



Foam electrodes for electrochemical wastewater treatment: A review of materials, mechanisms, and applications

Hind H. Thwaini ^{a, *}

a Department of Chemical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq

Abstract

Foam electrodes, represented by metal foams, are characterized by their highly porous three-dimensional structure and relatively large surface area. They have high electrical conductivity and advanced and promising functional materials in wastewater treatment. The unique design of the structure with porous materials provides increased catalytic sites, improved mass transfer, easier of electron transfer, and long-term durability under extreme operating conditions. These characterizations make them very suitable materials for electrochemical processes. This review focuses on the manufacturing materials of foam electrodes and their new applications in electrochemical oxidation, adsorption, and electrocoagulation processes. It was specifically mentioned various types of electrodes, such as nickel, copper, iron, and aluminum, RVC, graphene and highlights their ability to remove toxic organic contaminants, dyes, and heavy metals. The removal efficiency of the electrochemical processes ranged from 70% to 99% depending on the electrode material. Nickel foam followed by copper then graphene foam had the superior performance in advanced oxidation processes whereas COD removal varied from 40 to 92% depending on the operation conditions. A structured literature survey covering publications from 2015 to 2025 finally, foam electrodes play a significant role in wastewater treatment.

Keywords: Wastewater; Nickel foam; Copper foam; Electro-Fenton; RVC foam.

Received on 02/07/2026, Received in Revised Form on 02/08/2026, Accepted on 02/08/2026, Published on 30/09/2026

<https://doi.org/10.31699/IJCPE.2026.3.11>

1- Introduction

Major global environmental concern due to increase pollutants of water resources as expanding in industrial activities, rapid urban development, and population growth [1]. The wastewater discharged from industrial [2], agricultural [3], and domestic sources often contains a complex mixture of pollutants such as organic compounds, heavy metals [4], dyes [5], pharmaceuticals [6], and other contaminants. The discharge of these pollutants into natural water resources can negatively affect aquatic ecosystems [7], cause reduced water quality, and pose serious risks to public health. Conventional treatment technologies such as physical, chemical, and biological methods have been widely employed for wastewater remediation, but their effectiveness is often limited when dealing with intractable pollutants [8]. Furthermore, high energy consumption issues, operational involvement, and secondary waste generation have encouraged the search for more effective and environmentally sustainable treatment processes [9].

Electrochemical treatment has attracted a lot of attention lately than other process [10]. Because of its high efficiency, ease of operation, and ability to work under different conditions. These processes, such as electrooxidation [11], electrocoagulation [12], electrocatalysis, and electro-Fenton reactions [13],

showed high potential for the removal of pollutants from water and they have ability to break down complex organic compounds into easily removable components. Also, these technologies are primarily affected by the type and efficiency of the electrodes used, as well as the materials from which those electrodes are made, which in turn primarily control electron transport, catalytic activity, and mass transfer during processing [14].

The two-dimensional electrodes, are easy to operate and maintain are used for the conventional electrochemical oxidation process. However, a small plate electrode area with large electrode spacing, and a uniform and monotonous electrode surface are responsible for the major disadvantages of 2D electrochemical reactors, which include a limited electrode active surface area, limited mass transfer, and low current efficiency [15].

In recent decade, foam electrodes have emerged as 3D promising materials for electrochemical wastewater treatment because of its porous structures. Compared with traditioned electrodes, foam electrodes provide significantly higher surface areas, enhanced mass transfer, improved reactant accessibility, and a greater density of active sites. there are many types of foam materials, including nickel foam [16], copper foam [17], iron foam [18], stainless steel foam [19], and graphite foams [20], have been investigated as electrode substrates or catalytic supports for wastewater treatment applications.



*Corresponding Author: Email: hind.abd2107m@coeng.uobaghdad.edu.iq

© 2026 The Author(s). Published by College of Engineering, University of Baghdad.

This is an Open Access article licensed under a [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/). This permits users to copy, redistribute, remix, transmit and adapt the work provided the original work and source is appropriately cited.

Foam electrodes became as promising materials for electrochemical wastewater treatment because of reported in the treatment of various industrial effluents containing dyes [21], pharmaceutical [22], heavy metals [23], and other persistent pollutants.[24].

An overview of recent foam electrode research is given in this work, which also examines the mechanics and applications of these electrodes in wastewater treatment. Past reviewers either covered a wide range of 3D electrode materials in their studies or focused merely on a single foam electrode material without addressing or providing a sufficient comparison between different metallic and carbon-based foam electrodes. Therefore, this review aims to reduce the gap by systematically evaluating structural characteristics and preparation methods of various foam electrodes used in wastewater treatment as well as their electrochemical performance, removal efficiency and limitations.

2- Electrochemical wastewater treatment fundamentals

2.1. Electrochemical oxidation process

Electrochemical oxidation (EO) is advance oxidation technique that uses electrical energy to eliminate contaminants and impurities from water by using oxidation-reduction reactions, which take place at electrode surfaces and electrolytes, and this process has become a green process because their clean performance [25]. These processes detect as environmental compatibility and high treatment efficiency; also, they can destroy inorganic contaminants without any need for significant chemical additions. Briefly, there are two types of EO, the direct process [26], which degrades pollutants through direct electron transfer (DET) between the anode surface and impurities. However, in indirect EO [27], organic contaminants react uniformly with strong oxidants such as Cl_2 , H_2O_2 , HClO , ClO^- , SO_4^{2-} , and O_3 . Numerous variables, including electrode material, current density, electrolyte composition, initial concentration, solution pH, and the space between electrodes, can affect the electrochemical treatment [28]. the most famous oxidants were the hydroxyl radicals $\text{OH}^\bullet$ which considered the most effective one due to its high oxidation potential and non-selectivity toward a wide range of organic compounds, the generation of $\text{OH}^\bullet$ occurs through water discharge at the anode according to the following reaction Eq. 1:



2.2. Electrocoagulation process

In its simplest description electrocoagulation (EC) is an electrochemical process used for water treatment that uses sacrificial electrode metal like aluminum or iron to generate coagulants Eq. 2 and 3 [29], which is a phenomenon where charged particles in colloidal suspension agglomerate after being neutralized by mutual

collisions with counterions and followed by sedimentation [30]. Throw the process, metal ions released from the anode and react with hydroxide ions to form metal hydroxides, which destabilize and aggregate contaminants into removable floc. This method eliminates metals, colloidal solids and particles, dyes, and soluble inorganic contaminants from aqueous media. Compared with conventional chemical coagulation, it offers lower chemical consumption, reduced sludge production, and simpler operation [31, 32]. Fig. 1 shows the electrocoagulation mechanism.

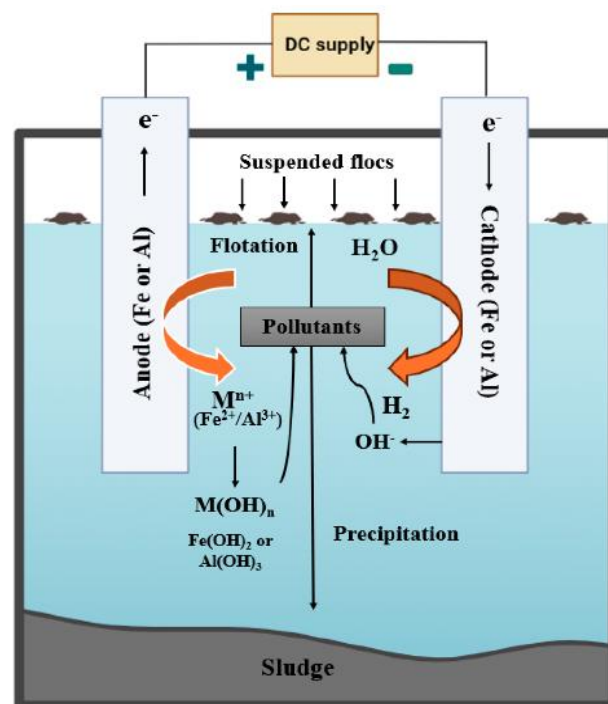


Fig. 1. EC treatment process from Ref. [33] under Creative Common CC BY license

2.3. Electro-Fenton process

The most important process was the electro-Fenton (EF) process is an advanced electrochemical oxidation technology were widely used for wastewater treatment which could removing different type of contaminate such as refractory organic pollutants, dyes, pharmaceuticals, pesticides, and industrial pollutant [34]. It is based on the in situ electrochemical generation of hydrogen peroxide (H_2O_2) and the catalytic production of hydroxyl radicals ($\text{OH}^\bullet$), which are highly reactive oxidizing species destroyed mineralizing organic pollutants into carbon dioxide, water, and inorganic ions [35] Fig. 2 represent the process mechanism. In the (EF) process, oxygen is reduced at the cathode to produce hydrogen peroxide according to the following reaction Eq. 4 [36]:



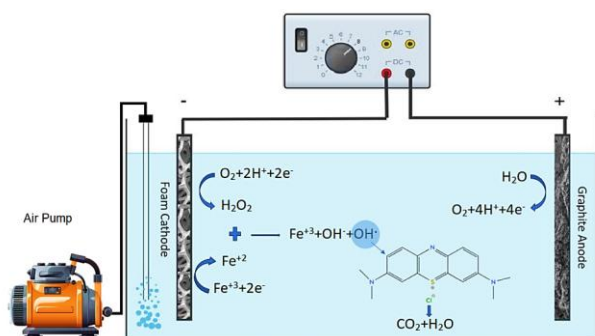
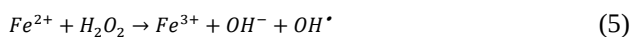


Fig. 2. Electro-Fenton process mechanism (created by the author)

The Ferrous ions (Fe^{2+}) can be added to the reactor directly in a suitable amount required to the reaction with (H_2O_2) or generated in electrochemical reaction to form hydroxyl radicals ($\text{OH}^\bullet$) by classical Fenton reaction Eq. 5 [37]:



The ferric ions (Fe^{3+}) during the reaction can be generated and continuously reduced back to (Fe^{2+}) at the cathode Eq. 6 [38]:



The EF offers many advantages by including high oxidation efficiency so it have the ability to remove a wide range of contaminant from wastewater also considered a friendly process when compared with conventional Fenton oxidation, and low energy consumption [39-41]. Although the high performance of electro Fenton process, there are several negative impacts the acidic pH range (2-4) and sludge generation at higher pH levels. Furthermore, the generation of iron sludge in

the reactor increases sludge handling and disposal costs as well as the energy consumption under high current densities also remains a significant economic concern [42, 43].

3- Foam electrodes materials in electrochemical systems

3.1. Metal foam electrodes

3.1.1. Nickel foam

Nickel foam electrode is one of the most important three-dimensional electrodes used in electrochemical wastewater treatment due to unique skeleton structure which provide large surface area for reaction and high electrical conductivity as well as excellent mechanical stability nickel metals have a strong corrosion resistance [44]. The porous structure of nickel foam allows efficient transport of electrolytes and reactants, providing a large of electroactive sites compared to conventional non porous electrodes. These characteristics enhance electron transfer and improve the overall efficiency of electrochemical reaction [45]. Fig. 3 shows the nickel foam electrode.

In electrochemical processes nickel foam can role as either an anode or a cathode depending on the process application. It is employed in wide range of electrochemical process such as electrochemical oxidation, electrocoagulation, and electro-Fenton systems, and electrochemical sensors. During electrochemical oxidation, the large surface area of nickel foam enhances the generation of reactive oxygen species such as hydroxyl radicals ($\bullet\text{OH}$), which are capable of degrading organic pollutants in wastewater [46, 47]. Table 1 summarize the nickel foam electrode recently.

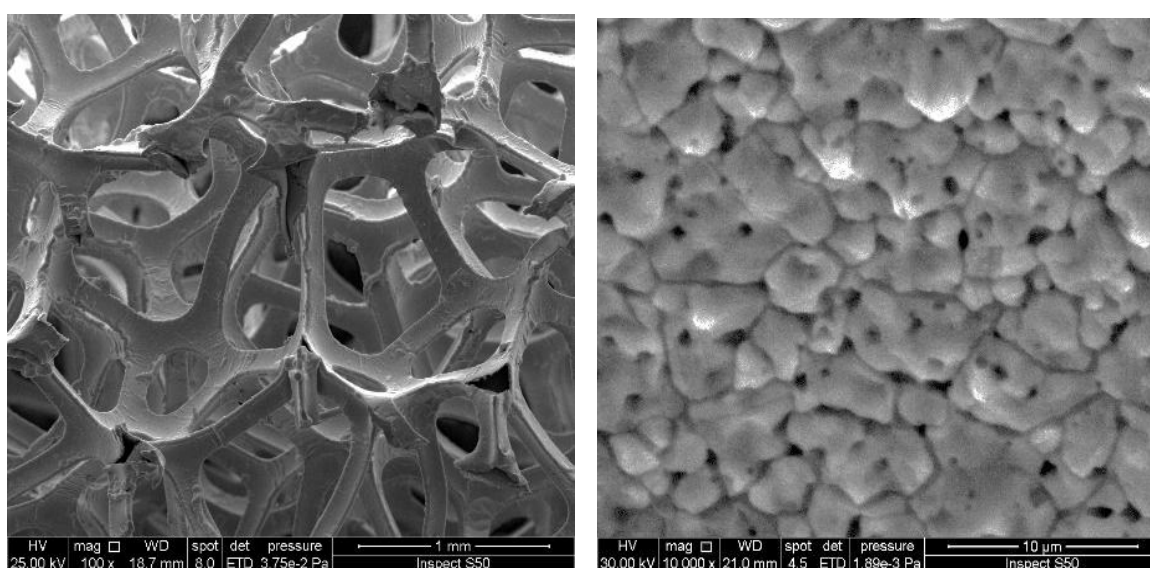


Fig. 3. Nickel foam cathode (1 mm and 10 μm) [51]

Table 1. Nickel foam electrode in electrochemical process

pollutant	Electrochemical process	Electrode	Removal efficiency%	year	Reference
Poly R-478	electro- Fenton	Nickel Foam Cathode	complete elimination	2016	[48]
phenol	electro- Fenton	composite nickel-iron-foam (Ni-Fe-F) electrode	100%	2018	[49]
rhodamine B (RhB)	electro- Fenton	three-dimensional nickel foam	92.5%	2020	[16]
phenol	electro- Fenton	Nickel Foam Cathode	100%	2020	[50]
phenol	electro- Fenton	Nickel Foam Cathode	81.335%	2023	[51]
Methylene blue (MB)	electro-Fenton process with anodic oxidation	Coated Nickel Foam Cathode	94.1 %	2023	[52]
bisphenol A (BPA)	Heterogeneous electro-Fenton	Nickel Foam Cathode	95.52%	2023	[53]
Ciprofloxacin	Heterogeneous electro-Fenton	Loaded Nickel Foam Cathode	95.11 %	2024	[54]
industrial wastewater	Microbial Electrolysis cell	Nickel Foam Cathode	COD 40%	2024	[55]

3.1.2. Copper foam

Copper foam electrode similar to nickel foam in structure both have a three-dimensional porous electrode material that has attracted considerable attention in electrochemical processes recently because of its high electrical conductivity, and low cost as well as excellent electron transfer properties [56]. The wide porous structure of copper foam provides many active sites and efficient mass transport of reactants and products this enhanced electrochemical performance compared with conventional planar copper electrodes.

In electrochemical wastewater treatment copper foam can work as an electrode and a catalyst support because of its porous structure which promotes the generation of reactive oxygen species and improves the contact between the pollutants and the foam electrode surface this led to increase degradation efficiency. same as nickel foam copper foam has been widely used in electro-Fenton and electrochemical oxidation. Furthermore, the surface can be modified with different metal oxides or other catalytic coatings to improve catalytic activity, and stability Table 2 summarize the copper foam electrode in electrochemical process and Fig. 4 shows the copper foam electrode in different PPI (porous per inch).

3.1.3. Iron foam

The researches previously employed 3D iron foam as a catalyst in the EF Fig. 5, demonstrating that it could consistently supply iron ions for EF [63]. A large effective contact area and a large number of micro-electrolysis cells are provided by the overall 3D electrode, and the electrochemical reaction occurs on the surface of each particle electrode. However, there are two advantages to employing iron foam. Iron foam fuels the reaction with Fe^{2+} , which combines with H_2O_2 to produce $\text{OH}^\bullet$, which oxidizes organic contaminant, and acts as a three-dimensional particle to provide active sites and boost reaction efficiency [18]. iron foam electrodes show high advantages over traditional powder catalysts in terms of streamlining electrode preparation procedures by lowering interfacial resistance and, increasing active site exposure, and boosting structural stability [64]. As well as iron offers mechanistic insights into catalyst corrosion and is in charge of the high selectivity and higher current densities [65, 66]. Table 3 summarize the iron foam electrode in electrochemical process.

Table 2. Copper foam electrode in electrochemical process

pollutant	Electrochemical process	Electrode	Removal efficiency%	year	Reference
methyl orange (MO)	electro- Fenton	copper Foam Cathode	98%	2025	[17]
antibiotic sulfamethoxazole (SMX)	electro- Fenton	$\text{Cu}_2\text{O}/\text{CNTs}/\text{CF}$ composites electrode	100%	2021	[57]
methyl orange	heterogeneous Fenton's reaction	Fe^0 electrodeposited onto Cu foam	full decolorization	2022	[56]
methyl orange	(3D) Three-Dimensional Electro-Fenton process	copper Foam Cathode	95.62%	2024	[58]
Norfloxacin	heterogeneous electro-Fenton	$\text{Cu}-\text{N}-\text{C}$ on Copper foam	97.36 %	2025	[59]
Landfill Leachate	heterogeneous electro-Fenton (EF)	Cu-coated Ni-foam cathode	72.74 % COD and 65.31 % TOC	2025	[60]
Copper ions industrial effluent	Electrochemical process	copper Foam Cathode	98%	1999	[61]

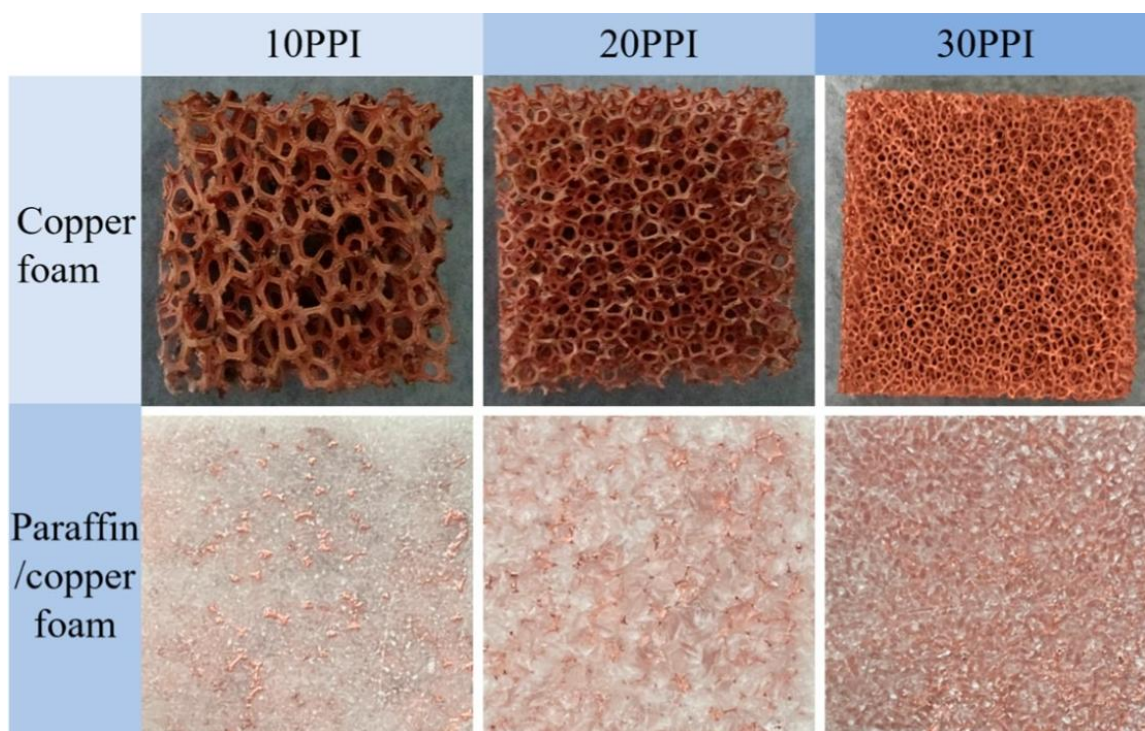


Fig. 4. Copper foam from ref.[62] under creative common CC BY license

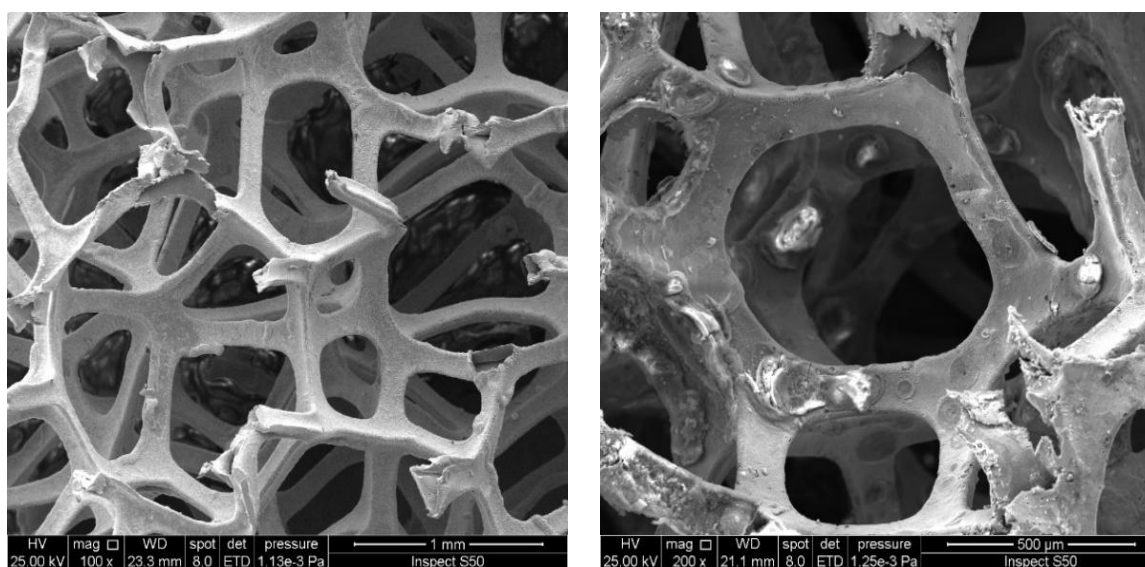


Fig. 5. Scanning electron microscope (SEM) images of iron foam structures [18] under a Creative Commons Attribution 4.0 International License

Table 3. Iron foam electrode in electrochemical process

pollutant	Electrochemical process	Electrode	Removal efficiency%	year	Reference
pharmaceutical wastewater	Heterogenous electro-Fenton	iron foam-derived electrode ($\text{FeO}_x/\text{if-400}$)	100%	2024	[67]
folic acid (FA)	electro-Fenton (EF)	three-dimensional (3D) iron foam was used as the particle electrode	COD and TN removal percentage of FA wastewater reached 43.5% and 70.4%	2019	[63]
Tripolyphosphate (TPP)	electro-Fenton (EF)	iron-foam catalyst	88.69%	2018	[68]
phenol	3D electro-Fenton technique	three-dimensional (3D) iron foam was used as the particle electrode	phenol removal of 92.58 % and (COD) of 89.33 %	2023	[18]

3.1.4. Aluminum foam

Aluminum foam electrode was a lightweight 3D dimensional porous electrode material with high electrical conductivity, and a large surface area. These unique mechanical and physical characteristics for these electrodes were usually used in electrocoagulation (EC) process in wastewater treatment applications where the dissolution of aluminum produces coagulant species in situ making it easier to remove suspended particles, colloids, organic matter, and heavy metals from water. During electrocoagulation process aluminum foam electrode was oxidized at the anode to release Al^{3+} ions,

which then hydrolyze to form aluminum hydroxide flocs. These flocs effectively adsorb and contaminants and increase their aggregation and easy to remove [69].

Compared with other conventional aluminum plates electrodes aluminum foam electrodes offer improved mass transport and increasing active surface area also enhanced treatment efficiency. Recent studies Table 4 have shown that aluminum foam used in electrocoagulation process can achieve high removal efficiencies for chemical oxygen demand (COD) and improve the removal of turbidity as well as organic matter also the researches show low chemical consumption [70].

Table 4. Aluminum foam electrode in electrochemical process

pollutant	Electrochemical process	Electrode	Removal efficiency%	year	Reference
Greywater samples collected from domestic sources	electrocoagulation (EC).	Aluminum foam	86.34%	2025	[71]
Synthetic groundwater solution	electrocoagulation (EC).	Aluminum foam	High removal efficiency	2022	[72]
Ground water treatment	electrocoagulation (EC).	aluminum (Al)-based electrocoagulation (EC)	85.1%	2025	[73]
Synthetic groundwater solution	electrocoagulation (EC).	sacrificial aluminum electrode	silicate removal of up to $50 \pm 4\%$, and hardness removal of $11 \pm 1\%$	2024	[74]
municipal wastewater	electrocoagulation (EC).	sacrificial aluminum, iron, and magnesium electrodes	Max. COD removal $Al = 68 \pm 9\%$; $(Fe-Fe = 60 \pm 30\%)$; and $Mg-Mg = 27 \pm 3\%$.	2019	[75]

3.2. Carbon based foam electrodes

3.2.1. Reticulated vitreous carbon (RVC)

Reticulated vitreous carbon (RVC) foam electrodes are the most popular and widely investigated carbon foam electrodes in electrochemical wastewater treatment processes [76]. Its three-dimensional porous skeleton structure provides a large specific surface area, and excellent electrical conductivity also its chemical stability enables it to facilitate the mass-transfer [77]. RVC foam has been successfully applied as an anode and cathode electrodes as well as work as a membrane in electro-Fenton and electrochemical oxidation processes due to its properties. The removal of organic pollutants and heavy metals from water used RVC as more efficient electrodes than carbon electrodes. Recent studies showed that modified RVC foam electrodes offered superior electrocatalytic activity in the generation of hydrogen peroxide compared with the conventional carbon electrodes [78]. Table 5 shows the commonly used of RVC in electrochemical system.

3.2.2. Graphene foam electrodes

Graphene foam has been widely used as a cathode or catalyst support in many electrochemical processes including electro-Fenton and electrochemical oxidation. The three-dimensional porous structure of graphene foam

allows for efficient generation of reactive oxygen species such as hydrogen peroxide H_2O_2 and hydroxyl radicals $OH^\bullet$. The presence of reactive oxygen species enhances the degradation of dyes, and other contaminants in waste water treatment [84]. The GF morphology also results in a decrease in mechanical strength the manufactured electrodes need extra metal support for the current collectors in a supercapacitor configuration due to this mechanical weakness [85]. Furthermore, graphene foam has the capability of being modified with metal nanoparticles, and metal oxides to increase its catalytic activity and overall electrochemical performance in comparing with flat sheet electrodes [86]. Table 6 shows the graphene foam and graphene foam-based electrodes.

3.2.3. Carbon foam electrodes

Because of their light weight and strong electrical and thermal conductivities carbon foams can be useful containers for active materials in a variety of applications [89]. The exceptional physicochemical features such as high porosity near to (97–99%) as well as strong structural integrity carbon foam (CF) is a versatile carbon material that may be used as a porous electrode or as a 3D current collector [90]. Also low density, and excellent thermal and electrical conductivity was a great attention in electrochemical process. For the gas separation and water purification carbon foam used as catalyst support electrodes of electrochemical double layer capacitors and

fuel cells, porous carbon structures have drawn a lot of attention [91]. Studies addressing the use of carbon foam as electrodes in oxidation processes are very limited, as it is often replaced by RVC foam. However, carbon foam has found in other than electrochemical fields such as capacitive deionization, and fuel cells. Table 7. Show the recent carbon foam used.

To provide more comprehensive comparison, Table 8 summarizes the main advantages, and disadvantage of the different foam electrode.

The important and efficiency of foam electrodes in the electrochemical treatment of wastewater are summarized in Fig. 6. And were assessed in this review. These electrode improvements have advanced significantly over the last ten years, 3D electrodes, a fundamental aspect technology, improve pollution removal and electro catalytic oxidation efficiency.

Table 5. Reticulated vitreous carbon (RVC) foam electrode in electrochemical process

pollutant	Electrochemical process	Electrode	Removal efficiency%	year	Reference
Blue Basic 9 (BB9), Reactive Black 5 (RB5) and Acid Orange 7 (AO7)	electro-Fenton (EF)	(RVC) foam electrode	90%	2015	[79]
Acid Orange 7	electro-Fenton (EF)	(RVC) foam electrode cathode	100%	2018	[80]
methylene blue	electro-Fenton (EF)	RVC electrode coated with magnetic iron oxide nanoparticles	100%	2022	[81]
Cr(VI)	microbial fuel cell	RVC-CNT electrode	80.9%	2017	[82]
Cd ²⁺ Ion	Electrodeposition	(RVC) electrode	99%	2002	[83]

Table 6. Summarized graphene foam and graphene foam-based electrodes

pollutant	Electrochemical process	Electrode	Removal efficiency%	year	Reference
phenol	electro-Fenton (EF)	Graphene foam as a cathode material	(78% after 3 h)	2016	[87]
Pharmaceutical wastewater (ibuprofen)	electro-peroxone process	graphene-coated nickel foam (Gr-NF)	75.0% TOC mineralization within 8 h, 85.9% of decolorization, 78% TSS, 85% turbidity	2022	[88]

Table 7. Summarized carbon foam electrodes

pollutant	Electrochemical process	Electrode	Removal efficiency%	year	Reference
Salt removal (NaCl)	Capacitive Deionization (CDI)	Free-standing porous carbon foam	99.8%	2026	[92]
Paracetamol, Triclosan, Bisphenol, Diclofenac	Three-dimensional Electrochemical Oxidation	Ceramic Carbon Foam Anode	High removal	2025	[93]

Table 8. Summarized advantage and disadvantage of foam electrode

Foam Electrode	Advantages	Disadvantage
Nickel Foam	High electrical conductivity and excellent H ₂ O ₂ generation	High cost
Iron Foam	In-situ Fe ²⁺ ion release	Corrosion prone and sludge formation
Copper Foam	Excellent Conductivity	Copper ion leaching and limited stability
Aluminum Foam	Efficient Al ³⁺ coagulant generation	The Al consumption
Carbon Foam	Light weight and good conductivity	Low catalytic activity without modification for wastewater treatment
Graphene Foam	High surface area than other foams	High cost
RVC Foam	Excellent chemical stability and have low flow resistance	Very high cost



Fig. 6. Summarized the important and efficiency of foam electrodes in the electrochemical treatment for wastewater synthesized from the findings of the reviewed literature (2015–2025) (created by the author)

4- Conclusion

The foam electrodes considered as a new generation of electrodes having a 3D porous skeleton structure used in electrochemical wastewater treatment owing unique characterization made it the preferred electrodes than a plate conventional one, due to high electrical conductivity and large specific surface area to increase mass transfer reaction also foam electrodes provide a significant number of electroactive sites for efficient charge transport all these properties enhanced the degradation of a wide range of pollutants.

Metallic foam electrodes such as nickel foam has demonstrated special performance in electro-Fenton and heterogeneous electro-Fenton processes due to their excellent conductivity and resistance, to corrosion. Iron foam shows notable effectiveness in electro-Fenton and electrocoagulation processes through the continuous release of Fe^{2+} ions in bulk solution and high catalytic activity. Aluminum foam is especially suitable for electrocoagulation because of its efficient production of

aluminum hydroxide flocs used for contaminant removal. Copper foam has also superior attention as an electrocatalytic substrate because of its high conductivity. Carbon-based foam electrodes such as reticulated vitreous carbon (RVC) and carbon foam as well as and graphene foam provide high chemical stability and corrosion resistance.

Although the considerable proceed achieved during the past decade due to increases using foam electrodes in waste water treatment several challenges remain before foam electrodes. These challenges include electrodes long-term structural stability due to severe condition in the bulk solution such pH value in electro-Fenton which was approximately 3 also leaching, electrode fouling, and the lack of studies used real wastewater conditions. So, it was very important to focus on developing environmentally friendly foam materials, and designing multifunctional composite foam electrodes such alloy foam electrodes and integrating electrochemical technologies with renewable energy systems.

References

- [1] M. Y. D. Alazaiza, T. M. Alzghoul, M. B. Ramu, S. S. A. Amr, M. F. M. Abushammala, and D. E. Nassani, "Global perspectives on industrial wastewater management: A bibliometric analysis of research output," *Journal of Hazardous Materials Advances*, vol. 17, no. November 2024, 2025, <https://doi.org/10.1016/j.hazadv.2024.100567>
- [2] R. Davarnejad and A. Sahraei, "Industrial wastewater treatment using an electrochemical technique: an optimized process," *Desalination and Water Treatment*, vol. 57, no. 21, pp. 9622–9634, May 2016, <https://doi.org/10.1080/19443994.2015.1030776>
- [3] A. A. Hambisa, M. B. Regasa, H. G. Ejigu, and C. B. Senbeto, "Adsorption studies of methyl orange dye removal from aqueous solution using Anchote peel-based agricultural waste adsorbent," *Applied Water Science*, vol. 13, no. 1, pp. 1–11, 2023, <https://doi.org/10.1007/s13201-022-01832-y>
- [4] S. S. Abu Amr, M. S. S. Abujazar, M. Y. D. Alazaiza, A. Albahnasawi, and F. Omer, "Heavy metals removal from industrial wastewater using date seeds powder and aluminum chloride-based hybrid natural/chemical coagulation," *Desalination and Water Treatment*, vol. 318, no. May, p. 100392, 2024, <https://doi.org/10.1016/j.dwt.2024.100392>
- [5] R. Al-Tohamy *et al.*, "A critical review on the treatment of dye-containing wastewater: Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety," *Ecotoxicology and Environmental Safety*, vol. 231, p. 113160, 2022, <https://doi.org/10.1016/j.ecoenv.2021.113160>
- [6] F. Ghanbari *et al.*, "Insights into paracetamol degradation in aqueous solutions by ultrasound-assisted heterogeneous electro-Fenton process: Key operating parameters, mineralization and toxicity assessment," *Separation and Purification Technology*, vol. 266, Jul. 2021, <https://doi.org/10.1016/j.seppur.2021.118533>
- [7] Ejike David Ugwuanyi, Zamathula Queen Sikhakhane Nwokediegwu, Michael Ayorinde Dada, Michael Tega Majemite, and Alexander Obaighbena, "Review of emerging technologies for nutrient removal in wastewater treatment," *World Journal of Advanced Research and Reviews*, vol. 21, no. 2, pp. 1737–1749, 2024, <https://doi.org/10.30574/wjarr.2024.21.2.0520>
- [8] Kusumlata, B. Ambade, A. Kumar, and S. Gautam, "Sustainable Solutions: Reviewing the Future of Textile Dye Contaminant Removal with Emerging Biological Treatments," *Limnological Review*, vol. 24, no. 2, pp. 126–149, 2024, <https://doi.org/10.3390/limnolrev24020007>
- [9] A. I. Adeogun, P. B. Bhagawati, and C. B. Shivayogimath, "Pollutants removals and energy consumption in electrochemical cell for pulping processes wastewater treatment: Artificial neural network, response surface methodology and kinetic studies," *Journal of Environmental Management*, vol. 281, Mar. 2021, <https://doi.org/10.1016/j.jenvman.2020.111897>
- [10] A. Majed and A. H. Abbar, "A Review on Induced Electro-Fenton Process for Wastewater Treatment," *IOP Conference Series: Earth and Environmental Science*, vol. 1507, no. 1, 2025, <https://doi.org/10.1088/1755-1315/1507/1/012045>
- [11] N. R. Neti and R. Misra, "Efficient degradation of Reactive Blue 4 in carbon bed electrochemical reactor," *Chemical Engineering Journal*, vol. 184, pp. 23–32, Mar. 2012, <https://doi.org/10.1016/j.cej.2011.12.014>
- [12] R. H. Salman, E. M. Khudhair, K. M. Abed, and A. S. Abbas, "Removal of E133 brilliant blue dye from artificial wastewater by electrocoagulation using cans waste as electrodes," *Environmental Progress and Sustainable Energy*, vol. 43, no. 2, 2024, <https://doi.org/10.1002/ep.14292>
- [13] H. H. Thwaini and R. H. Salman, "Modification of Electro-Fenton Process with Granular Activated Carbon for Phenol Degradation – Optimization by Response Surface Methodology," *Journal of Ecological Engineering*, vol. 24, no. 9, pp. 92–104, 2023, <https://doi.org/10.12911/22998993/168411>
- [14] Y. Zhang *et al.*, "Three-dimensional heterogeneous Electro-Fenton system with a novel catalytic particle electrode for Bisphenol A removal," *Journal of Hazardous Materials*, vol. 393, Jul. 2020, <https://doi.org/10.1016/j.jhazmat.2019.03.067>
- [15] Z. M. Hameed and R. H. Salman, "Elimination of Methyl Orange Dye with Three Dimensional Electro-Fenton and Sono-Electro-Fenton Systems Utilizing Copper Foam and Activated Carbon," *Ecological Engineering & Environmental Technology*, vol. 25, no. 10, pp. 44–59, 2024, <https://doi.org/10.12912/27197050/191199>
- [16] Y. Zhu, S. Qiu, F. Deng, F. Ma, G. Li, and Y. Zheng, "Three-dimensional nickel foam electrode for efficient electro-Fenton in a novel reactor," *Environmental Technology (United Kingdom)*, vol. 41, no. 6, pp. 730–740, Mar. 2020, <https://doi.org/10.1080/09593330.2018.1509890>
- [17] Z. M. Hameed and R. H. Salman, "Optimizing Methyl Orange Degradation via Electro-Fenton with Copper Foam Cathode: A Comparative Approach Using Iron Waste vs. Iron Salts and Exploring Catalyst and Cathode Durability," *Applied Science and Engineering Progress*, May 2025, <https://doi.org/10.14416/j.asep.2025.05.002>

- [18] H. H. Thwaini and R. H. Salman, "Phenol removal by electro-Fenton process using a 3D electrode with iron foam as particles and carbon fibre modified with graphene," *Journal of Electrochemical Science and Engineering*, vol. 13, no. 3, pp. 537–551, 2023, <https://doi.org/10.5599/jese.1806>
- [19] Y. Maribel Allcca Castillo *et al.*, "Benchmarking three-dimensional metal foam electrodes for the electrochemical reduction of nitrate," *Journal of Electroanalytical Chemistry*, vol. 968, no. June, 2024, <https://doi.org/10.1016/j.jelechem.2024.118499>
- [20] R. Saini, D. K. Rajak, T. Joshi, D. K. Singh, V. A. N. Chilla, and S. Sathaiah, "Critical review of ultra-lightweight foam materials," *Next Nanotechnology*, vol. 7, no. January, 2025, <https://doi.org/10.1016/j.nxnano.2025.100138>
- [21] M. Tripathi *et al.*, "Recent Strategies for the Remediation of Textile Dyes from Wastewater: A Systematic Review," *Toxics*, vol. 11, no. 11, 2023, <https://doi.org/10.3390/toxics11110940>
- [22] W. Yang, M. Zhou, N. Oturan, Y. Li, and M. A. Oturan, "Electrocatalytic destruction of pharmaceutical imatinib by electro-Fenton process with graphene-based cathode," *Electrochimica Acta*, vol. 305, pp. 285–294, May 2019, <https://doi.org/10.1016/j.electacta.2019.03.067>
- [23] M. W. Khalid and S. D. Salman, "Adsorption of Heavy Metals from Aqueous Solution onto Sawdust Activated Carbon," *Al-Khwarizmi Engineering Journal*, vol. 15, no. 3, pp. 60–69, 2019, <https://doi.org/10.22153/kej.2019.04.001>
- [24] N. T. Hoang, "Application of 3D electrodes in various electrocatalytic systems for the degradation of organic pollutants in the last 5 years (2019 – 2024)," *Chemical Engineering Journal*, vol. 515, p. 163676, 2025, <https://doi.org/10.1016/j.cej.2025.163676>
- [25] A. Martínez-Huitle and M. Panizza, "Electrochemical oxidation of organic pollutants for wastewater treatment," *Current Opinion in Electrochemistry*, Oct. 01, 2018, Elsevier B.V. <https://doi.org/10.1016/j.coelec.2018.07.010>
- [26] N. H. Jawad and S. T. Najim, "Removal of Methylene Blue by Direct Electrochemical Oxidation Method Using a Graphite Anode," *IOP Conference Series: Materials Science and Engineering*, vol. 454, no. 1, 2018, <https://doi.org/10.1088/1757-899X/454/1/012023>
- [27] L. Ma *et al.*, "Indirect electrochemical oxidation of pentachlorophenol in the presence of different halides: Behavior and mechanism," *Desalination and Water Treatment*, vol. 52, no. 7–9, pp. 1462–1471, 2014, <https://doi.org/10.1080/19443994.2013.785369>
- [28] M. S. Najafinejad, S. Chianese, A. Fenti, P. Iovino, and D. Musmarra, "Application of Electrochemical Oxidation for Water and Wastewater Treatment: An Overview," *Molecules*, vol. 28, no. 10, pp. 1–24, 2023, <https://doi.org/10.3390/molecules28104208>
- [29] A. M. Zafar, A. Naeem, M. A. Minhas, M. J. Hasan, S. Rafique, and A. Ikhlaiq, "Removal of reactive dyes from textile industrial effluent using electrocoagulation in different parametric conditions of aluminum electrodes," *Total Environment Advances*, vol. 9, no. December, p. 200087, 2024, <https://doi.org/10.1016/j.teadva.2023.200087>
- [30] P. B. Bhagawati *et al.*, "Electrocoagulation Technology for Wastewater Treatment: Mechanism and Applications," no. July, pp. 305–318, 2022, https://doi.org/10.1007/978-981-19-0987-0_13
- [31] Y. Xia, H. Shang, Q. Zhang, Y. Zhou, and X. Hu, "Electrogeneration of hydrogen peroxide using phosphorus-doped carbon nanotubes gas diffusion electrodes and its application in electro-Fenton," *Journal of Electroanalytical Chemistry*, vol. 840, pp. 400–408, May 2019, <https://doi.org/10.1016/j.jelechem.2019.04.009>
- [32] S. Sadaf *et al.*, "Electrocoagulation-based wastewater treatment process and significance of anode materials for the overall improvement of the process: A critical review," *Journal of Water Process Engineering*, vol. 62, p. 105409, 2024, <https://doi.org/10.1016/j.jwpe.2024.105409>
- [33] S. Jo, R. Kadam, H. Jang, D. Seo, and J. Park, "Recent Advances in Wastewater Electrocoagulation Technologies: Beyond Chemical Coagulation," *Energies*, vol. 17, no. 23, 2024, <https://doi.org/10.3390/en17235863>
- [34] T. Luo *et al.*, "Efficient degradation of tetracycline by heterogeneous electro-Fenton process using Cu-doped Fe@Fe₂O₃: Mechanism and degradation pathway," *Chemical Engineering Journal*, vol. 382, p. 122970, Feb. 2020, <https://doi.org/10.1016/J.CEJ.2019.122970>
- [35] A. Wang, J. Qu, J. Ru, H. Liu, and J. Ge, "Mineralization of an azo dye Acid Red 14 by electro-Fenton's reagent using an activated carbon fiber cathode," *Dyes and Pigments*, vol. 65, no. 3, pp. 227–233, Jun. 2005, <https://doi.org/10.1016/j.dyepig.2004.07.019>
- [36] Sirés and E. Brillas, "Upgrading and expanding the electro-Fenton and related processes," *Current Opinion in Electrochemistry*, Jun. 01, 2021, Elsevier B.V., <https://doi.org/10.1016/j.coelec.2020.100686>
- [37] R. Q. Al-Khafaji and A. H. A. K. Mohammed, "Optimization of Continuous Electro-Fenton and Photo electro-Fenton Processes to Treat Iraqi Oilfield Produced Water Using Surface Response Methodology," in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Jun. 2019. <http://doi.org/10.1088/1757-899X/518/6/062007>
- [38] F. Duan, Y. Li, H. Cao, Y. Wang, J. C. Crittenden, and Y. Zhang, "Activated carbon electrodes: Electrochemical oxidation coupled with desalination for wastewater treatment," *Chemosphere*, vol. 125, pp. 205–211, Apr. 2015, <https://doi.org/10.1016/j.chemosphere.2014.12.065>

- [39] Z. Zhang, H. Meng, Y. Wang, L. Shi, X. Wang, and S. Chai, "Fabrication of graphene@graphite-based gas diffusion electrode for improving H₂O₂ generation in Electro-Fenton process," *Electrochimica Acta*, vol. 260, pp. 112–120, Jan. 2018, <https://doi.org/10.1016/j.electacta.2017.11.048>
- [40] E. Marlina, "Electro-Fenton for Industrial Wastewater Treatment: A Review", *The 4th International Conference on Energy, Environment, Epidemiology and Information System (ICENIS 2019)*, vol. 125, 03003, 2019, <http://doi.org/10.1051/e3sconf/201912503003>
- [41] S. Bangia, R. Bangia, and A. Daverey, "Pharmaceutically active compounds in aqueous environment: recent developments in their fate, occurrence and elimination for efficient water purification," *Environmental Monitoring and Assessment*, vol. 195, no. 11, p. 1344, 2023, <https://doi.org/10.1007/s10661-023-11858-7>
- [42] A. Martínez-Huitle, M. A. Rodrigo, I. Sirés, and O. Scialdone, "Single and Coupled Electrochemical Processes and Reactors for the Abatement of Organic Water Pollutants: A Critical Review," *Chemical Reviews*, vol. 115, no. 24, pp. 13362–13407, 2015, <https://doi.org/10.1021/acs.chemrev.5b00361>
- [43] Brillas and C. A. Martínez-Huitle, "Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods. An updated review," *Applied Catalysis B: Environmental*, vol. 166–167, pp. 603–643, 2015, <https://doi.org/10.1016/j.apcatb.2014.11.016>
- [44] W. Liu, Z. Ai, and L. Zhang, "Design of a neutral three-dimensional electro-Fenton system with foam nickel as particle electrodes for wastewater treatment," *Journal of Hazardous Materials*, vol. 243, pp. 257–264, 2012, <https://doi.org/10.1016/j.jhazmat.2012.10.024>
- [45] Bocos, D. Pérez-Álvarez, M. Pazos, M. C. Rodríguez-Argüelles, and M. Á. Sanromán, "Coated nickel foam electrode for the implementation of continuous electro-Fenton treatment," *Journal of Chemical Technology and Biotechnology*, vol. 91, no. 3, pp. 685–692, Mar. 2016, <https://doi.org/10.1002/jctb.4626>
- [46] X. Hu, X. Tian, Y. W. Lin, and Z. Wang, "Nickel foam and stainless steel mesh as electrocatalysts for hydrogen evolution reaction, oxygen evolution reaction and overall water splitting in alkaline media," *RSC Advances*, vol. 9, no. 54, pp. 31563–31571, 2019, <https://doi.org/10.1039/c9ra07258f>
- [47] M. S. Ratsoma *et al.*, "Application of Nickel Foam in Electrochemical Systems: A Review," *Journal of Electronic Materials*, vol. 52, no. 4, pp. 2264–2291, 2023, <https://doi.org/10.1007/s11664-023-10244-w>
- [48] Bocos, O. Iglesias, M. Pazos, and M. Ángeles Sanromán, "Nickel foam a suitable alternative to increase the generation of Fenton's reagents," *Process Safety and Environmental Protection*, vol. 101, pp. 34–44, May 2016, <https://doi.org/10.1016/j.psep.2015.04.011>
- [49] Deng, H. Olvera-Vargas, O. Garcia-Rodriguez, S. Qiu, J. Yang, and O. Lefebvre, "The synergistic effect of nickel-iron-foam and tripolyphosphate for enhancing the electro-Fenton process at circum-neutral pH," *Chemosphere*, vol. 201, pp. 687–696, 2018, <https://doi.org/10.1016/j.chemosphere.2018.02.186>
- [50] F. Deng *et al.*, "Unconventional electro-Fenton process operating at a wide pH range with Ni foam cathode and tripolyphosphate electrolyte," *Journal of Hazardous Materials*, vol. 396, Sep. 2020, <https://doi.org/10.1016/j.jhazmat.2020.122641>
- [51] H. Thawini, R. H. Salman, and W. S. Abdul-Majeed, "Performance of Electro-Fenton Process for Phenol Degradation Using Nickel Foam as a Cathode," *Iraqi Journal of Chemical and Petroleum Engineering*, vol. 24, no. 3, pp. 13–25, 2023, <https://doi.org/10.31699/IJCPE.2023.3.2>
- [52] Molla Nadali Pishnamaz, H. Farimaniraad, M. Baghdadi, B. Aminzadeh Goharrizi, and S. Mahpishanian, "Application of nickel foam cathode modified by single-wall carbon nanotube in electro-Fenton process coupled with anodic oxidation: Enhancing organic pollutants removal," *Journal of Electroanalytical Chemistry*, vol. 929, p. 117130, 2023, <https://doi.org/10.1016/j.jelechem.2022.117130>
- [53] H. M. Nadali Pishnamaz, E. Ranjbar, and M. Baghdadi, "Application of iron-intercalated graphite for modification of nickel foam cathode in heterogeneous electro-Fenton system: Bisphenol A removal from water at neutral pH," *Chemosphere*, vol. 339, p. 139787, 2023, <https://doi.org/10.1016/j.chemosphere.2023.139787>
- [54] G. Zhang *et al.*, "Endogenous iron-enriched biochar loaded nickel-foam cathode in electro-Fenton for ciprofloxacin degradation: performance, mechanism and DFT calculation," *Chemical Engineering Journal*, vol. 498, p. 155446, 2024, <https://doi.org/10.1016/j.cej.2024.155446>
- [55] O. Guerrero-Sodric, J. A. Baeza, and A. Guisasaola, "Enhancing bioelectrochemical hydrogen production from industrial wastewater using Ni-foam cathodes in a microbial electrolysis cell pilot plant," *Water Research*, vol. 256, no. March, p. 121616, 2024, <https://doi.org/10.1016/j.watres.2024.121616>
- [56] M. Vainoris, A. Nicolenco, N. Tsyntaru, E. Podlaha-Murphy, F. Alcaide, and H. Cesiulis, "Electrodeposited Fe on Cu foam as advanced fenton reagent for catalytic mineralization of methyl orange," *Frontiers in Chemistry*, vol. 10, no. September, pp. 1–10, 2022, <https://doi.org/10.3389/fchem.2022.977980>
- [57] S. Mao, X. Sun, H. Qi, and Z. Sun, "Cu₂O nanoparticles anchored on 3D bifunctional CNTs/copper foam cathode for electrocatalytic degradation of sulfamethoxazole over a broad pH range," *Science of the Total Environment*, vol. 793, p. 148492, 2021, <https://doi.org/10.1016/j.scitotenv.2021.148492>

- [58] Z. M. Hameed and R. H. Salman, "Elimination of Methyl Orange Dye with Three Dimensional Electro-Fenton and Sono-Electro-Fenton Systems Utilizing Copper Foam and Activated Carbon," *Ecological Engineering and Environmental Technology*, vol. 25, no. 10, pp. 44–59, 2024, <https://doi.org/10.12912/27197050/191199>
- [59] Z. Zhang *et al.*, "Binder free Cu–N–C on copper foam electrode by in-situ growth strategy: Engineering Cu–N sites for enhanced heterogeneous electro-Fenton degradation of norfloxacin," *Separation and Purification Technology*, vol. 379, p. 134817, 2025, <https://doi.org/10.1016/j.seppur.2025.134817>
- [60] X. Lan *et al.*, "Dual-cathode synergy in heterogeneous electro-Fenton: Copper-driven H₂O₂ activation for efficient leachate nanofiltration concentrate treatment," *Journal of Water Process Engineering*, vol. 77, p. 108378, 2025, <https://doi.org/10.1016/j.jwpe.2025.108378>
- [61] M. Panizza, C. Solisio, and G. Cerisola, "Electrochemical remediation of copper (II) from an industrial effluent Part 2: tree-dimensional foam electrodes," *Resources, Conservation and Recycling*, vol. 27, pp. 299–307, 1999, [https://doi.org/10.1016/S0921-3449\(99\)00002-6](https://doi.org/10.1016/S0921-3449(99)00002-6)
- [62] S. He, J. Zhao, D. Ouyang, and M. Chen, "Leakage-Proof and High-Conductivity Composite Phase Change Material Using Low-Melting-Point-Alloy-Encapsulated Copper Foam/Paraffin for Superior Thermal Homogeneity in Lithium-Ion Battery Modules," *Materials (Basel)*, vol. 18, no. 19, 2025, <https://doi.org/10.3390/ma18194604>
- [63] Y. Zheng, S. Qiu, F. Deng, Y. Zhu, G. Li, and F. Ma, "Three-dimensional electro-Fenton system with iron foam as particle electrode for folic acid wastewater pretreatment," *Separation and Purification Technology*, vol. 224, pp. 463–474, Oct. 2019, <https://doi.org/10.1016/j.seppur.2019.05.054>
- [64] D. Li *et al.*, "Self-supported transition-metal-based electrocatalysts on iron foam for water splitting," *Chemical Engineering Journal*, vol. 516, p. 163602, 2025, <https://doi.org/10.1016/j.cej.2025.163602>
- [65] N. A. P. Syamaladevi, A. Dutta, and P. Broekmann, "Electrochemically Stabilized Iron Foam Enables Selective and Durable Nitrate-to-Ammonia Conversion at Industrial Current Densities," no. June, 2025, <https://doi.org/10.26434/chemrxiv-2025-g53rc>
- [66] R. Alavi, A. Trenggono, S. Champagne, and H. Hermawan, "Investigation on mechanical behavior of biodegradable iron foams under different compression test conditions," *Metals (Basel)*, vol. 7, no. 6, 2017, <https://doi.org/10.3390/met7060202>
- [67] Z. Xu *et al.*, "In situ generated iron oxide nanosheet on iron foam electrode for enhanced electro-Fenton performance toward pharmaceutical wastewater treatment," *Journal of Hazardous Materials*, vol. 465, p. 133193, 2024, <https://doi.org/10.1016/j.jhazmat.2023.133193>
- [68] F. Deng, O. Garcia-Rodriguez, H. Olvera-Vargas, S. Qiu, O. Lefebvre, and J. Yang, "Iron-foam as a heterogeneous catalyst in the presence of tripolyphosphate electrolyte for improving electro-Fenton oxidation capability," *Electrochimica Acta*, vol. 272, pp. 176–183, 2018, *Electrochimica Acta* 272 (2018) 176–183, <https://doi.org/10.1016/j.electacta.2018.03.160>
- [69] R. A. Jasim and R. H. Salman, "Use of Nano Co-Ni-Mn Composite and Aluminum for Removal of Artificial Anionic Dye Congo Red by Combined System," *Ecological Engineering and Environmental Technology*, vol. 25, no. 7, pp. 133–149, 2024, <https://doi.org/10.12912/27197050/188266>
- [70] S. Al-Marri, A. B. Abouedwan, M. I. Ahmad, and N. Bensalah, "Electrocoagulation using aluminum electrodes as a sustainable and economic method for the removal of kinetic hydrate inhibitor (polyvinyl pyrrolidone) from produced wastewaters," *Frontiers in Water*, vol. 5, 2023, <http://doi.org/10.3389/frwa.2023.1305347>
- [71] B. Yazıcı Karabulut, "Electrochemical Coagulant Generation via Aluminum-Based Electrocoagulation for Sustainable Greywater Treatment and Reuse: Optimization Through Response Surface Methodology and Kinetic Modelling," *Molecules*, vol. 30, no. 18, pp. 1–19, 2025, <https://doi.org/10.3390/molecules30183779>
- [72] G. G. Jang *et al.*, "Neutron tomography of porous aluminum electrodes used in electrocoagulation of groundwater," *Frontiers in Chemical Engineering*, vol. 4, no. November, pp. 1–11, 2022, <https://doi.org/10.3389/fceng.2022.1046627>
- [73] G. G. Jang *et al.*, "Understanding the Dissolution and Passivation of an Aluminum Electrode during Electrocoagulation of Groundwater Using Neutron and X-ray Reflectometry," *ACS Applied Materials and Interfaces*, vol. 17, no. 17, pp. 25996–26012, 2025, <https://doi.org/10.1021/acsaami.5c02215>
- [74] C. M. Khor *et al.*, "Physical and Electrochemical Characterization of Aluminum Electrodes during Electrocoagulation," *ACS ES and T Water*, vol. 4, no. 1, pp. 44–56, 2024, <https://doi.org/10.1021/acsestwater.3c00263>
- [75] T. R. Devlin, M. S. Kowalski, E. Pagaduan, X. Zhang, V. Wei, and J. A. Oleszkiewicz, "Electrocoagulation of wastewater using aluminum, iron, and magnesium electrodes," *Journal of Hazardous Materials*, pp. 862–868, 2019, <https://doi.org/10.1016/j.jhazmat.2018.10.017>
- [76] W. Zhou *et al.*, "Green electrochemical modification of RVC foam electrode and improved H₂O₂ electrogeneration by applying pulsed current for pollutant removal," *Environmental Science and Pollution Research*, vol. 25, no. 6, pp. 6015–6025, 2018, <https://doi.org/10.1007/s11356-017-0810-8>

- [77] F. C. Walsh, L. F. Arenas, C. Ponce de León, G. W. Reade, I. Whyte, and B. G. Mellor, "The continued development of reticulated vitreous carbon as a versatile electrode material: Structure, properties and applications," *Electrochimica Acta*, vol. 215, pp. 566–591, 2016, <https://doi.org/10.1016/j.electacta.2016.08.103>
- [78] A. Dell'Era, C. Lupi, E. Ciro, F. A. Scaramuzzo, and M. Pasquali, "Divalent Metal Ion Depletion from Wastewater by RVC Cathodes: A Critical Review," *Materials (Basel)*, vol. 17, no. 2, 2024, <https://doi.org/10.3390/ma17020464>
- [79] Y. A. Bustos, J. G. Rangel-Peraza, M. N. Rojas-Valencia, E. R. Bandala, A. Álvarez-Gallegos, and L. Vargas-Estrada, "Treatment of industrial effluents by electrochemical generation of H₂O₂ using an RVC cathode in a parallel plate reactor," *Environmental Technology (United Kingdom)*, vol. 37, no. 7, pp. 815–827, 2016, <https://doi.org/10.1080/09593330.2015.1086820>
- [80] B. Ramírez-Pereda, A. Álvarez-Gallegos, J. G. Rangel-Peraza, and Y. A. Bustos-Terrones, "Kinetics of Acid Orange 7 oxidation by using carbon fiber and reticulated vitreous carbon in an electro-Fenton process," *Journal of Environmental Management*, vol. 213, pp. 279–287, 2018, <https://doi.org/10.1016/j.jenvman.2018.01.022>
- [81] F. L. Rivera, N. Menendez, E. Mazarío, and P. Herrasti, "Electrofenton with Reticular Vitreous Carbon and Iron Oxide Nanoparticles for Dye Removal: A Preliminary Study," *Applied Sciences (Switzerland)*, vol. 12, no. 16, 2022, <https://doi.org/10.3390/app12168293>
- [82] Fei, T. S. Song, H. Wang, D. Zhang, R. Tao, and J. Xie, "Electrophoretic deposition of carbon nanotube on reticulated vitreous carbon for hexavalent chromium removal in a biocathode microbial fuel cell," *Royal Society Open Science*, vol. 4, no. 10, 2017, <https://doi.org/10.1098/rsos.170798>
- [83] Tramontina, D. S. Azambuja, and C. M. S. Piatnicki, "Removal of Cd²⁺ ion from diluted aqueous solutions by electrodeposition on reticulated vitreous carbon electrodes," *Journal of the Brazilian Chemical Society*, vol. 13, no. 4, pp. 469–473, 2002, <https://doi.org/10.1590/S0103-50532002000400010>
- [84] Tian Yu and Carmel B. Breslin and E. Process, "Graphene-Modified Composites and Electrodes and," *Materials (Basel)*, vol. 13, no. 1, p. 2254, 2020. <https://doi.org/10.3390/ma13102254>
- [85] Lu Zhang, Derek DeArmond, Noe T. Alvarez, Daoli Zhao, Tingting Wang, Guangfeng Hou, Rachit Malik, William R. Heineman, Vesselin Shanov; "Beyond graphene foam, a new form of three-dimensional graphene for supercapacitor electrodes". *Journal of Materials Chemistry A*, 2016; 4 (5): 1876–1886. <https://doi.org/10.1039/c5ta10031c>
- [86] Lee, J. Lee, K. W. Kwon, M. S. Park, J. H. Hwang, and K. J. Kim, "3D Graphene-Ni Foam as an Advanced Electrode for High-Performance Nonaqueous Redox Flow Batteries," *ACS Applied Materials and Interfaces*, vol. 9, no. 27, pp. 22502–22508, 2017, <https://doi.org/10.1021/acsami.7b04777>
- [87] E. Mousset, Z. Wang, J. Hammaker, and O. Lefebvre, "Physico-chemical properties of pristine graphene and its performance as electrode material for electro-Fenton treatment of wastewater," *Electrochimica Acta*, vol. 214, pp. 217–230, 2016, <https://doi.org/10.1016/j.electacta.2016.08.002>
- [88] R. Srinivasan and I. M. Nambi, "An electro-peroxone-based multi-pronged strategy for the treatment of ibuprofen and an emerging pharmaceutical wastewater using a novel graphene-coated nickel foam electrode," *Chemical Engineering Journal*, vol. 450, p. 137618, 2022, <https://doi.org/10.1016/j.cej.2022.137618>
- [89] Inagaki, J. Qiu, and Q. Guo, "Carbon foam: Preparation and application," *Carbon*, vol. 87, no. C, pp. 128–152, 2015, <https://doi.org/10.1016/j.carbon.2015.02.021>
- [90] Mourshed, R. Ahmed, M. G. Kibria, and M. R. Islam Sarker, "Carbon foam for next-generation electrochemical energy storage: advances, challenges, and outlook," *Energy Conversion and Management: X*, vol. 28, no. July, p. 101281, 2025, <https://doi.org/10.1016/j.ecmx.2025.101281>
- [91] Amini, K. F. Aguey-Zinsou, and Z. X. Guo, "Processing of strong and highly conductive carbon foams as electrode," *Carbon*, vol. 49, no. 12, pp. 3857–3864, 2011, <https://doi.org/10.1016/j.carbon.2011.05.022>
- [92] J. De, A. K. Singh, S. Saxena, and S. Shukla, "Free-Standing Porous Conductive Carbon Foam Electrode for Capacitive Deionization-Based Sustainable Water Purification," *Advanced Sustainable Systems*, vol. 10, no. 3, p. e01224, Mar. 2026, <https://doi.org/10.1002/adsu.202501224>
- [93] J. Froment *et al.*, "Transformation Product Formation and Removal Efficiency of Emerging Pollutants by Three-Dimensional Ceramic Carbon Foam-Supported Electrochemical Oxidation," *ACS ES T Water*, vol. 5, no. 2, pp. 902–912, 2025, <https://doi.org/10.1021/acsestwater.4c00928>

الأقطاب الكهربائية الرغوية لمعالجة مياه الصرف الصحي كهروكيميائياً: مراجعة للمواد والآليات والتطبيقات

هند حسن ثويني^{١، *}

^١ قسم الهندسة الكيميائية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

تتميز الأقطاب الكهربائية الرغوية، التي تُمثلها الرغوات المعدنية، ببنيته ثلاثية الأبعاد عالية المسامية ومساحة سطحها الكبيرة نسبياً. تتمتع هذه الأقطاب بموصلية كهربائية عالية، وتُعد مواد وظيفية متطورة وواعدة في معالجة مياه الصرف الصحي. يوفر التصميم الفريد لهذه البنية، بموادها المسامية، مواقع تحفيزية متزايدة، ونقلًا أفضل للكتلة، وسهولة أكبر في نقل الإلكترونات، ومثانة طويلة الأمد في ظل ظروف التشغيل القاسية. هذه الخصائص تجعلها موادًا مناسبة جدًا للعمليات الكهروكيميائية. تركز هذه المراجعة على مواد تصنيع الأقطاب الكهربائية الرغوية وتطبيقاتها الجديدة في عمليات الأكسدة الكهروكيميائية، والامتزاز، والتخثير الكهربائي. وقد ذُكرت على وجه التحديد أنواع مختلفة من الأقطاب، مثل الفولاذ المقاوم للصدأ، والنيكل، والنحاس، والحديد، والالمنيوم، وسلط الضوء على قدرتها على إزالة الملوثات العضوية السامة، والأصبغ، والمعادن الثقيلة. تراوحت كفاءة إزالة الملوثات في العمليات الكهروكيميائية بين ٧٠% و ٩٩% تبعًا لمادة القطب. وقد أظهرت رغوة النيكل، تليها رغوة النحاس ثم رغوة الجرافين، أداءً فائقًا في عمليات الأكسدة المتقدمة، بينما تراوحت نسبة إزالة الطلب الكيميائي للأكسجين (COD) بين ٤٠% و ٩٢% تبعًا لظروف التشغيل. وأظهر مسح منهجي للأدبيات المنشورة بين عامي ٢٠١٥ و ٢٠٢٥ أن أقطاب الرغوة تلعب دورًا هامًا في معالجة مياه الصرف الصحي.

الكلمات الدالة: مياه الصرف الصحي، رغوة النيكل، رغوة النحاس، الكتروفنتون، رغوة PVC.