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Electrochemistry

eHydrogenation: Hydrogen-free Electrochemical Hydrogenation

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Abstract: Hydrogenation reactions are staple transformations commonly used across scientific fields to synthesise pharmaceuticals, natural products, and various functional materials. However, the vast majority of these reactions require the use of a toxic and costly catalyst leading to unpractical, hazardous and often functionally limited conditions. Herein, we report a new, general, practical, efficient, mild and high-yielding hydrogen-free electrochemical method for the reduction of alkene, alkyne, nitro and azido groups. Finally, this method has been applied to deuterium labelling.

The hydrogenation of alkenes and alkynes is a textbook reaction, though few practical methods have been developed to achieve this transformation. Of the available methods, preferred conditions still involve hydrogenation using explosive and flammable hydrogen gas and expensive, sometimes toxic, catalysts.[1] While this approach can also be used to incorporate deuterium atoms to access novel bioactive or biotracer compounds, challenges remain in the sourcing and handling of D_2 due to its cost.[2] The importance of hydrogenation reactions can be demonstrated by the endowment of the 2001 Nobel Prize in Chemistry to Knowles and Noyori for their contributions to asymmetric hydrogenation.[3] These types of reaction have been described as one of the most important catalytic transformations in synthetic organic chemistry due to the broad scope, the abundance of functional groups that can be selectively hydrogenated, high yields, mild conditions in the liquid phase, and its scale-up is relatively unproblematic.[1,4] Although there have been significant developments in conventional, long-established hydrogenations, the vast majority of these reactions are still constrained by the use of expensive and toxic transition metal catalysts such as ruthenium, rhodium and iridium, and also by substantially harsh conditions including high reaction temperatures and high pressure of dihydrogen.[5,6,7] Recent advancements in the field include the utilization of frustrated Lewis pair species in non-metal mediated hydrogenation catalysis (Figure 1).[8] Yet, these expensive catalysts still require activation by toxic reagents such as chlorosilanes, boranes and selenium.[8]

Diimide reductions have proven to be a viable complementary method to catalytic hydrogenations.[9] These reactions proceed via a cyclic transition state to facilitate the symmetrical transfer of hydrogen from cis diimide across a double or triple bond and are driven by the formation of dinitrogen.[10,11] In contrast to catalytic hydrogenations, diimide reductions avoid the use of expensive high-pressure equipment and handling of dihydrogen, can be carried out efficiently with readily available laboratory apparatus, and are milder, thereby avoiding the reductive cleavage of heteroatom bonds which is often a problem of catalytic hydrogenations.[9] The reduction using diimide (HN=NH) is an exciting metal-free alternative, yet also has challenges. Diimide can be generated either from an explosive salt (KOOC–NH=HN–COOK) or by oxidising hydrazine to diimide with pure oxygen at temperatures above the flash point of many solvents.[9] In addition, since diimide can disproportionate to hydrazine and dinitrogen, a large excess is needed and hydrazine is very often used as solvent.[9] The use of hydrazine itself also reduces the general applicability of this approach, especially in terms of scalability, since

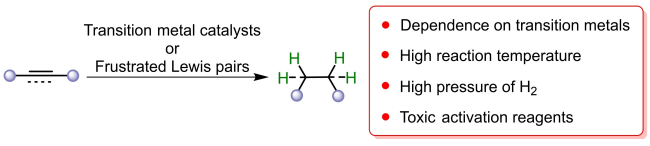

Figure 1. Previous approaches to hydrogenation.

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hydrazine is highly toxic and an energetic material. However, provided adequate safety measures are implemented, this does not limit the utility of this strategy on reaction scales common in medicinal chemistry.

Along with hydrogenation, deuteration is an extremely desirable transformation in the realm of analytical, pharmaceutical and synthetic chemistry.[2] Cleavage of the carbon-deuterium bond is much more demanding than that of the carbon-hydrogen bond due to a higher bond energy and deuterium, a non-radioactive isotope of hydrogen, is reasonably inexpensive, thus rendering it notably enticing in a plethora of fields including pharmaceutical research where deuterium incorporation tends to improve the pharmacokinetic properties and reduce the toxicity of corresponding non-deuterated drugs.[2,12] This is evident in the FDA approved deuterium labelled drugs deutetrabenazine (2017) and deucravacitinib (2022). Furthermore, deuterated compounds find wide applications as structural labels in a variety of analytical techniques and are key to mechanistic investigations based on the measurement of kinetic isotope effects (KIEs).[13] In recent years, a number of electrochemical deuteration methods have been developed as attractive alternatives to conventional deuteration strategies requiring harsh reaction conditions (eg., high temperatures, high pressure of expensive and unrecoverable D_2 gas), transition metal catalysts and/or stoichiometric reducing agents.[14] Nevertheless, effective electrochemical approaches for the reductive deuteration of unactivated olefins remain underrepresented.

The electrochemical hydrogenation and deuteration of alkenes and alkynes has been reported previously but these methods have not been applicable to the reduction of nitro- and azido-compounds to generate amines, which are immensely relevant precursors in the field of synthetic organic chemistry.[8] They are often used as starting materials in the synthesis of pharmaceuticals and biologically active molecules.[15] Their production from nitro and azide compounds have therefore attracted widespread attention from the chemical industry. The reduction of azides and nitro compounds have been extensively studied but tend to be limited by the ready availability, selectivity and toxicity of reducing agents.[16,17] The electrochemical reduction of these compounds presents a viable solution to these complications.

Organic electrochemistry is now being used to overcome many limitations intrinsic to conventional synthetic approaches,[18,19,20,21] and it paves the way for a multitude of efficient, economical and green redox transformations by employing electricity as the sole source of electrons.[22] In recent times, electrochemical hydrogenation comprising cathode reduction has become increasingly prominent due to the removal of high pressure molecular hydrogen, metal catalysts and expensive reducing and activating agents, but also by virtue of being an environmentally friendly and sustainable synthetic transformation and the ready availability of renewable electricity (Figure 2).[8,23] In the past ten years particularly, considerable breakthroughs in electrochemical hydrogenation have been accomplished. Cheng et al. demonstrated atmospheric gaseous ammonia could be used as a hydrogen source to perform the hydrogenation of various activated, terminal and internal olefins.[24] However, this transformation poses significant health risks associated with the use of gaseous ammonia and is limited to the hydrogenation of activated olefins.[24] Moreover, Huang

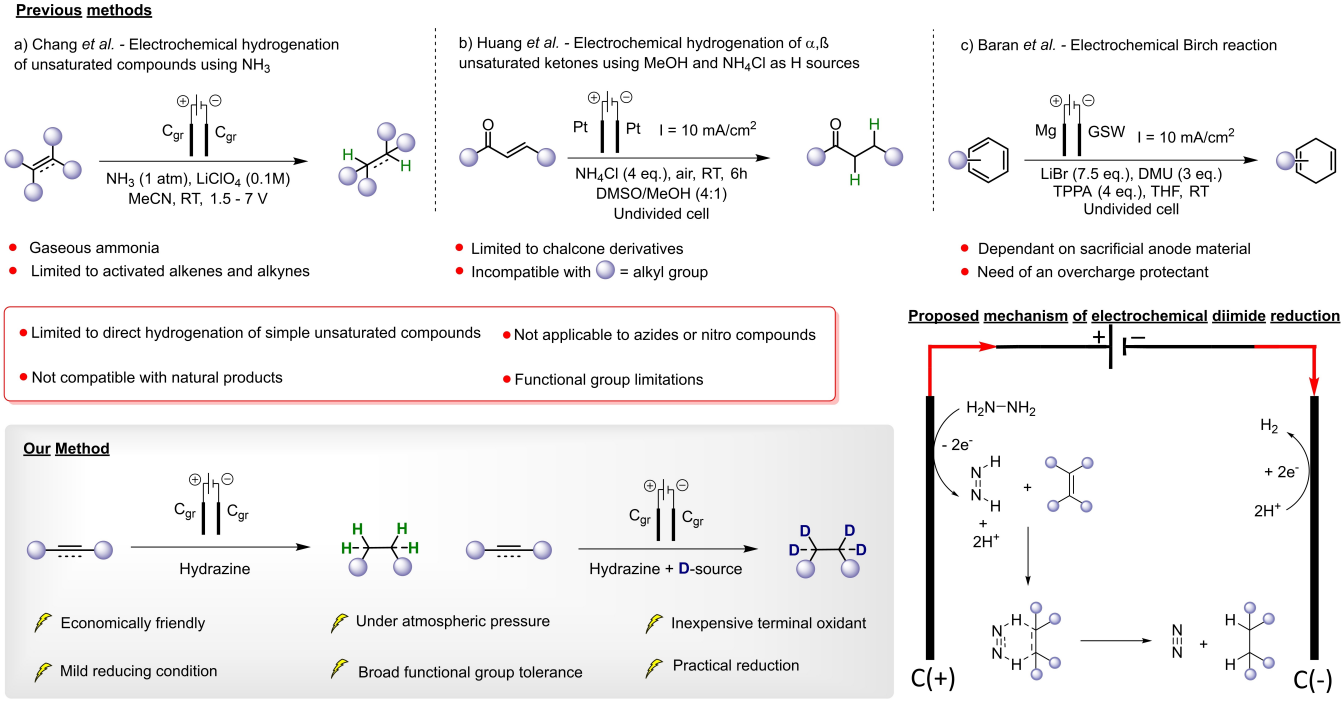


Figure 2. Recent advances in electrochemical hydrogenation.

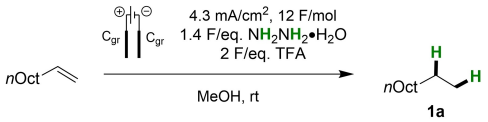
et al. reported an electrochemical chemoselective 1,4-reduction of α,β-unsaturated carbonyls using ammonium chloride and methanol as hydrogen donors.[25] While powerful, this method lacks general applicability and the scope was limited to activated chalcone derivated starting materials, and it is not compatible with alkyl functional groups.[25] Baran et al. also evolved the traditional Birch electroreduction to overcome obstacles such as scalability.[26] Nonetheless, this elegant approach is reliant on a sacrificial and more expensive anode material and is also dependent on an overcharge protectant, namely tris(pyrrolidino)phosphoramide (TPPA).[26] Furthermore, although these hydrogenation methods have demonstrated great advances on previous transformations, some tend to be incompatible for late stage hydrogenation and are restricted in not being applicable to the reduction of other moieties, such as nitro- and azido- compounds.

The electrochemical behaviour of hydrazine has been extensively studied due to its potential to replace the oxygen evolution reaction during the water splitting for hydrogen production.[27] Under aqueous conditions, it is known that hydrazine is converted to dinitrogen.[28] However, when the anodic oxidation of hydrazine is performed under non aqueous conditions, diimide has been postulated to be produced.[29] Therefore, we hypothesised that this partial oxidation of hydrazine in a non-aquous medium could be exploited as a practical way to perform hydrogenation. The hydrogenation of unsaturated moieties via a diimide reduction is hypothesised to proceed by a concerted process shown in Figure 2.[9,30]

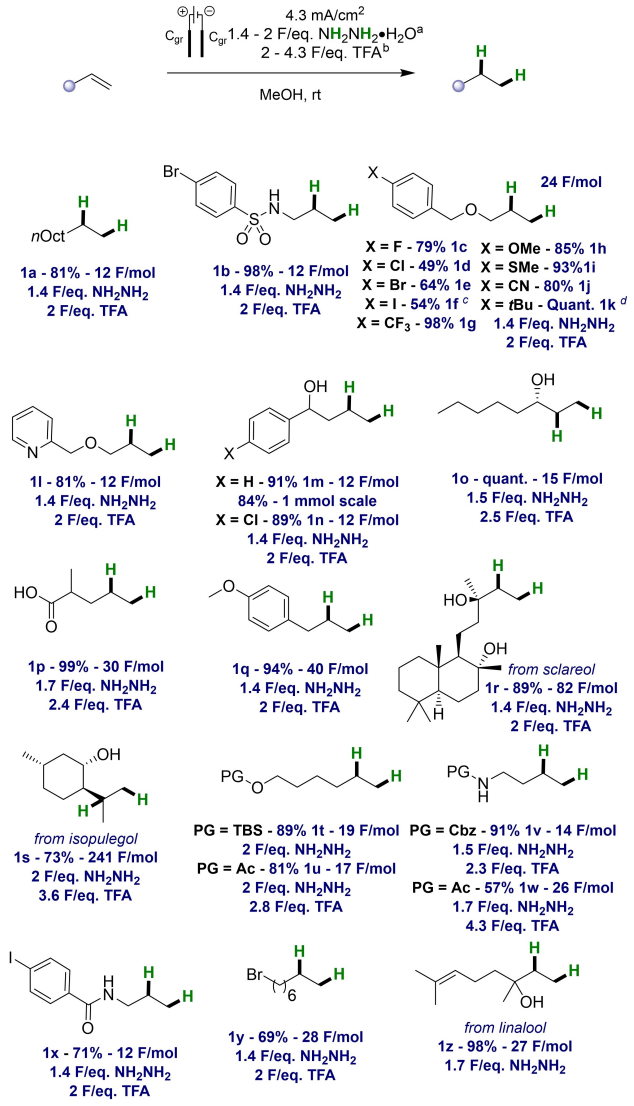
Indeed, a low anodic current will allow for a slow release of diimide in solution favouring the hydrogenation of the desired olefin over disproportionation of the diimide. Although MeOH is polar enough to conduct the electrolysis without the need for a wasteful supporting electrolyte, when the substrate bears an easily reducible functional group, the addition of a proton source (such as TFA) is vital. In such a case, the proton is reduced to H_2, avoiding the substrate being reduced (See Supporting Information for cyclic voltammetry studies). The addition of TFA forms a supporting electrolyte in situ (H_2N-NH_2·TFA) which increases the conductivity of the medium, while reports suggest that, in some cases, the acid can accelerate the hydrogenation of the compounds.[30,31] Furthermore, since hydrazine can easily be deuterated by a rapid exchange of its protons in presence of a deuterium source, our new methodology will also be able to be used for deuterogenation. Herein, we describe a new, practical reduction and deuteration which involves diimide reduction and can be applied to a variety of unsaturated compounds.

Through extensive optimisation of the reaction variables, the reduction of decene was achieved, affording **1a** in 81 % yield (Table 1). Inexpensive graphite electrodes, a low current of 10 mA, methanol as solvent and TFA were employed to affect this transformation (full optimisation table available in the Supporting Information). No reaction was observed in either the absence of hydrazine, when using substituted hydrazines derivatives or without electricity (Entry 2–5). Additionally, in the absence of TFA, a lower yield was observed (Entry 6). We hypothesise the acid additive aids primarily in preventing reduction of the electrolabile functionalities (i.e. Ar–I, R–Br, etc.) while enhancing the conductivity of the solution. In all cases, the reaction was electrolysed until full disappearance of the starting material, leading to the amount of hydrazine, TFA and the total charge varying dependant on the substrate. With these optimised conditions in hand, we evaluated the efficacy of the transformation with a variety of terminal alkenes. A variety of alkenes bearing a diverse array of functional groups could be reduced in moderate to excellent yield (Scheme 1). Aryl sulfonamide **1b** was generated in 98 % yield without reduction of the aryl bromide. A variety of allyl ethers bearing halogen, electron rich (OMe, SMe) and electron poor functional groups were smoothly reduced to the corresponding alkanes (**1c**–**1k**) in moderate to excellent yield. Notably, the reaction tolerates reduction of an alkene in the presence of a sulfide (**1i**), and a pyridine (**1l**) which could be challenging using palladium catalysis due to catalyst poisoning. Alkenes bearing free alcohols and carboxylic acids were also highly competent substrates for this transformation, affording alkanes **1m**–**1p** in up to quantitative yield. A scale-up reaction was also performed with the amount of alkene starting material increased from 0.4 mmol to 1 mmol. This successfully gave product **1m** in 84 % which was comparable to the reaction carried out on a smaller scale. Moreover, natural compounds sclareol and isopulegol were successfully reduced to the corresponding alkanes **1r** and **1s** in 89 % and 73 % yields respectively, requiring longer reaction times up to 241 F/mol. A variety of protected alcohols (OTBS, OAc) and amines (NCbz, NAc) were reduced without any observed deprotection in high yields (**1t**–**1w**). In the case of compound **1t**, the reaction was performed in the absence of TFA to prevent deprotection. The mildness of this method was demonstrated by the reduction of a double bond in the presence of an alkyl bromide or aryl iodide, affording **1x** and **1y** respectively in good yield, which would be challenging with conventional palladium catalysed approaches. The unique selectivity of the in situ form diimide could be exploited to exclusively hydrogenate the, more accessible, terminal alkene in linalool to generate **1z** in 98 % yield.

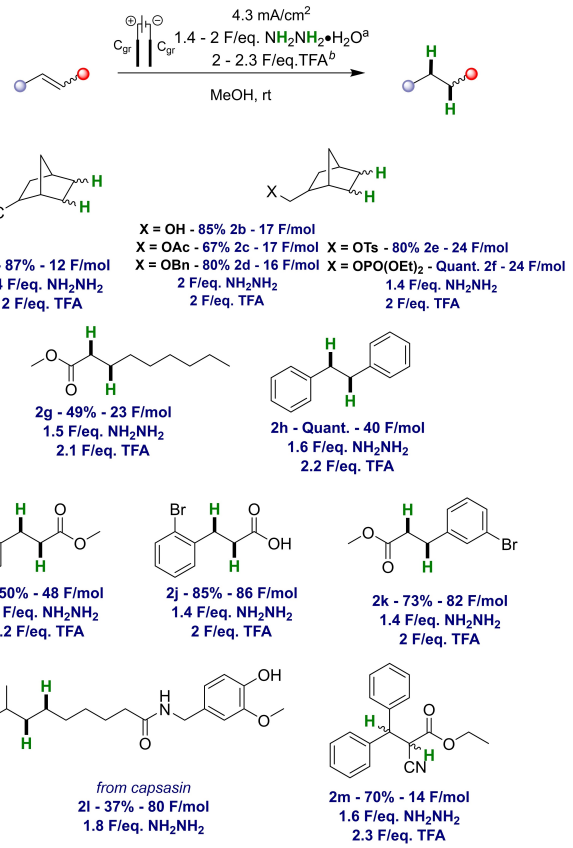
Table 1: Control reactions. Reactions performed on 0.4 mmol scale. Yields reported are those from isolated products.



Entry	Deviation from standard conditions	Yield [%]
1	none	81
2	No Hydrazine	0
3	tBu Hydrazine	0
4	1-Aminopyrrolidine	0
5	No Electricity	0
6	No TFA	32



Scheme 1. Substrate scope for the electrochemical hydrogenation of terminal alkenes. Reactions performed on 0.4 mmol scale. [a] Ratio of the charge required to complete the transformation per equivalent of hydrazine monohydrate; [b] Ratio of the charge required to complete the transformation per equivalent of trifluoroacetic acid; [c] **1f** was electrolysed until a charge of 30 F/mol has passed, 1.8 F/eq.NH_2NH_2 and 2.5 F/eq.TFA were applied to complete the reaction; [d] **1k** was electrolysed until a charge of 30 F/mol has passed, 1 F/eq.NH_2NH_2 and 1.7 F/eq.TFA were applied to complete the reaction.

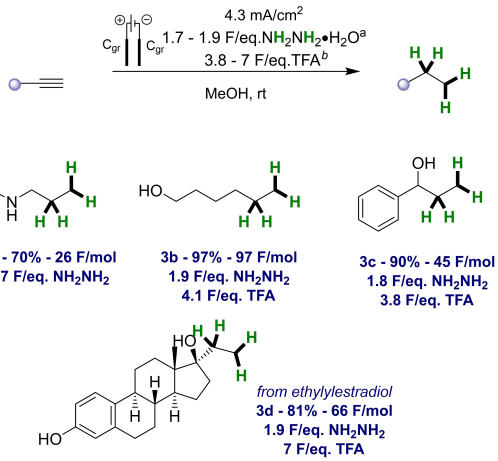


Scheme 2. Substrate scope for the electrochemical hydrogenation of internal alkenes. Reactions performed on 0.4 mmol scale. [a] Ratio of the charge required to complete the transformation per equivalent of hydrazine monohydrate; [b] Ratio of the charge required to complete the transformation per equivalent of trifluoroacetic acid.

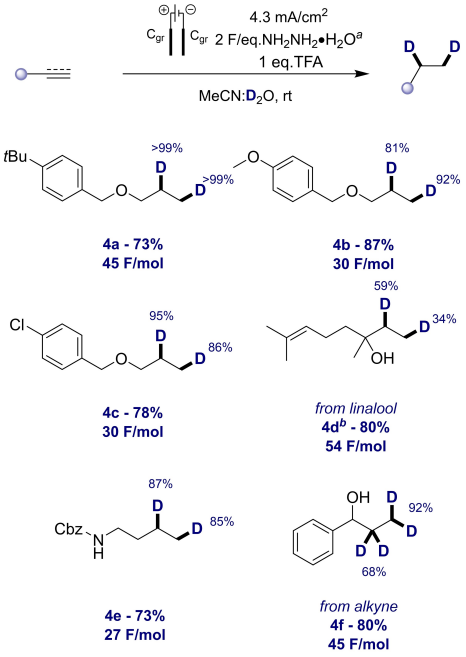
In addition to the reduction of terminal alkenes, internal alkenes were also effective substrates for electrochemical hydrogenation (Scheme 2). A range of norbornene derivatives were effectively hydrogenated in 67 %-quantitative yield (**2a**–**2f**). The reduction of activated internal alkenes was also effective, allowing conversion of acrylate, stilbene and cinnamic acid derivatives to the corresponding alkanes in up to quantitative yield, with only a slightly lower yield when only one electron withdrawing group was present on the alkene, affording alkane **2g** in 49 %. The application of this method to the late stage reduction of capsasin successfully afforded the hydrogenated product, demonstrating the efficacy of this method to even challenging less accessible alkenes. It was possible to also reduce a fully substituted and functionally dense alkene to form **2m** in high yield.

In addition to the reduction of double bonds, this electrochemical hydrogenation was also highly efficacious in the reduction of alkyne substrates (Scheme 3). *N*-Boc propargylamine was reduced fully to alkane **3a** in 70 % without any observed deprotection of the acid labile Boc group. Similar to compound **1s**, the synthesis of **3a** was performed without TFA to avoid deprotection. Primary and secondary alcohol functional groups were also tolerated in the alkyne reduction to generate alkanes **3b** and **3c** in >90 % yield. This could also be extended to the reduction of estradiol derivative **3d** in 81 %.

Montanari previously reported the deuteration of double bonds via the in situ formation of DN=ND from hydrazine and an inexpensive deuterium source.[32] Given this report, we hypothesised that the electrochemical deuteration of alkenes and alkynes would be feasible by modification of our reaction conditions. By modification of our optimised conditions using a mixed acetonitrile:D_2O solvent system, deuteration was achieved in high yields and good deuterium incorporation (Scheme 4). Especially high deuterium incorporation was achieved for alkanes **4a**–**c** in up to >99 %



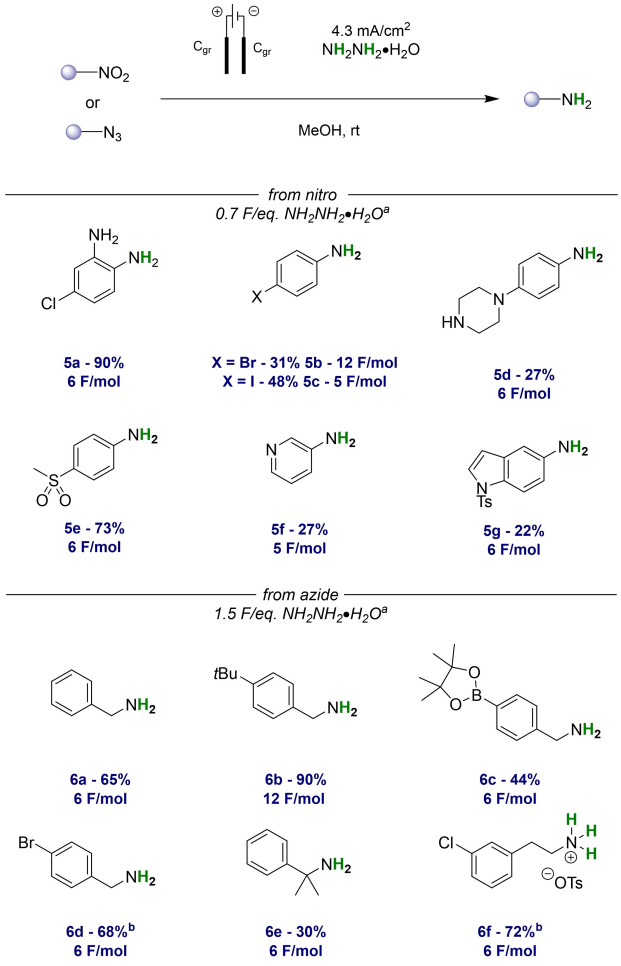
Scheme 3. Substrate scope for the electrochemical hydrogenation of alkynes. Reactions performed on 0.4 mmol scale. [a] Ratio of the charge required to complete the transformation per equivalent of hydrazine monohydrate; [b] Ratio of the charge required to complete the transformation per equivalent of trifluoroacetic acid.



Scheme 4. Substrate scope for the electrochemical deuteration of unsaturated compounds. Reactions performed on 0.4 mmol scale. [a] Ratio of the charge required to complete the transformation per equivalent of hydrazine monohydrate; [b] trifluoroacetic acid was omitted.

deuterium incorporation. The selective deuteration of linalool was conducted, which afforded **4d** in good yield however with moderate deuterium incorporation. This procedure could also be applied to the deuteration of a propargylic alcohol, affording **4f** in 80 % yield and moderate to excellent D incorporation across the molecule. Curiously, the extent of D incorporation is not uniform in several cases but is most prominent in **4d** and **4f** in which a larger disparity in %D incorporation was observed. This could be due to incomplete exchange of protons and deuterons during the generation of the diimide, leading to the formation of a HN=ND species concurrently with formation of the fully deuterated diimide.

In addition to hydrogenation, this method could be applied to the reduction of nitro and azide moieties to the corresponding free amines.[33] By slight modification of the reaction conditions, omitting trifluoroacetic acid, many aromatic nitro derivatives were successfully reduced to the corresponding anilines (Scheme 5), while the direct reduction of nitro compounds in the absence of hydrazine leads to low yields of the amine along with a complex mixture of side-products. Notably, 2-amino-4-chloroaniline **5a** a key intermediate for the production of Tizanidine, was synthesised in high yield (89 %) and obtained pure without further purification. Various other nitroarenes were also effective substrates in the reaction, including those bearing halogen, piperazine, sulfone, pyridine and indole functionalities **(5b–5g)**.



Scheme 5. Substrate scope for the electrochemical reduction of nitro and azide compounds. Reactions performed on 0.4 mmol scale. [a] Ratio of the charge required to complete the transformation per equivalent of hydrazine monohydrate. [b] Reaction performed on 0.8 mmol scale.

These conditions were applied to the reduction of azide compounds **(6a–6f)**. Similar to the reduction of nitro compounds, a variety of amine derivatives with diverse functional groups, including a BPin group, were successfully synthesized in up to 90% yield.

In summary, the general, practical and mild electrochemical hydrogenation and deuteration of unsaturated compounds was achieved, using hydrazine as an inexpensive H_2 source. This practical metal free methodology allowed the reduction of the wide range of alkenes and alkynes, to afford the corresponding alkanes in moderate to excellent yields. This methodology was also applicable for the reduction of nitro and azide compounds to the corresponding amines. Furthermore, the mild reaction conditions conferred a high degree of functional group tolerance. We expect this report to offer a powerful and user friendly strategy to complement conventional hydrogenation techniques.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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