IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 3, April 2025
Impact Factor: 7.67

Sustainable Electrochemistry: Examples and Challenges

Komal Patil[1], Pratibha Mhatre[2], Anushka Mhatre[3], Gurumeet C. Wadhava[4], Smita M. Tandale[5], Sajid F. Shaikh[6], Amod N. Thakkar[7]

Students P.G. Department of Chemistry, Veer Wajekar College Phunde, Uran[1,2,3]
Assistant Professor Department of Chemistry, Veer Wajekar College Phunde, Uran[4]
Vice Principal and Head Department of Chemistry, Veer Wajekar ASC College, Phunde, Uran[5]
Department of Chemistry, Anjuman Islam Janjira Degree College of Science, Murud Janjira, Raigad[6]
Principal, Veer Wajekar ASC College, Phunde, Uran[7]

Abstract: *Electrochemical methods have emerged as a promising approach for the synthesis of organic compounds, including the conversion of CO_2 into value-added products. These methods offer a pathway toward environmentally friendly, sustainable, and energy-efficient chemical production. However, despite their potential, electrochemical synthesis has not been widely adopted in industrial applications. Key challenges include scalability, electrode stability, reaction selectivity, and economic feasibility. This paper explores recent research advancements in green electrochemistry, highlighting both opportunities and barriers to its broader implementation in sustainable chemical manufacturing.*

Keywords: Organnic copunds, Eletrochemical Method

I. INTRODUCTION

Electrochemical synthesis must compete with conventional industrial methods such as heterogeneous and homogeneous catalysis, as well as emerging alternatives like enzymatic and photocatalysis. All chemical transformations require energy input, and electrochemical synthesis achieves this through the application of electrical potential across active electrode surfaces, where the flow of current facilitates oxidation or reduction reactions. Comprehensive reviews on electroorganic synthesis are available [1–4].

Several characteristics make electrosynthesis environmentally advantageous [5]. First, electrons serve as reactants, reducing the need for additional chemical reagents. Second, these reactions often occur at lower temperatures, minimizing energy consumption and reducing risks associated with corrosion, material degradation, and hazardous emissions. Additionally, electrosynthesis can utilize low-volatility or non-volatile solvents, further improving environmental safety. Electrodes act as heterogeneous catalysts, simplifying product separation, while supporting electrolytes and electrochemically active mediators can be regenerated and reused, enhancing sustainability.

Green chemistry research currently focuses on alternative solvents (e.g., supercritical carbon dioxide or ionic liquids), renewable feedstocks, and novel catalyst systems, including biological catalysts. Although electrochemical synthesis has been extensively studied within the electrochemistry community, broader industrial adoption remains limited. There is a need for quantitative tools to assess the environmental impact of electrochemical routes. The following sections present examples illustrating the scope and potential of electrosynthesis in sustainable chemistry.

Examples

Defining Green Synthesis

A sustainable synthesis route is characterized by its minimal environmental footprint. Green chemistry principles advocate for the use of renewable feedstocks, safer solvents, and efficient catalysts. Electrochemical waste treatment and remediation, as discussed by Pletcher and Weinberg [7,8], represent early applications of "green electrochemistry," but modern definitions emphasize electroorganic syntheses that improve atom efficiency, utilize less hazardous raw materials, or lower emissions.

DOI: 10.48175/IJARSCT-25007

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 5, Issue 3, April 2025 Impact Factor: 7.67

Electrochemical Reduction of CO_2 to Methanol

One potential strategy for mitigating CO_2 emissions involves its electrochemical conversion into methanol, which can serve as a precursor for higher-value chemicals. While this approach may sequester only limited amounts of CO_2, its broader application in sustainable energy and material synthesis is of significant interest [9–12]. Li and Prentice [12] demonstrated methanol synthesis using a high-pressure CO_2-water-ethanol system with LiCl as the electrolyte and a copper cathode. The reaction, conducted at 80°C and 68 bar CO_2 pressure, achieved a peak current efficiency of 40%, which remains below commercial viability. However, the use of dense-phase CO_2 as both solvent and reactant offers mass transfer advantages over conventional liquid-phase electrosynthesis.

Electrochemical Synthesis of Organic Carbamates

Casadei et al. [13–14] reported an electrochemical method for synthesizing organic carbamates via superoxide (O_2^-) and CO_2. Superoxide, generated at the cathode, facilitates the conversion of NH-protic amines into carbamates and primary or secondary alcohols into carbonates. These compounds are valuable intermediates in pharmaceuticals and biochemistry. The reaction, conducted in acetonitrile with tetraethylammonium perchlorate (TEAP) as the electrolyte, achieved yields of 50–90%. This approach eliminates the need for phosgene, a hazardous reagent commonly used in commercial carbamate synthesis, making it an environmentally preferable alternative.

Electrochemical Substitution for Chlorine-Based Activation

Chlorine is traditionally used to activate organic intermediates, generating HCl as a byproduct. BASF has developed an electrochemical alternative that significantly reduces environmental impact [15]. For example, Steckhan et al. [5] describe the synthesis of p-methoxybenzaldehyde from p-methoxytoluene using a chlorine-based route:

$$CH_3–Ph–OCH_3 + 2\ Cl_2 \rightarrow CHCl_2–Ph–OCH_3 + 2\ HCl$$
$$CHCl_2–Ph–OCH_3 + H_2O \rightarrow CHO–Ph–OCH_3 + 2\ HCl$$

This method produces four moles of HCl per mole of product, complicating chlorine recovery. In contrast, the BASF electrochemical process, conducted in methanol with sodium benzene sulfonate as the supporting electrolyte, avoids chlorine and HCl emissions:

$$CH_3–Ph–OCH_3 + 2\ MeOH - 4\ e^- \rightarrow CH(OCH_3)_2–Ph–OCH_3 + 4\ H^+$$
$$CH(OCH_3)_2–Ph–OCH_3 + H_2O \rightarrow CHO–Ph–OCH_3 + 2\ MeOH$$

This direct electrosynthesis offers improved atom efficiency, with methanol serving as both reactant and regenerable component, making it a sustainable alternative.

Other Research Avenues

Innovations such as solid polymer electrolytes, which eliminate liquid waste from supporting electrolytes, and electroenzymatic synthesis, which uses redox enzymes for improved selectivity, are gaining attention [1,4,5,17]. These advancements could further enhance the feasibility of electrochemical methods in green chemistry applications.

Research and Technology Needs

Despite promising developments, industrial adoption of electrochemical synthesis remains limited. Companies like BASF have commercialized certain processes, yet widespread implementation faces significant challenges. Unlike petrochemical processes, electrochemical reactions do not scale in a straightforward manner due to mass transfer limitations associated with bulk electrodes. Additional hurdles include electrode degradation, corrosion, and deactivation, which are often more problematic than in heterogeneous catalysis. Special reactor designs and complex cost estimations further complicate commercialization [1].

A key principle of green engineering is early-stage environmental impact assessment. However, electrochemistry has been slow to gain traction, partly due to a lack of trained R&D personnel in this field. Reliable life-cycle analyses and comprehensive environmental impact studies are necessary to justify investment in electrochemical alternatives.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 3, April 2025
Impact Factor: 7.67

Economic considerations, particularly in terms of sustainability metrics, play a crucial role in determining industrial feasibility.

While large-scale adoption remains uncertain, electrochemical methods show significant promise for high-value, low-volume applications such as pharmaceuticals [18-23] and specialty chemicals [19]. Continued research and development, along with supportive regulatory and economic incentives, could accelerate the integration of electrochemical synthesis into mainstream green chemistry practices[20-26].

REFERENCES

[1]. D. Degner. Top. Curr. Chem. **148**, 1–95 (1988).
[2]. D. Degner. Techniques of Electroorganic Synthesis, Part III, Ch. 32, pp. 251–265, Wiley, New York (1985).
A. J. Fry. Synthetic Organic Electrochemistry, Harper & Row, New York (1972).
[3]. J. Utley. Chem. Soc. Rev. **26**, 157–167 (1997).
[4]. E. Steckhan, T. Arns, W. R. Heineman, G. Hilt, D. Hoorman, J. Jorissen, L. Krone, B. Lewall, H. Putter. Chemosphere **43**, 63–73 (2001).
[5]. A S. Matlack. Introduction to Green Chemistry, Marcel Dekker, New York (2001).
[6]. D. Pletcher and N. L. Weinberg. Chem. Eng. **99** (8), 98–103 (1992).
[7]. D. Pletcher and N. L. Weinberg. Chem. Eng. **99** (11), 132 (1992).
[8]. X. Xiaoding and J. A. Moulijn. Energy Fuels **10**, 305–325 (1996).
[9]. V. A. Grinberg and V. M. Mazin. Russ. J. Electrochem. **34** (3), 223–229 (1998).
[10]. A P. Abbott and C. A. Eardley. J. Phys. Chem. B. **104**, 775–779 (2000).
[11]. J. Li and G. Prentice. J. Electrochem. Soc. **144** (12), 4284–4288 (1997).
[12]. M. A. Casadei, S. Cesa, F. M. Moracci, F. Micheletti Moracci, A. Inesi, M. Feroci. J. Org. Chem. **61**, 380 (1996).
[13]. M. A. Casadei, F. M. Moracci, G. Zappia, A. Inesi, L. Rossi. J. Org. Chem. **62**, 6754 (1997).
[14]. Nitin A. Mirgane, Vitthal S. Shivankar, Sandip B. Kotwal, Gurumeet C. Wadhawa, Maryappa C. Sonawale, Degradation of dyes using biologically synthesized zinc oxide nanoparticles, Materials Today: Proceedings,Volume 37, Part 2021, 849-853, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2020.06.037.
[15]. Nitin A. Mirgane, Vitthal S. Shivankar, Sandip B. Kotwal, Gurumeet C. Wadhawa, Maryappa C. Sonawale, the Waste pericarp of ananas comosus in green synthesis zinc oxide nanoparticles and their application in wastewater treatment, Materials Today: Proceedings, Volume 37, Part 2, 2021, 886-889, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2020.06.045.
[16]. Shubhada S. Nayak, Nitin A. Mirgane, Vitthal S. Shivankar, Kisan B. Pathade, Gurumeet C. Wadhawa, Adsorption of methylene blue dye over activated charcoal from the fruit peel of plant hydnocarpuspentandra, Materials Today: Proceedings, Volume 37, Part 2, 2021, 2302-2305, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2020.07.728.
[17]. Patil, D.D.; Mhaske, K.D.; Wadhawa, C.G., Antibacterial and Antioxidant study of Ocimumbasilicum Labiatae (sweet basil), Journal of Advanced Pharmacy Education & Research (2011) 2, 104-112.
[18]. Dinanath PD, Gurumeet WC, 2013. Antibacterial, antioxidant and antiinflammatory studies of leaves and roots of Solanum xanthocarpum. Unique J Ayurvedic Herb Med (2013) ;(3):59-63.
[19]. Dynashwar K. Mhaske, Dinanth D. Patil, Gurumeet C. wadhawa. Antimicrobial activity of methanolic extract from rhizome and roots of Valerianawallichii. International Journal on Pharmaceutical and Biomedical Research, 2011; 2(4):107- 111
[20]. Patil DD, Mhaske DK, Gurumeet MP, Wadhawa C. Antibacterial and antioxidant, anti-inflammatory study of leaves and bark of Cassia fistula. Int J Pharm 2012; 2(1):401-405.
[21]. G. C. Wadhawa, M. A. Patare, D. D. Patil and D. K. Mhaske, Antibacterial, antioxidant and antiinflammatory studies of leaves and roots of Anthocephaluskadamba. Universal Journal of Pharmacy, 2013.
[22]. Shubhada S. Nayak, Nitin A. Mirgane, Vitthal S. Shivankar, Kisan B. Pathade, Gurumeet C. Wadhawa, Degradation of the industrial dye using the nanoparticles synthesized from flowers of plant

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 3, April 2025
Impact Factor: 7.67

Ceropegiaattenuata, Materials Today: Proceedings, Volume 37, Part 2, 2021, Pages 2427-2431, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2020.08.274.

[23]. G. C. Wadhawa, V. S. S. Hivankar, Y. A. Gaikwad, B. L. Ingale, B. R. Sharma, S. S. Hande, C. H. Gill and L. V. Gavali, Eur. J. Pharm. Med. Res., 3, 556 (2016).

[24]. Patil, Dinanath D., Gurumeet C. Wadhava, and Arun K. Deshmukh. "One Pot Synthesis of Nitriles fromAldehydes and Hydroxylamine Hydrochloride Using Ferrous Sulphate in DMF Under Reflux Condition."Asian Journal of Chemistry 24.3 (2012): 1401.

[25]. Patil DD, Mhaske DK, Wadhawa GC. Green Synthesis of 3,4dihydropyrimidinone using ferrous sulphate