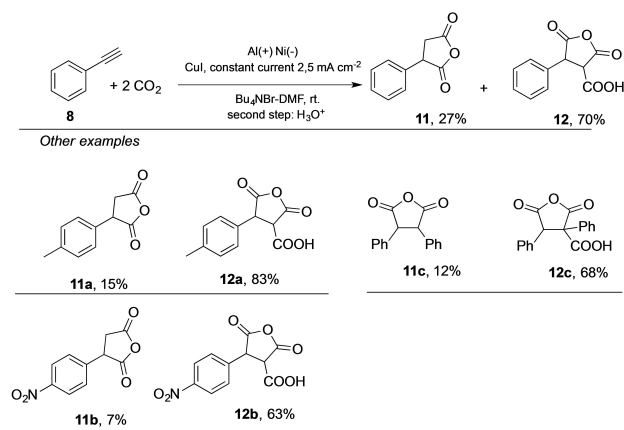
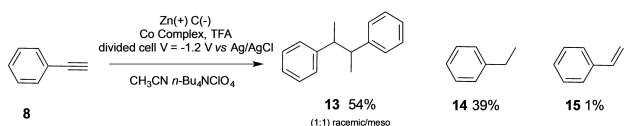
Scheme 5. Electrocatalytic hydrogenation by the proton-exchange membrane reactor and Pd catalyst.^[15]

Scheme 6. Electrochemical carboxylation of phenylacetylene.^[17]

ways, also involving Al^{+3} ions generated at the anode forming stable aluminium carboxylates, to afford the corresponding phenyl maleic anhydride **9** in excellent isolated yield, while the saturated phenyl succinic acid **10** was obtained in 90% yield in the presence of small amounts of water.

The electro-carboxylation of terminal alkynes with carbon dioxide and metal salt (CuI , FeCl_3) as catalyst was studied in 2010 by Huanfeng and co-workers.^[18] The results appear different from those of the previous work, proving that the presence of a metal salt has influence on the products and their yield distribution (Scheme 7).

Through the use of the B12 model complex, heptamethyl cobyrinate perchlorate (Co-Complex), in 2017 Shimakoshi, Hiseada and co-workers achieved the reductive coupling and hydrogenation of alkynes.^[19] Also in this case the use of a mediator for an indirect electrolysis made possible the redox process of the substrate through a lower applied potential that resulted in an efficient molecular transformation. ESR spin trapping experiments using 5,5-dimethylpyrroline *N*-oxide (DMPO) revealed that a cobalt-hydrogen complex (Co-H complex) could be formed during the electrolysis, acting as an intermediate for the alkyne reduction. The results of the phenylacetylene electrolysis are reported in Scheme 8.

Scheme 7. Electrocarboxylation of alkynes with CO_2 and CuI catalyst.^[18]Scheme 8. Indirect electrolysis with reductive coupling and hydrogenation of phenylacetylene.^[19]

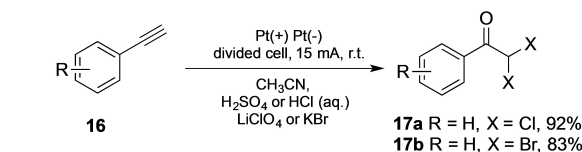
3. Anodic Reactions

The position of the triple bond in alkynes defines their reactivity. Alkynes with triple bond at the end of a molecule are named terminal alkynes and the terminal C–H is called acetylenic hydrogen. This group can undergo deprotonation by a strong base. If the triple bond is present between two alkyl or aryl groups, the alkyne is called internal. Alkyl alkynes are less acidic and less reactive than aryl ones, such as phenylacetylene or conjugated polyynes.^[20] Terminal alkynes were used as precursors for the synthesis of internal alkynes. In this section, the anodic processes relating to alkynes will be described, organized into two sections: one concerning terminal alkynes and another concerning internal alkynes.

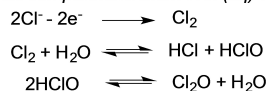
3.1. Anodic Processes with Terminal Alkynes

In 2020 Wang and co-workers chose phenyl acetylene as the model substrate to obtain the α,α -dihaloketones **17a–b** using an efficient and convenient electrochemical method.^[21] The electrochemical procedure allowed avoiding the use of additional oxidants used in traditional process of the oxyhalogenation of alkynes, making this method greener than the classical synthetic way. The reaction was carried out in two cells separated by a membrane permeable to the positive ions, under air, at room temperature and at constant electric current; the Pt–Pt electrodes couple resulted the best choice for the reaction (Scheme 9).

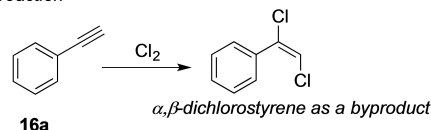
HCl was used as halogen source: Cl^- is anodically oxidized to form molecular chlorine Cl_2 , which produces the more reactive species Cl_2O able to react with the substrate to form α,α -dichloroacetophenone **17a**.^[22] Cl_2O and Cl_2 species can also act in synergy to give chlorination of phenylacetylene, leading to the formation of α,β -dichlorostyrene as a by-product detected by GC-MS (Scheme 9). To extend the scope of the reaction, the optimized conditions were modified to obtain α,α -dibromoacetophenone **17b**. In order to avoid the interference of Cl^- , H_2SO_4 was the acid, used alone in MeCN in the cathodic



Anodic compartment when HCl (aq) was used as a halogen source:



Side reaction

Scheme 9. Electrochemical synthesis of α,α -dihaloacetophenones.^[21]

compartment, while KBr was the bromine source in the anodic compartment. Under this modified condition, the yield of α,α -dibromoacetophenone **17b** was 83 %.

In 2000, Nishiguchi and co-workers^[23] described the electrochemical synthesis of 1-iodo-2-phenylacetylene and several aliphatic 1-iodoacetylenes starting from terminal acetylenes. The constant current electrolyses were carried out by using an electrochemical cell equipped with platinum plates both as anode and cathode. This electrochemical iodination is influenced by the nature of solvent, the amount of supplied electricity and the type of electrolysis cell. The best results were obtained in a divided cell at constant current, with methanol as solvent, as reported in Scheme 10. The mono-iodinated 1-iodo-2-phenylacetylene **19a** was formed in 88 % isolated yield with 3.0 F/mol of electricity. A drastic decrease in yield (43 %) was obtained using undivided cells, with diglyme as solvent and 4.0 F/mol of electricity. The paper presented the results for many other terminal acetylenes; the presence of various functional groups such as hydroxyl and chlorine atom were well tolerated, providing the corresponding mono-iodinated products in good yields. Despite the good results obtained in this paper, the authors were not able to describe a reaction mechanism. In particular, as regards the reactive intermediate, it was hypothesized that a key intermediate may involve a complex containing iodonium methoxide (MeO^-I^+), formed by the reaction of electrogenerated iodonium cation (I^+) with methanol, the terminal alkynes and hydrogen iodide.

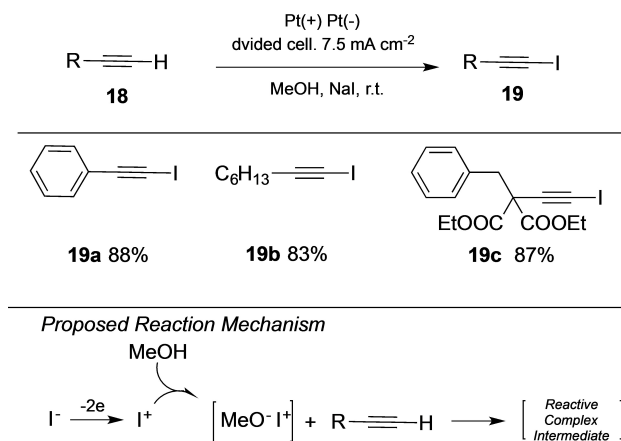
Metal acetylide are valuable and important intermediates in many synthetic processes. In 2010, Tanaka, Mitsudo and co-workers^[24] reported an electro-oxidative method for generating

silver acetylides **21** from acetylenes using Ag as anode. The electrolysis was performed in a two-compartment cell separated by a glass filter and performed at constant current. In the anodic compartment terminal alkyne and DBU (the presence of the base was indispensable for the reaction) were added to a solution of $\text{CH}_3\text{CN-Et}_4\text{NOTs}$ and the cathodic chamber was filled with the same solvent-electrolyte solution. Under this conditions, silver acetylides (**21 a-c**) were obtained from aryl alkynes in 65 % up to 88 % yields (Scheme 11).

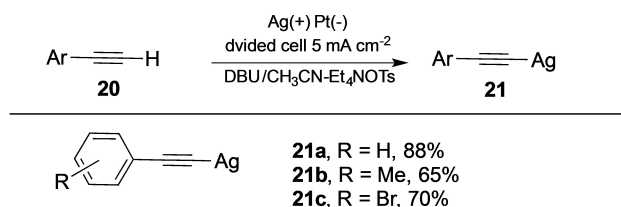
The electro-oxidative method for preparing silver acetylides was integrated with a Pd-catalyzed Sonogashira-type reaction, using catalytic amount of $\text{Pd}(\text{OAc})_2$ and 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) and arylboronic acids. During the process, the electro-generated silver acetylides reacted with arylboronic acids to afford the corresponding coupling adducts in high yields. To evaluate the advantage to have a silver acetylide in situ, the synthetic procedure was studied using several different anodes: e.g. with a Cu anode the reaction gave internal alkyne **22** (Scheme 12) in 56 % yield, but only a trace amount of coupling product was obtained with a non-sacrificial anode as Pt. These results showed that a metal acetylide, such as silver acetylide or copper acetylide, is pivotal for the reaction. The presence of an Ag source, as simple wire when Pt anode was used, gave the coupling product in 36 % yield. The lower yield is probably due to the lower efficiency in the generation of silver acetylide. However, the electro-oxidative method for preparing silver acetylides integrated with the synthetic procedure of Pd-mediated cross coupling with aryl boronic acids resulted effective and the electro-oxidative coupling of **8** and phenylboronic acid under the optimized conditions afforded **22** in 93 % yield (Scheme 12).

Wilden and co-workers in 2018 reported another example of electrochemical functionalization of terminal alkynes with metals. They explored the reactivity of terminal acetylene in the synthesis of copper(I) acetylides using a sacrificial copper anode.^[25] The synthesis of copper(I) acetylides, by the classical chemical procedure, is obtained by reacting terminal alkynes with a copper halide in aqueous ammonia, EtOH or DMF and K_2CO_3 .^[26] In the electrochemical procedure an oxidative constant potential was applied to the graphite rod electrode coated with metallic copper in a divided cell, with a Pt wire as counter-electrode and a silver wire as quasi reference-electrode. The electrolysis afforded the copper acetylide derivatives in excellent yields (Scheme 13).

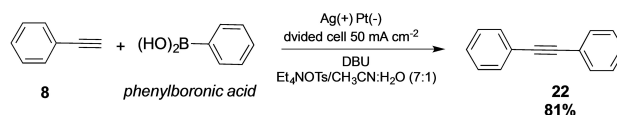
The same group improved the above-described electrochemical procedure using tetrabutylammonium (TBA) electrolyte salt to produce Bu_3N . The reduction of TBA occurs by a single-electron transfer/Hofmann-type elimination able to gen-



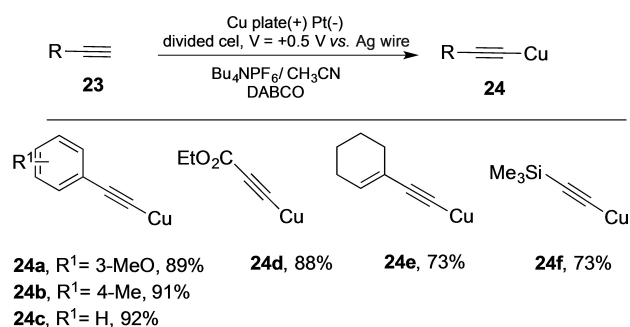
Scheme 10. Iodination of terminal acetylenes and proposed reaction mechanism.^[23]



Scheme 11. Electro-oxidative synthesis of several silver acetylides.^[24]



Scheme 12. Pd-catalysed electro-oxidative coupling of terminal alkynes and arylboronic acids.^[24]

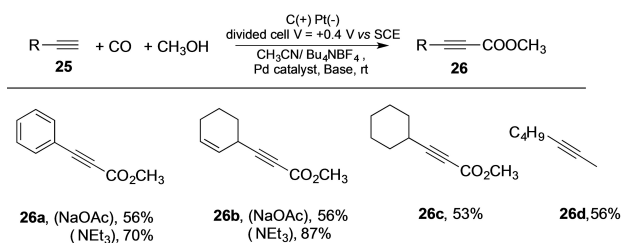


Scheme 13. Synthesis of copper(I) acetylides using a sacrificial copper anode.^[25]

erate tertiary amine bases and to avoid the use of other bases such as DABCO.^[27]

Carbon monoxide was widely used in the past as building block in organic synthesis. In 2002, Chiarotto and Carelli reported a procedure for the electrochemical synthesis of methyl acetylene carboxylates from alkynes, under mild conditions, using a palladium complex as catalyst, carbon monoxide under atmospheric pressure and methanol at room temperature (Scheme 14). In the classic synthetic procedures, the reaction with a Pd catalyst implies the use of an oxidant reagent in stoichiometric amount to transform Pd(0) (that results from the reaction) into Pd(II) (the reactive species of the catalyst).

When carrying out this reaction by classical chemical methods, usually high pressures of CO and O₂ are necessary, sometimes in combination with I₂; alternatively, CO, O₂, and copper salts can be used.^[29] The oxidative carbonylation by atmospheric pressure of carbon monoxide using Pd(II) catalyst, combined with its anodic recycling at a graphite electrode, represents a valid method to obtain a mild, selective and environmentally friendly system for the oxidation of Pd(0) into Pd(II). Afterwards, the same group applied this methodology to the synthesis of *N,N*-disubstituted ureas from aromatic and aliphatic primary amines,^[30] and to the synthesis of oxazolidin-2-ones starting from 2-amino-1-alkanols and carbon monoxide, achieving these heterocyclic compounds in very good yields.^[31] The proposed mechanism for the electro-carbonylation of terminal alkynes considered the presence of a base, essential as a proton trapper. The base could proceed to the elimination of H⁺ in the β position of intermediate complex. The yields of carbonylation products **26a–b**, obtained in the presence of

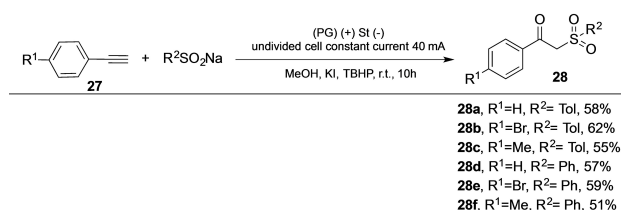


Scheme 14. Oxidative carbonylation of terminal alkynes.^[28]

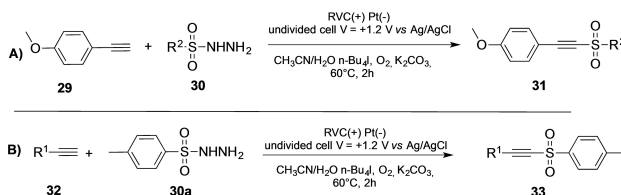
sodium acetate or triethylamine, showed that NEt₃ was more efficient than AcO[−] in this reaction. In fact, when NEt₃ was used as a base, the reaction occurred in shorter times, suggesting that the Pd(II) catalyst is more efficiently recycled in this condition. Both alkyl and aryl terminal acetylides were converted in acetylene carboxylates, without reducing the triple bonds, in good yields.^[32]

In 2020 Yavari and Shaabanzadeh^[33] reported the synthesis of β-ketosulfones *via* sulfination of aryl acetylides with sodium sulfonates. The electrochemical procedure was carried out under mild conditions and it gave the product in discrete yield with respect to the chemical yields. This electrochemical method was also applied to aryl methyl ketones, but it was studied for the first time on alkynes (Scheme 15). The use of electricity as energy source made this strategy more convenient and practical compared to the classical synthetic procedure, also for using inexpensive electrodes such as stainless steel and porous graphite (PG).

The oxidative cross-coupling reaction involving terminal alkynes represents an important synthetic target to obtain C–C bonds. In 2020, Huang, Tang and co-workers reported an electrochemical oxidative cross-coupling reaction between terminal alkynes and sulfonyl hydrazides under electrolysis conditions to obtain alkynyl sulfone compounds using tetrabutylammonium iodide as electrolyte and source of iodine involved as redox catalyst.^[34] *p*-Methoxyphenylacetylene **29** and *p*-toluenesulfonyl hydrazide **30a** were used as model substrates, and the best results were obtained at constant potential, by using an undivided cell (Scheme 16). The base plays a key role in this reaction, and the desired product was not detected without K₂CO₃ or DBU as alternative base. Moreover, water was necessary for the reaction, since only traces of product were found using dry CH₃CN. The optimized conditions were used to study the scope of alkynes including substrates bearing methyl and tertiary butyl groups at the para- or ortho-position of the phenyl ring and aryl/heteroarylsulfonyl hydra-



Scheme 15. Synthesis of β-ketosulfones via sulfination of aryl acetylides with sodium sulfonates.^[33]



Scheme 16. Oxidative cross-coupling reaction between terminal alkynes and sulfonyl hydrazides. **A)** Substrate scope of aryl/heteroarylsulfonyl hydrazides; **B)** Substrate scope of terminal alkynes.^[34]

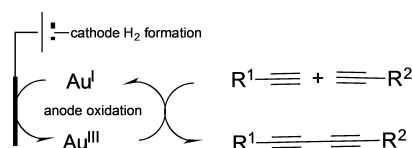
zides. Para- and ortho-methyl substituted benzenesulfonyl hydrazides demonstrated good reactivity in this transformation giving the desired products in excellent yields.

Moreover, the authors underlined the importance of alkynyl sulfones **33** as useful synthetic intermediates in diverse types of reactions to give alkynes derivatives.^[35–36]

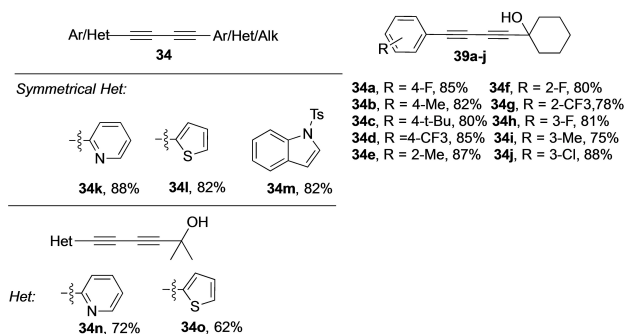
In 2019, Guo, Chen, Shi and co-workers^[37] reported the first example of direct electrochemical anodic oxidation of Au(I) to Au(III) resulting an attractive, eco-friendly and sustainable alternative to the chemical route (Scheme 17).^[38]

In fact, the electrochemical gold redox catalysis, does not require any external oxidant and it was used to obtain symmetrical or unsymmetrical conjugated diynes from terminal alkynes through an oxidative homo-cross-coupling. A wide variety of unsymmetrical diynes **34** was obtained from aryl alkynes, heteroaryl alkynes and aliphatic alkynes (Scheme 18).

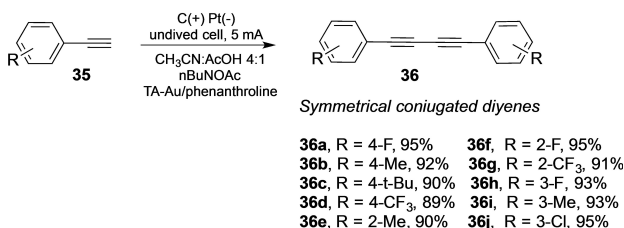
The authors also reported a preliminary study to verify the gold redox chemistry under electrochemical conditions. Therefore, the Au(I) pyridine complex was prepared and used in typical electrochemical conditions in the presence of alkynes. The corresponding Au(III) complex was obtained, confirming the goodness of the method. The homocoupling reaction of various alkynes was tested under the best conditions employing



Scheme 17. Gold redox catalysis in electrochemical synthetic applications.^[38]



Scheme 18. Substrate scope of diynes coupling: representative examples of aromatic, heterocycles and alkyl substituents.^[37]



Scheme 19. Optimal conditions for gold redox catalysis.^[37]

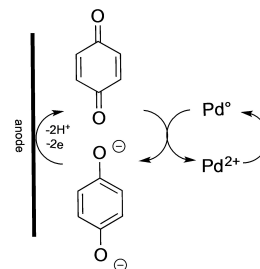
gold 1,2,3-triazole complexes (TA-Au) and phenanthroline (Scheme 19).

In 2012, Suga, Mitsudo and co-workers^[39] developed the “Electrochemical Reaction Site Switching” strategy for sequential coupling reactions directed toward bis(diaryl)butadiynes by the on/off application of electricity. In fact, the developed system can perform the electro-oxidative homo-coupling of terminal alkynes (electricity ON) and the subsequent Suzuki-Miyaura coupling (electricity OFF) to give bis(diaryl)butadiynes in high yields.

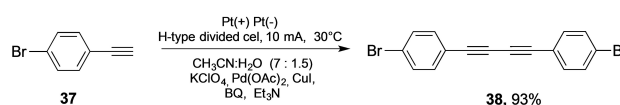
The oxidative homo-coupling reactions require stoichiometric amounts of an oxidant and the use of electro-oxidation sounds as an ecological and sustainable alternative. Therefore, in this synthesis 1,4-benzoquinone (BQ) was employed as a redox-active organic molecule coupled with the electrochemical oxidation. The electrochemical joining method resulted useful because it did not need an excess of oxidant. Pd(OAc)₂ as a catalyst together with BQ as cheap oxidant were used in the efficient oxidative coupling reaction between aniline derivatives and acrylates by de Vitries, van Leeuwen et al.^[40] The electrochemical application of BQ as oxidant was reported also by Jutand, Amatore and co-workers in the palladium(II) acetate-catalysed Heck type reactions.^[41] This reaction proceeded with catalytic amount of BQ which was used to oxidize the Pd(0) to the active Pd(II) species able to activate the Ar–H bond (Scheme 20).

The electro-oxidation was carried out in a H-type divided cell (glass filter) equipped with two platinum electrodes. In a typical procedure, a catalytic amount of copper salt (CuI) was essential for the reaction (Scheme 21).

For the subsequent reaction, after the electro-oxidative homo-coupling of *p*-bromophenylacetylene, the electricity was turned off and the analyte was poured into a Schlenk flask, with Cs₂CO₃, P(*t*-Bu)₃·HBF₄, *p*-tolylboronic acid and DME to give the 1,4-bis(diaryl)-1,3-butadiynes. Based on these results the same group used the procedure with success in the synthesis of 1,4-bis(diaryl)-1,3-butadiynes bearing two amino moieties, which showed solvatochromic fluorescence.^[42] These compounds find



Scheme 20. Pd/benzoquinone-catalytic system.^[41]



Scheme 21. The electro-oxidation of *p*-bromophenylacetylene **37** to diyne **38**.^[39]

applications in fluorescent environment-sensitive probes, as dyes typically designed to change their fluorescence intensity or colour in response to change in microenvironment polarity or viscosity.^[43]

3.2. Anodic Processes with Internal Alkynes

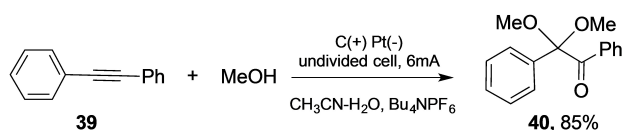
The electrochemical processes concerning organic compounds can occur directly at the working electrode or indirectly using mediators according to the electron transfer type. In the following examples some anodic processes involving alkynes take place directly at the electrode, thus resulting catalyst/metal, oxidant, and additive free.

In 2020, Shi, Tao Wang, Lei and co-workers presented a direct electrochemical oxidation of alkynes for the synthesis of benzoin bis-ethers, in the absence of external oxidant and transition metal catalyst.^[44] Diphenyl acetylene **39** and methyl alcohol were used as model substrates to test the reaction and under the best conditions 2,2-dimethoxy-1,2-diphenylethane-1-one **40** was isolated in 85 % yield (Scheme 22).

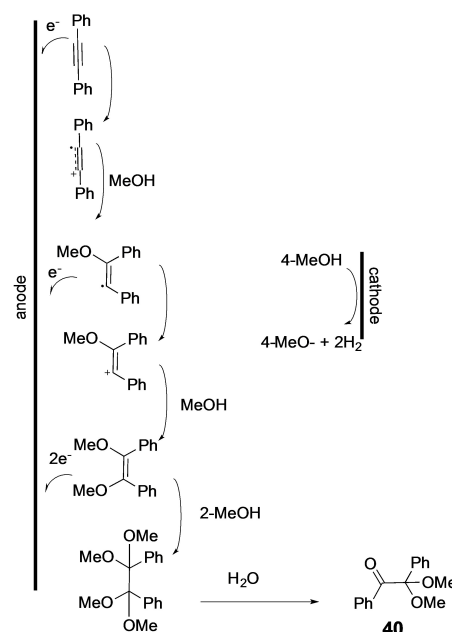
The process runs under mild reaction conditions and various alkynes and alcohols resulted compatible in the applied conditions. Moreover, the obtained products are important radical-type photo-initiators; the benzoin bis-ethers and their derivatives are largely applied in polymerization reactions by irradiation in the near UV-visible range (typically 340–450 nm range).^[45] In the proposed mechanism, the diphenylacetylene underwent a single electron transfer process at the anode to give an alkyne radical cation that in the presence of alcohol as nucleophile generates a radical species. A second single electron transfer process led to a cation which underwent a second nucleophilic attack by methanol to give a (Z)-1,2-dimethoxy-1,2-diphenylethane. The latter underwent further oxidation and a third nucleophilic attack by methanol to achieve the radical intermediate, which was again oxidized and underwent the attack by water to give **40** as the final product. At the cathode methanol was reduced to methoxide ion and molecular hydrogen (Scheme 23).

In 2020 the same authors presented an electrochemical esterification of alkynes starting from diols and their derivatives.^[46] Also in this method a green protocol was applied, being the process without catalysts, oxidants and additives and also observing the atom economy. Moreover, in this paper the first example of electrochemical reaction via cleavage of C–C triple bond with diols was reported.

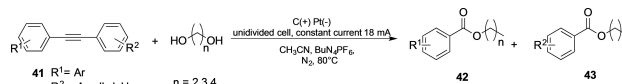
The best set of conditions is reported in Scheme 24. The choice of MeCN as solvent was crucial for this reaction; in fact no product was obtained using other solvents such as DMF,



Scheme 22. Metal-free electrooxidation of alkynes for the synthesis of benzoin bis-ethers.^[44]



Scheme 23. Plausible mechanism for the reaction of electro-oxidation of alkynes to benzoin bis-ethers.^[44]



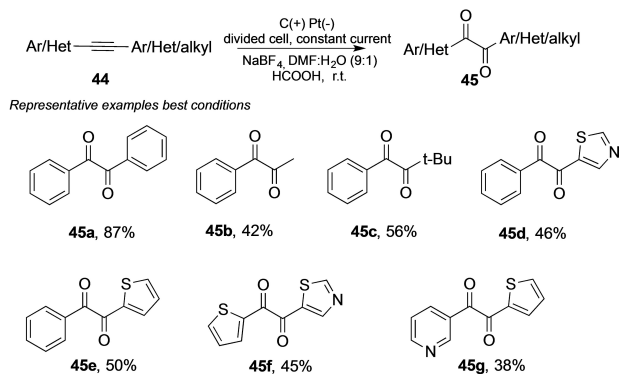
Scheme 24. Electrochemical dialkoxylation of diaryl acetylenes.^[46]

DMSO, H₂O. Internal and terminal alkynes were all suitable for this reaction, giving similar results in terms of product yield, even if the latter is a little lower for terminal alkynes. Regarding the alcohols, both linear and non-linear diols run in this reaction.

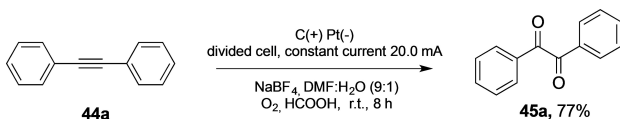
In 2019, Dai, Xu and co-workers presented an electrochemical method to obtain 1,2-diketones by direct oxidation of internal alkynes under mild conditions and air atmospheres.^[47] The synthetic strategy shows up as a green and efficient electrochemical method under catalyst free conditions, with inexpensive reagents and a wide substrate scope. A variety of functional groups and heterocyclic-compounds resulted to be well tolerated under these conditions (Scheme 25).

In a H-type divided cell with an anion exchange membrane at constant current (20 mA), the 1,2-diphenylethane-1,2-dione **45a** was obtained in 87 % yield by anodic oxidation of **44a** solution in a mixture of DMF and H₂O with NaBF₄ as supporting electrolyte, under air atmosphere (Scheme 25). The cathodic reaction was the formation of hydrogen (H₂), which was identified by GC analysis. The presence of acid was essential in the cathodic solution. Lower yields were obtained in the absence of HCOOH or in the presence of HOAc, while a moderate yield was obtained using CF₃COOH. Moreover, only low yield of product was obtained using an undivided cell.

Using O₂ atmosphere rather than air the reaction proceeded less effectively (Scheme 26). This result was associated with the observation of a certain amount of benzoic acid detected by



Scheme 25. Direct oxidation of internal alkynes to obtain 1,2-diketones.^[47]



Scheme 26. Synthesis of 1,2-diphenylethane-1,2-dione **45a** by direct oxidation of 1,2-diphenylethyne **44a** under O₂ atmosphere.^[47]

GC-MS analysis derived from further oxidation of the 1,2-diketone.

The reaction seems to proceed by radical species, because the formation of 1,2-diketone was completely halted by using radical scavengers, e.g. TEMPO.

The importance of these electrochemical methods that pursue new synthetic approaches is emphasised, providing new opportunity to develop catalyst free conditions and the use of inexpensive reagents.

4. Summary and Outlook

The more and more pressing demand for new strategies for sustainability is reflected in the need for more eco-sustainable and green synthetic methodologies and procedures. Thus, the development of a more sustainable and green chemistry is a topic that is taken into great consideration by the scientific community, as well as the input for new methodologies is a very important goal. Electrochemistry represents an attractive and powerful tool to carry out synthetic procedures, because this technique uses only electrons as reagent, that do not give waste products, providing a clean and sustainable way to get reaction products. Nowadays, a gradually larger part of the energy is produced by renewable sources; so, electrochemical applications result increasingly economically attractive.

Electrochemical methodologies have often many benefits over traditional chemical transformations, such as excellent atom economy, without the need to use expensive oxidants, catalysts or ligands. The use of electric current as a reagent gives a clean and efficient alternative to obtain the control of reactive species in the reactions. In fact, the profit of electrosynthesis is the possibility to modulate the electrical potential, or the amount of electricity, to tune the rate of electron transfer.

This aspect is thus important and permits to carry out the reactions under mild conditions with no chemical oxidants, making the process more selective and avoiding the generation of by-products. Here, we have presented a list of the more recent applications to perform reactions on alkynes by electrochemical procedures. In this review, we have presented the studies on the alkynes electrochemistry in the 21th century. The works were organized mainly in two sections: cathodic reactions and anodic reactions, further divided into processes on terminal alkynes and on internal alkynes. It is important to underline that there is a positive trend in recent years with a progressive increase in the number of publications on the use of electrochemistry applied to these classes of compounds. However, several other aspects deserve to be explored and certainly among these: (1) the discovery and application of new organic and inorganic mediators; (2) the use of new metal electrodes less precious but more efficient; (3) the development and improvement of organic chemistry most used reactions by redox control.

We wish that more and more research groups can make use of opportunities and benefits of electrochemical technology and we hope that its use in organic chemistry will be increasingly widespread.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords: alkynes • molecular electrochemistry • electrochemical procedures • C–C triple bond • sustainability

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