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Review Report

Production of Cooking Gas through Electrochemical Decomposition of Organic Matter

Rodolphe N'Dedji Sodokin[1], Chika Oliver Ujah[1,2], Daramy Vandi Von Kallon[2], Gildas David Farid Adamon[3]

[1]Africa Centre of Excellence for Sustainable Power and Energy Development (ACE-SPED), University of Nigeria, Nsukka 410001, Nigeria
[2]Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, Johannesburg 2006, South Africa
[3]Department of Energy, National Higher Institute of Industrial Technology of the National University of Sciences, Technologies, Engineering and Mathematics (INSTI/UNSTIM), BP 133 Lokossa, Republic of Benin

***Correspondence:** Chika Oliver Ujah, Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, Johannesburg 2006, South Africa (Email: chikau@uj.ac.za).

Abstract: In recent decades, the use of electrochemistry has increased exponentially. Electrochemistry has demonstrated their effectiveness in the cleaning of manufactured effluents and the decomposition of complex hydrological compounds for water treatment. Looking at the efficiency of the technology in the decomposition of organic matter, one wonders if it is not capable of doing more than just the de-pollution and treatment of water. Of course, there are other uses of electrochemistry, but in the literature, it is understood that it is used more for water treatment and de-pollution. This work is a review of the literature to identify the major works in electrochemical decomposition of organic matter to see to what extent this technology can be used for methane production (cooking gas) using pasty organic matter. The list of works appearing in this review is not exhaustive, but it is sufficient to give a clear idea of the technology, its progress and, above all, the challenges it faces. This review opens the way to other applications of electrochemical decomposition to meet today's energy challenges.

Keywords: Cooking Gas, Electrochemical Decomposition, Electrochemistry, Hydrological Compounds, Organic Matter

1. Introduction

Electrochemical methods bring together two fascinating disciplines—chemistry and electricity—to produce a very accurate outcome. Applications of electrochemistry for environmental treatment and sanitization have grown significantly in the last several decades. This has been the subject of countless scientific investigations (Lacasa et al., 2019). There are several distinct benefits to electrochemistry wastewater treatment over chemical and biological techniques (Djamel Ghernaout & Elboughdiri 2020). While particle size is undoubtedly important in waste treatment, it is important to remember that residence and sedimentation times allow one to assess the process's efficacy (Saiba et al., 2010). The oxidation of organic materials and electrolytic processes result in the cathodic deposition of metals that is seen during electrowinning and electrorefining (Djamel Ghernaout, & Kellil 2009). Ghernaout, Saiba, et al., (2009) has been observed that even though the yields are higher when the electrodes have a neutral pH, a higher energy efficiency (almost 100%) is recorded for an EM preparation in combination with an EC treatment, and the continuous treatment is less effective when humic acids (HA) are electrocoagulated (EC) in a bulk of artificial HA liquid using two aluminum electrochemical cells. Ghernaout, Boucherit, et al. (2009) concluded from their results that the EC method with aluminium electrodes (more effective than iron electrodes) is very effective for the elimination of HA by load equalisation and electroadsorption with an efficiency of at least 70%.

These deposits form on the surface of the anode either directly, it is possible for deposition to occur on the anode with an interim layer, or even on the surface of the cathode (Belhout et al., 2010). With the aim of applying the electrochemistry approach to the industrial-scale cleaning of organic matter in aqueous media, using a series of aluminum electrodes, it is essential to undertake investigations into the decrease in cloudiness, conductivity and organic matter (Ghernaout et al., 2010).The chemical industry is an important part of the world's economy and is constantly improving. Despite the continuous improvement of its processes, it is still confronted with difficulties in the management of its waste water and end-of-life products. The vast majority of these products are discharged into natural bodies of water without having been systematically treated by policy-approved processes. In particular, numerous substances contained in industrial discharges are poisonous to the ecosystem (Weiss-Hortala, 2006). Electrochemical degradation processes have shown advantages in breaking down carbon dioxide and hydrogen from biological materials.

Electrowinning of organic matter is a significant advance in the management of human, industrial and municipal animal waste. This technique has three advantages: First, it makes it possible to process waste very quickly and very efficiently to reduce greenhouse gases from the aerobic decomposition of waste. Then, this Technique makes it possible to produce combustible gases which can be used as energy as part of the production of renewable energy. Finally, it opens the way to other research with the direct combination of electricity and biomass as part of the optimization of existing energy systems. The biological degradation of organic matter for the production of biogas is a natural and relatively slow process. This does not allow the sector to compete effectively with fossil fuels. Several authors have worked on electrochemistry. Some have gone further to studying the behavior of electrodes in the face of electrolytes. Others have worked on water treatment using electrocoagulation. The aim of this study is to review the work and progress made in the electrochemical degradation of more complex organic compounds, with a view to considering their application in the field of biogas production.

2. Problem Statement

As methanization is a natural process, it is relatively slow. This slowness in the process is a brake on its effective integration and a limit to its competition with fossil fuels as a domestic fuel. The fact that the process is natural, even if it has been relatively successfully mastered in recent years, means that there are problems associated with reliable prediction to enable households to accurately assess the methanogenic potential of their waste and, above all, to know with certainty how long this biogas will be available. These uncertainties lead to problems of biogas disruption and households running out of gas when cooking food. Faced with these limitations of methanization (a natural process), there is an urgent need to develop a reliable and effective technology for producing methane from organic waste. This technology must be able to operate with parameters that can be easily managed and varied according to what we need and in real time. Electrochemistry has proved to be a very reliable option, thanks to the advances it has made over the last few decades. Our research aims to explore the technology of electrochemical decomposition of organic matter to produce methane for culinary use.

3. Review Questions

(a) What is the fundamental principle of electrochemical decomposition?
(b) What are the notable advances in the electrochemical decomposition of organic matter?
(c)What advances have been made in electrode technology and electrodes?
(d) What are the stages and products of electrochemical decomposition of organic matter?
(e) How can methane be produced using electrochemical decomposition of organic matter?

4. Materials and Methods

The literature review methodology used for the work can be summarized in 3 parts: the search for and collection of data, the grouping and sorting of the data and finally the use and deployment of the data. The data in our work consists of all information and articles consulted as part of this review. During the research and information gathering phase, we consulted online scientific article platforms using the Google search engine. We mainly used Google scholar to search for information. To carry out the searches, we used keywords. Examples of keywords used are electrochemistry, electrochemical decomposition, electrochemical treatment of biomass, advances in electrode technology, importance of electrode choice, electrolytes used, etc. The data gathering and sorting phase consists of reading the articles downloaded during the first phase (research and information gathering) and classifying these articles according to the way in which they address the question and the relevance of the results to our subject. In this way, we formed three groups of articles (useful and important, not useful and important, not useful and not important). It should be noted that we consulted 209 articles. All the articles are labeled and registered under numbers ranging from 1 to 209. The third phase, which is the use and deployment of the data, consists of exploiting the information in the data classified as "useful and important" for this work. Sometimes we realized that some of the information classified as "not useful and important" contained data that was very important for the completion of certain points that were very important for the subject. We have therefore used this information to explain and give examples in order to facilitate comprehension.

5. Results and Discussion

5.1. Electrochemical decomposition: electrodes, electrolytes and reactions

Electrolysis uses direct current (DC), which causes involuntary chemical reactions. Electrolysis is widely used in commercial activities because of its ability to separate elements from natural sources, such as ores, using an electrolytic cell. The main components required for electrolysis are electrolyte, electrodes, and external power supply. Throughout the electrolysis process, the electrodes are in contact with an exterior energy supply. This source provides the energy required for chemical reactions to take place. The electrons flow through the external circuit and the ions move through the electrolyte after a voltage has been applied to the electrodes. Depending on their charge, the ions will either undergo an oxidation or a reduction reaction at the electrodes (*Electrolysis*, n.d.)

Competitive electron-consuming processes, for example, the formation of peroxide species, sometimes limits the direct oxidation of organic compounds present in solution by raising the electrode to a higher voltage than is required to release oxygen. These oxidising species react with the organic compounds to oxidise them in turn. These oxidising species, and in particular hydroxyl radicals, are not generated with the same efficiency by all materials (Weiss-Hortala, 2006). Figure 1 shows concentration profiles of volatile organic substances during the electrowinning of 1 liter of 0.1M H_2SO_4 solution containing 0.02M phenol in a cell without a separator.

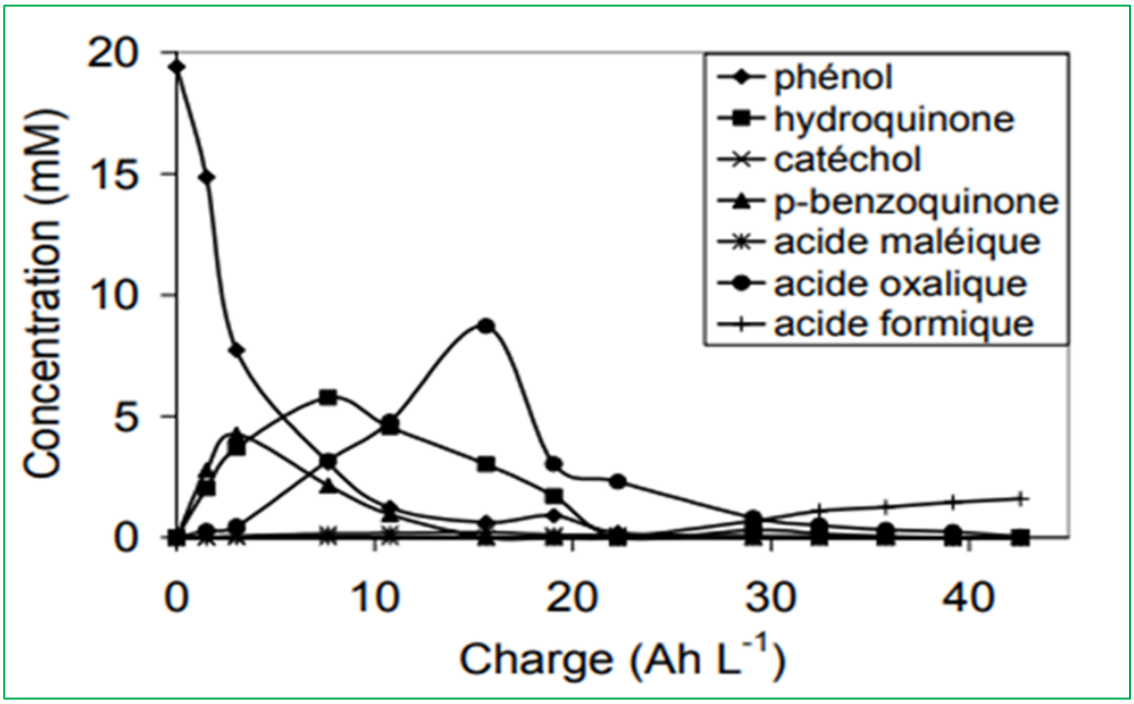

Figure 1: Change in concentration of volatile organic substances resulting from the electrowinning of 1 liter of 0.1M H_2SO_4 solution containing 0.02M phenol in a cell without a separator (Weiss-Hortala, 2006).

Over the past few years, various research studies have taken a close interest in the study of the purification of effluents and water polluted with solid and semi-solid organic matters. On the electro-oxidation of organic substances (aromatic, aliphatic, nitrated), there are several works. More in the Bibliography, two main types of electrodes have been used: metal dioxides and boron-doped diamond. Various research has been conducted on metal dioxide anodes in recent years. With the aim of carrying out electrochemical syntheses, Fleszar and Poszyńska (1985) carried out work on oxidising natural substances using a PbO_2 cationic electrode. As a working hypothesis, they considered that the oxidation of benzene and phenol on a PbO_2 anode is based on the direct hydroxylation of these components into phenol (benzene), hydroquinone and pyrocatechol (benzene and phenol) by hydroxyl radicals that formed on the anode. Harrison and Mayne (1983) and others with similar aims suggested how the oxidation process can be applied to the large-scale production of the appropriate polyaromatic alcohols and aldehydes. With the SnO_2 electrode, Comninellis (1994) generated a large number of free hydroxyl radicals. To study the electrochemical oxidation of organic substances, he introduced a highly simplified mechanism. According to this mechanism, oxidation took place at the oxide-layer (MOX), forming the highest oxide (MOX+1) at the electrodes, and there is an accentuation of OH^- radicals. He then confirmed the mechanism by detecting these radicals. The results obtained by Wabner and Grambow (1985) validated this conclusion with PbO_2 compared to platinum. They carried out experiments to trap unbound reactive precursors in anodic aqueous media, employing p-nitrosodimethylaniline (RNO) as a trapping support, to confirm their proposed model for the possible involvement of unbound hydroxyl radicals in the formation of ozone at plumb ash anodes. Kötz et al., (1991a) was able to degrade industrial waste water using the tin electrode. In this work, the degradation was studied in terms of reactivity, lifetime and the nature of the dopant. Figure 2 shows the mechanism of oxidation, together with the presence of the redox couple quinone / hydroquinone in the experiments conducted with platinised anode made of titanium.

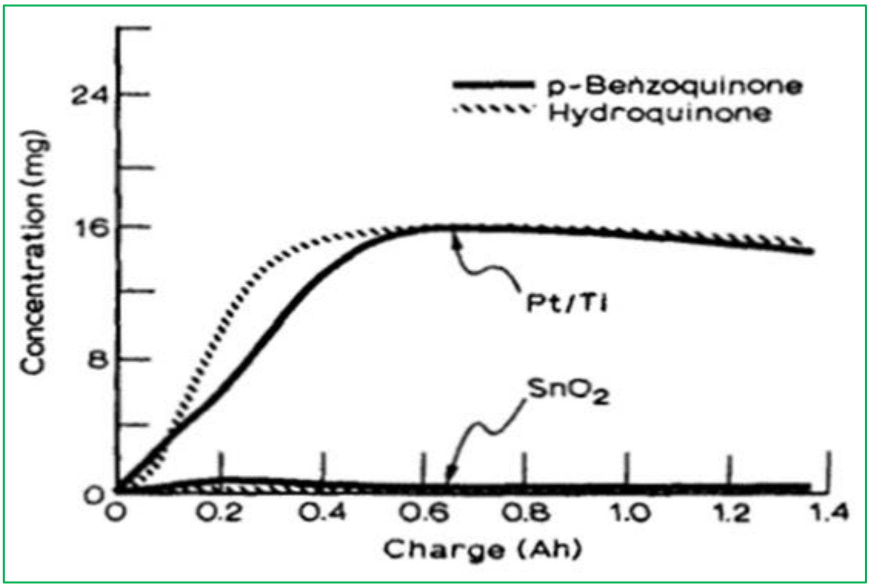

Figure 2: The mechanism of oxidation conducted with platinised anode made of titanium. (Kötz et al., 1991a).

Kötz, Stucki, and Carcer (1991b) compared PbO_2 and SnO_2 electrodes under the same operating conditions with synthetic solutions representative of aqueous waste water (carboxylic acids, aniline, nitrobenzene, chlorophenol, dyes, etc.) as well as with real waste water. They found that the organic compounds disappear faster when the SnO_2 electrode is used. On the other hand, Bonfatti et al. (2000) in the course of their work, found out that the incorporation of platinum in the tin dioxide electrode rendered it almost inert for the oxidation of glucose. But lead dioxide allowed a very rapid disappearance of the starting compound under strictly identical operating conditions. The application of the Boron-doped diamond (BDD) has been investigated for the purpose of evaluating the efficiency of the measuring electrode composition materials for the electrochemical degradation of organic compounds. This consideration can be found in several articles. Although the employment of diamond doped with boron in the removal of contaminants from aqueous effluents began with the Kodak patent (Carey, 1995), it should be noted that Pelskov et al. (1987) was the first to use it in electrochemistry. They later studied in detail the photoelectrochemical behavior of diamond. In this way, the photoelectrochemistry of the entire diamond was characterised by the following terms of the model of light generation and charge distribution in the underlying film of the semiconductor. They measured the plate-band voltage as a function of sample surface preparation and solution composition. They also demonstrated the existence of surface influences on the electro-chemical behaviour of diamond semiconductors. Duo et al. (2004) concluded that after anodic treatment, the electro-chemical behaviour of boron-doped diamond anodes are stable. This stability made it possible to consider their use in waste water decontamination operations carried out by Katsuki et al. (1998). Their measurements showed that the depletion of the doped species was very small relative to the depletion of the platinum-plated anodized sample. They therefore concluded that diamond is dimensionally stable under extreme conditions. With the aid of X-ray diffraction, Raman studies and scanned electron microscopy, the functional disruption pathway was revealed. A crumbling of the substrate film was observed. For them, this is the result of inherent tensions that have built up throughout the manufacturing operation, which is conducted at elevated temperatures. Panizza and Cerisola (2005) summarized and discussed the most recent findings available in Published scientific papers on the application of diamond-based electrodes in the field of electrochemistry, such as the purification of water and the electrosynthesis of both organic and inorganic substances, and found that the extraordinary qualities of diamond as a carbon electrode metal are ideal for the demands of electrochemical processes. In his research work for the doctoral degree, Weiss-Hortala (2006) concluded that the diamond-tipped carbon electrode is a suitable material for the production of hydroxyl radicals, which opens new applications for the manufacturing of powerful oxidants from inorganic compounds, and appears to promote the complete mineralization of many organic compounds.

Like electrodes, electrolytes have also been studied. Michaud (2002) have tested several oxidants. Among the oxidants we can find ozone, hydrogen peroxide and hydroxyl radicals. Komatsu et al. (2003) was among the first to provide clear quantitative demonstration of the formation of hydroxide radicals by coumarin and subsequent fluorescence monitoring of its hydroxymethyl product. Nosaka and Nosaka (n.d.) worked on the formation of hydroxyl radicals and opined that the peroxide produced during the formation of hydroxyl groups is a very important intermediate product during the oxidation of water.

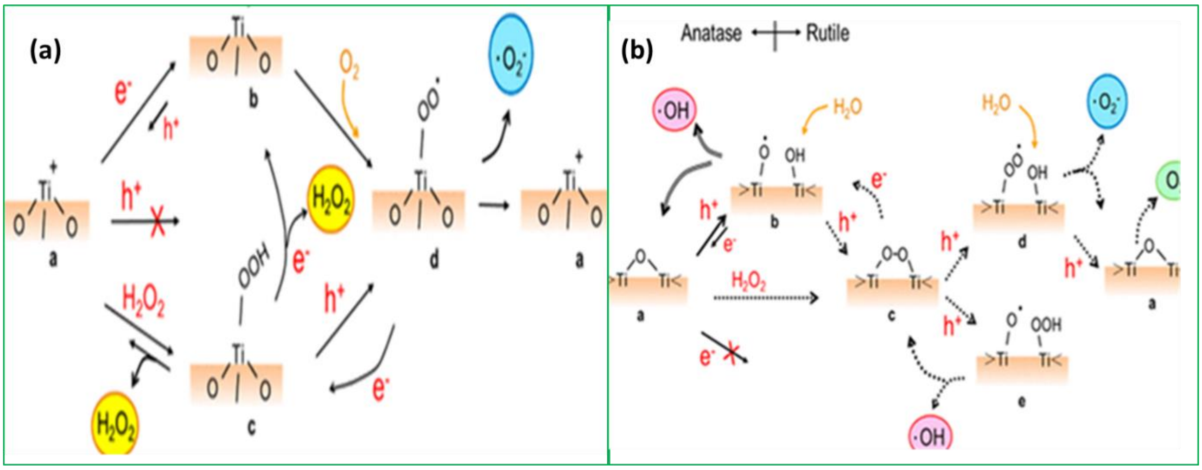

Figure 3: Formation of Hydroxide Radicals: (a) Possible photocatalytic reaction pathways at the terminal H_2O_2 site of TiO_2, (b) Possible photocatalytic reaction pathways at a TiO_2 bridge OH site, continuous arrows represent anatase (Li insertion into TiO_2) and dotted arrows represent rutile (Nosaka

& Nosaka, 2016).

Michaud et al. (2003) studied electrolysis in the presence of dissolved aqueous solutions of 1 mM $HClO_4$ and 1 mM H_2SO_4 with BDD electrodes in galvanostatic operating environment. They found that small amounts of O_3 and H_2O_2 were formed in the two electrolytes. At the end of their work, they proposed a very simplified mechanism which involves hydroxyl radicals' formation by water rejection in the oxidation of water on the anodes in diamond doped with boron. Ferro et al. (2000) highlighted chlorinated species such as hypochlorous acid. They studied chlorine release reaction on thin diamond film electrodes heavily doped with boron. They carried out voltametric measurements which show the formation of a redox couple before the start of the release of oxygen (Fig. 4). The results constitute evidence of the creation of oxygenated groups (diamond oxide) on the diamond surface.

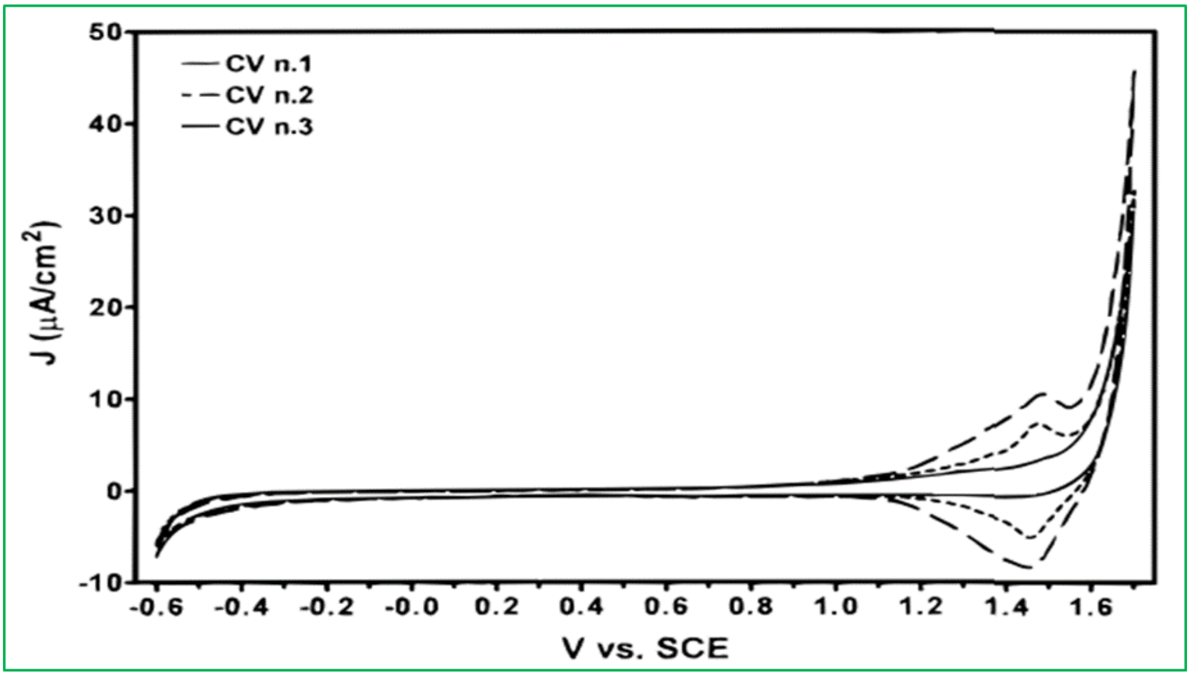

Figure 4: Cyclic voltammetry for a diamond thin film in (1 2 x) M NaClO4/x M HClO4 at a measured solution pH of 3.50, (-) before working in oxygen evolution conditions, (-----) after incipient oxygen evolution (polarization from 1.55 to 1.30 V vs. SCE, 0.5 mV s^{-1}, step potential 0.45 mV), (– – –) after pronounced oxygen evolution (polarization from 1.70 to 1.30 V vs. SCE) (Ferro, et al., 2000).

Gandini et al. (1999) worked on the basic conductivity of model organic compounds on boron-doped synthetic diamond thin-film electrodes. They found that while this system is nonreversible on electrodes in diamond, in the potential stabilization region of the supporting electrolyte, only single-transfer reactions, like those involving hydroquinone/benzoquinone, are viable. In the work of (Serrano et al., 2002) inorganic peroxo-compounds such as peroxosulfates were highlighted. They noticed that the main side reactions were the release of oxygen. Although small quantities of peroxomosulphuric acid (caro acid) have been identified, it should be emphasised that high flow densities can be maintained for the conversion of sulphuric acid to peroxodisulphuric acid in the presence of dissolved H_2SO_4 (> 2 M) at ambient temperatures (8 to 10°C). Cañizares and Sáez (2005) used peroxophosphates to carry out this electrochemical work while Saha et al. (2004) used peroxocarbonates. Both came to the same conclusion that peroxo compounds are very reactive and can also be used as powerful oxidants in the treatment of aqueous organic wastes. Bouamrane et al. (1996) had work done on reduction with the aim of treating waste. They were based on the reduction of nitrates to ammonia.

Perret et al., (1999) focused on the precipitation of heavy metals. Initial expérimental results have demonstrated the largest reported electrochemical range prior to water degradation, opening up new possibilities for both anodic and cathodic reactions. The data show direct oxidation with about 40% current efficiency for concentrated solutions. The current efficiency was greatly enhanced at low cyanide concentrations by the presence of Cl^- ion. Iniesta et al. (2002), focused on solutions of phenol and quinones for electrode in diamond doped with boron experiments. The influence of factors like current density, pH and applied voltage on the decomposition of phenol and the decrease in COD were studied during laboratory investigations on the electrochemical processing of industrial effluents at the anode. During this research, aliphatic carboxylic acids and unknown alcoholic substances were the most important oxidation compounds. The findings revealed that the ultimate COD value was less than 1000 ppm. They found that after electrochemical treatment, the residual phenol concentration was less than 1 ppm and the COD reduction was 70-80%. Iniesta et al. (2001) carried out work on the electrochemical decomposition of organic materials. According to them it is feasible to achieve full conversion of phenol to CO_2 or partial oxidation of phenol to other aromatic compounds (benzoquinone, hydroquinone, catechol) by varying the values of the applied current and the phenol concentration. Sopchak et al. (2002) by using rotating ring-disk electrode (RRDE) configurations, were able to compare the activity of BDDs to graphite, and also from gold and electrodes in platinum. They noted a large potential release of oxygen with the BDD. This shows that these electrodes allow improvement of anodic transformation of p-methoxyphenol and hydroquinone to higher quinone stage output. In addition to this conversion advantage, the BDD electrodes exhibited no signs of corrosion or contamination in these operating conditions.

Other studies like Cañizares et al., (2004) which was based on compounds like dinitrophenol and Panizza et al. (2001) which used 2-naphthol, are also interested in the behaviors of these electrolytes during electrochemical decomposition. Cañizares et al. (2004) Implementation of a single compartment recycle cycle electrochemical plant for the achievement of large capacity electrochlorination. At the heart of this device is BDD and the cathode is made of stainless steel materials (AISI 304). After testing, they proposed a very simple and complete mechanism. The result was the production of carbon dioxide (CO_2). They discovered that, in the first step, the oxidation of 2,4-DNP gives rise to phenolic and quinonic substances and the liberation of the nitro groups from the aromatic nucleus. In a second step, they concluded that the organic compounds are transformed to carboxylic acids (maleic acid and oxalic acid in particular). Panizza et al. (2001) evidence suggests that there are a number of very sophisticated oxidation reactions involving electrogenerated hydroxyl species. This process resulted in the full combustion of 2-naphthol within the electrolyte degradation zone and corrosion of the electrode was inhibited in these conditions as shown in Figure 5. Meanwhile, it was observed that in certain regions of the potential, polymeric materials are generated causing electrode fouling. They concluded that electrolysis at high positive potentials in the electrolyte decomposition region causes complex oxidation reactions by electrogenerated hydroxyl radicals leading to complete combustion of 2-naphthol. They also noted that electrode fouling is prevented in these operating conditions.

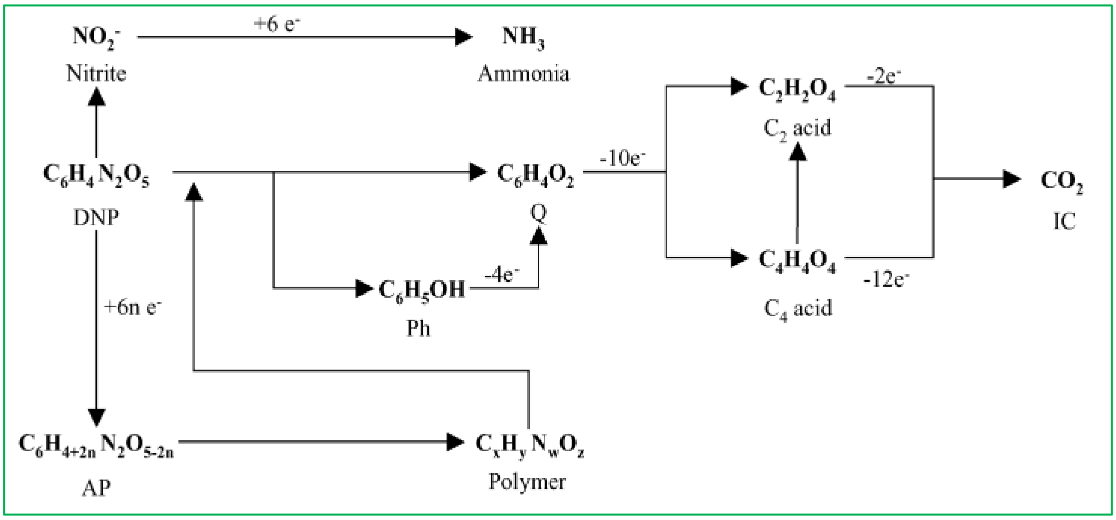

Figure 5: Diagram of the simplified mechanical system model describing the principal operations of electrochemical processing of 2,4-DNP residues with BDD anodes (Panizza, et al., 2001).

Aniline was used by Mitadera et al. (2004) and Polcaro et al. (2004) while Chailapakul et al. (2000) and Martínez-Huitle et al. (2004) carried out their investigations on oxalic acid. Mitadera et al., (2004) observed that acidic surroundings are more conducive to the effective electrochemical oxidation of aniline. This is because the voltage needed to avoid electrode fouling is lower in low-pH media than in neutral or alkaline media. Aniline is converted into CO_2 more efficiently when there are high potentials at the anode, as demonstrated by long-term polarization measurements. However, they pointed out that the direct oxidation process has no effect on the aniline's total electrochemical incineration. Polcaro et al. (2004) aimed at the enhancement of the reagent substance exchange with the membrane surface of the electrode by using an impacting jet cell with three electrodes. They observed the synthesis of short-chain organic acids, which under some circumstances function as intermediary products. They discovered that the processes entail the oxidative cleavage of the cycle, creating stoichiometric amounts of ammonium and chloride ions, using ion chromatographic and HPLC studies. Chailapakul et al. (2000) discovered that alanine and malic acid are more sensitive to organic matter electrochemical reactions. They were able to get distinct peaks for the oxidation of cysteine and citric acid during their investigation. They came to the conclusion that BDD is more sensitive to these chemicals than graphite cathode (GC). Martínez-Huitle et al. (2004) had observed, after conducting oxidation on the anode, that the electrode's material is a crucial factor in process optimization. They opined that the polymer membrane and the surface of electrode engage in extremely complicated interactions. In order to verify their results, they carried out an experiment using electrovoltammetry, with the aim of obtaining data on the electro-activity of OA at electrodes such as IrO_2-Ta_2O_5, PbO_2 and BDD, before anodic oxygen generation. Analogous experiments were carried out on Pt and Au electrodes, for which CV characteristics are well known from the existing literature, in order to have an internal and external reference. Fig. 6 shows the results of the respective voltammetric tests with Ti/IrO_2–Ta_2O_5 electrode and BDD electrode.

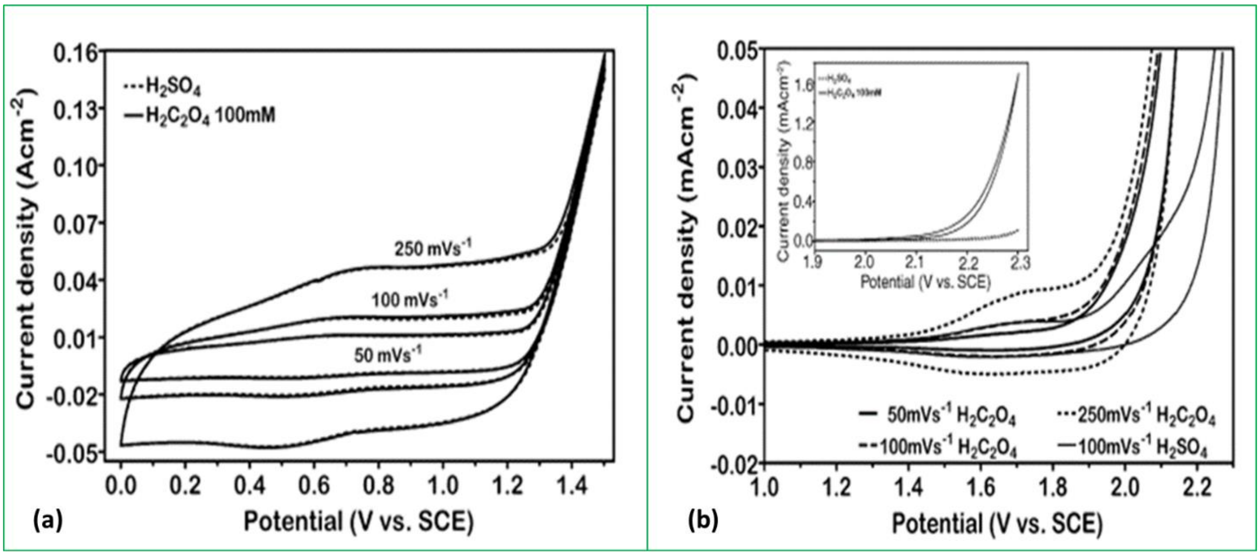

Figure 6: Cyclic Voltammetry (CV) Curves, (a) CV curves for the Ti/IrO$_2$–Ta$_2$O$_5$ electrode, in the presence of the pure supporting electrolyte (0.5 M H$_2$SO$_4$) and with oxidizing agent in solution (100 mM) (data obtained at different scan rates, and at room temperature), (b)CV curves for the BDD electrode, in the presence of the pure supporting electrolyte (0.5 M H$_2$SO$_4$) and with oxidizing agent solution (100 mM) (data obtained at different scan rates. Inset: effect of the addition of OA on the recorded CV. All results are in ambient (Martínez-Huitle et al., 2004). In their work, Iniesta et al. (2001) as well as that of Zhi et al. (2003), it has been demonstrated that choosing either of electrolysis potential or intensity significantly impacts the mineralization process. It is discovered that the electrode's surface just beneath the water discharge region is where the phenol oxidizes. As a result, a polymer layer forms, significantly lowering the electrode's efficiency.

5.2. Factors Influencing Electrochemical Decomposition of Organic Matter

For Priyadarshini et al. (2022) several operating parameters influence the effectiveness and capacity of electrochemical technologies in the context of organic compound breakdown and pollution removal. These include the initial concentration of contaminants, electrode media, CD, concentration of electrolyte, duration of electrolysis, charging, distance between electrodes, etc. They gave a thorough analysis of the usage of microbial electrochemical technologies (MET) and electrochemical technologies (ET) in treating wastewater that contains emerging contaminants (EC). Their work provides an extremely thorough analysis of the mechanism, removal efficiency, relative benefits and drawbacks, and variables influencing how well ETs and METs perform. Weiss-Hortala (2006) investigated the consequences of strength and flow rate on the degradation of phenol with different types of electrodes. She came to the conclusion that employing high electrolysis current with PbO$_2$ electrodes results in a loss of efficiency. It was observed that diamond electrodes doped with boron were more effective as well. For Fleszar and Poszyńska (1985), one of the elements affecting the organic material's electrochemical breakdown is the crystallized makeup of the substance utilized to create the electrode. Yeo et al. (1989) used structural X-ray data. They concluded that even when the Bi(III) concentration was raised, the structure of anodically deposited purified β-PbO$_2$ containing Pb(II) from HC104 1.0M was maintained, despite the lack of evidence for the creation of a new oxide phase. Yeo et al. (1989) worked on the refractive index of materials and how it influences their electrochemistry. They observed that the refractive index has an important function in the field of materials and several optical technologies. For them, the refractive index may be obtained using a UV-Vis spectrophotometer to determine the absorption, emission and reflection of materials (Figure 7). They noticed that the refractive index was high at a low energy and varied with the coating density, as can be seen in Fig. 7a. Figure 7b gives the relationship between refractive index and wavelength dispersion for pure CS, CS-PbO and CS-BiO composites. In the work, Zaki et al. (2021) showed that the inferior constituents are more pronounced than the superior 'satellites'. Fig. 7c shows that a related but less pronounced satellite feature is evident in the O 1s core line of b-PbO_2, with the separation of the two components close to 0.69 eV. In the simplest scenario, the high energy spikes represent exceptionally powerful conduction electron plasmon satellites. Figure 7d shows the energy required to break the liaison of the molecule.

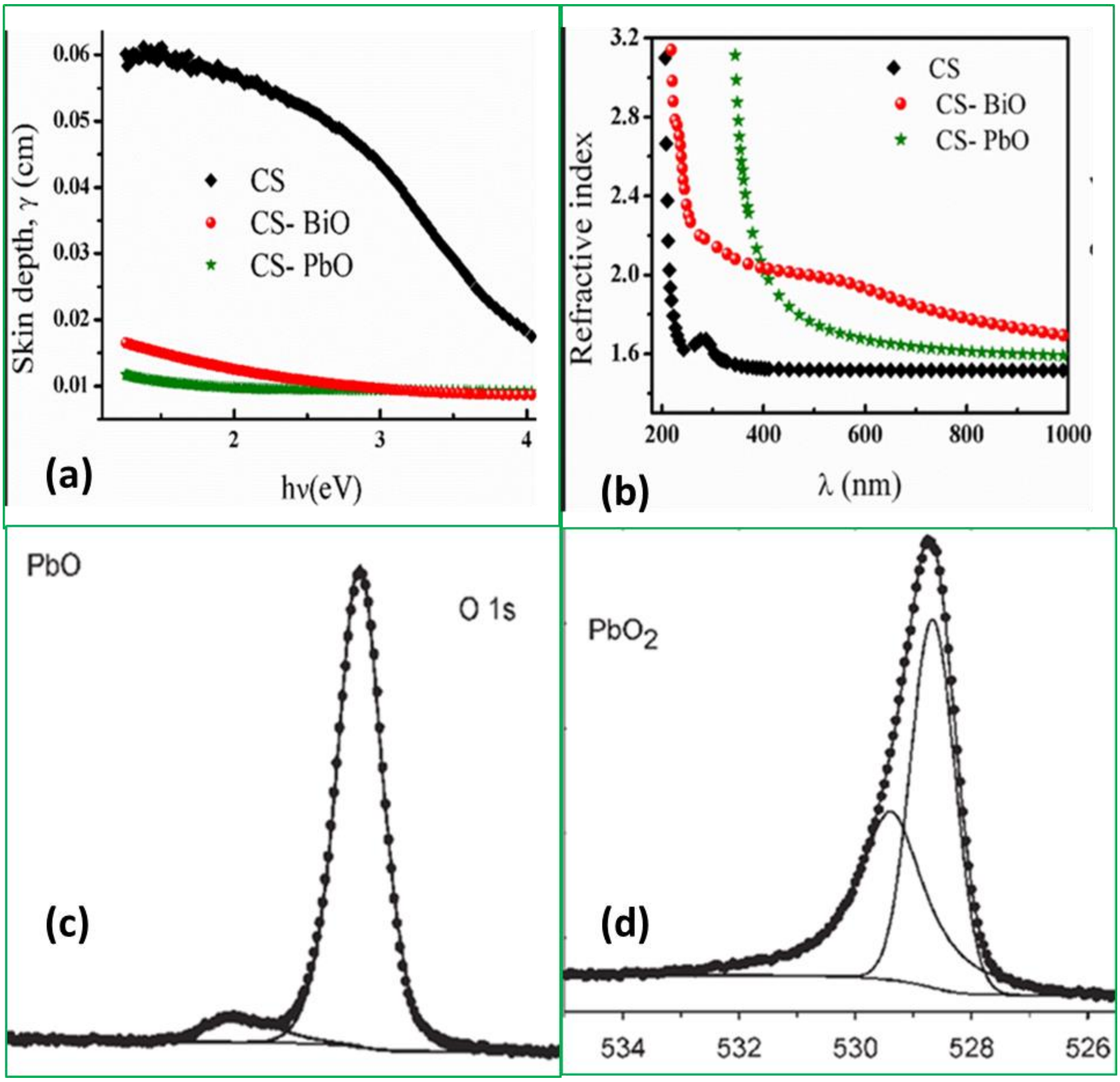

Figure 7: Spectral X-ray absorption spectroscopy data for I~-Pb02 and mixed Bi-Pb complex oxide materials (a) Skin depth Pb0, Bi0 (Zaki et al., 2021), (b) The refractive index dispersion of Pb0, Bi0 (Zaki et al., 2021), (c) Photoemission Spectra of a-PbO and b-PbO2 (Payne et al., 2007), (d) Binding Energy (Payne et al., 2007).

Austin et al. (1984) discovered that the electrochemical reaction is only temporary, due to the transient lifespan of the PtOH and the fact that the reaction products are highly adsorbed to prevent additional surface activity. Their initial findings made it possible to identify $As(OH)^{3-}$ and the corresponding thiourea at constant voltage on a β-PbO_2 electrode. Abaci et al. (2005) observed the levels of maleic acid, phenol, and benzoquinone while the organic compounds were being electrochemically treated. They come to the conclusion that during phenol degradation, β surfaces react and function better than α surfaces. According to (Belhadj-Tahar, 1996), a significant factor influencing the rate at which organic compounds decompose is the substrate that is utilized.

The substances called electrolytes that are employed as supports in the electrochemical breakdown of organic molecules also significantly impact the process. Michaud et al. (2003) used sulfuric acid to aid in the breakdown of organic materials. Michaud et al. (2003) and Marselli et al. (2003) examined the effects of this électrolyte during electrochemical breakdown using perchlorate. Their decision is as a result of the perchlorate ion's weak polarizing and complexing abilities. This explains why perchloric acid is used in basic research. It was because of this that Cañizares et al. (2003) employed acid phosphoricum in a study. They observed a current peak on the anode using the voltmeter. This suggested that there is a process of direct oxidization that takes place on the surface of the anode. They observed the precision of the voltmeter's values when using the galvanostat, which supports the presence of oxidation reactions. The waste is subsequently mineralized, and the carboxylic acids were immediately converted to carbon dioxide. These outcomes were independent of the temperature, the medium, the initial organic acid content, and the current intensity.

When we talk about the factors that influence material decomposition and transmission, it is also very important to consider the external factors. Among these external factors, we can talk about the source of voltage, the quality of the energy and especially the characteristic of the conductive wires. Ujah, Kallon and Aigbodion (2022) worked on the importance of some conductive materials used in development of wires for the transport and transmission of electrons and ions. According to their work, this parameter influences the transmission of the transmission in a consistent way. This parameter in transmission and transport can easily be enhanced with only advanced materials with zero or resistivity. More so, Ujah, Kallon, Aikhuele, et al., (2022) considered in their work advances in the materials development sector. It was opined that new and more robust conductor materials need to be developed to enhance efficiency of ion and electron transmission.

5.3. Advancements in the Electrochemical Decomposition of Organic Matter

5.3.1. Advances in electrode design technology

Electrochemistry is used more in water treatment than in the decomposition of solid organic matter. Several studies have focused on the decomposition of organic fractions present in water. The results of these studies depend on the electrodes and electrolyte supports used. In this section, we focus on the studies devoted to move forward in the design of electrodes for the treatment of organic fractions. According to Jing et al. (2023) when more than one type of metal oxide is combined in the design of electrodes, the reactions at the electrodes are improved. In their experiments, Sun et al. (2021) created CuO-SnO_2-SbO_x electrodes with Ti the base. They discovered that in less than five hours, the hazardous p-nitrophenol had mineralized on its own. This resulted from the composite electrodes' quicker response when compared to the conventional Ti/SnO_2-SbO_x electrodes, as the former had a higher potential for oxygen release. The diagram is shown in Figure 8.

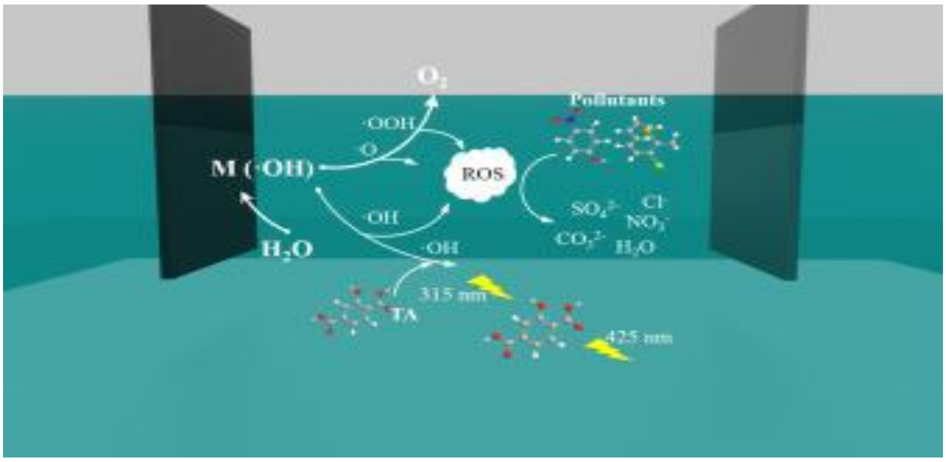

Figure 8: Ti substrate and CuO-SnO2-SbOX electrode (Sun et al., 2021).

In order to improve the electrodes' performance during electrochemical breakdown, Man et al. (2022) used the hydrothermal approach to produce a three-dimensional intermediate layer of Sb-doped SnO_2 nanoflower on a Ti substrate. They were able to obtain high reactivity electrodes by using this technique. Shao et al. (2022) created magnetically assembled electrodes (MAE) by using magnetic nanotubes (CNTs) on the nanometric scale on the surface of metal oxide-based electrode structures. They saw a rise in the quantity of active websites. Treatment of organic wastewater is now more effective. Previously, there was insufficient data to have a deeper comprehension of the MAE mechanism. Therefore, the completion of this information was made possible. Zhang et al. (2023) worked on a topic that was a follow-up to earlier research by Shao et al. (2022). Zhang et al. (2023) discovered that the solution that was left over after the substrate was electrochemically decomposed and characterized by cyclic voltammetric analysis, Tafel method and plate analysis and electrochemical conductivity spectroscopy. By adjusting the amount of AE, they were able to remove all contaminants from the effluent. Weiss-Hortala, (2006) worked with electrodes doped with boron. It was concluded that the DDB anode had the best electrocatalytic and energetic properties, as demonstrated by the mineralization of phenol in aqueous solution.

5.3.2 Advances in materials used

The very first thing to consider in selecting an electrode is to know the characteristics of the material used to design it. The work of Martínez-Huitle et al. (2015) demonstrated how crucial it was to choose the right anode material because it has an immediate influence on the mitigation potential, various forms of treatment, and current efficiency (EC). Shestakova and Sillanpää (2017) completed a study with the goal of reviewing data on anodes now in use in electrochemical oxidation procedures, including their performance, field of use, pros and cons. They concluded that despite the availability of several anode types, some of them are still prohibitively expensive to employ for significant water use. Some consist of extremely hazardous metals. Martínez-Huitle et al. (2018) conducted a research on the pulp and paper, textile, pharmaceutical, and home/urban wastewater businesses. The discussion of the benefits, drawbacks, and strategies for integrating electrochemical techniques with renewable energy sources to create sustainable installations was the most significant aspect of the work. Chen (2004) has worked on several electrochemistry processes, such as electrodeposition, electro-oxidation, electro-flotation, and electrocoagulation. They concluded that the stable and reactive electrodes that had been manufactured recently for the production of oxygen would no doubt accelerate the spread of the technology. Chaplin (2014) opined that though it is a promising new technology, the environmental effects of using Electrochemical Advanced Oxidation Processes (EAOP) and the pathways underlying the oxidation of organic substances have not been fully explored. Their work included a thorough assessment that considered the types of EAOP electrodes, the oxidation pathways of specific classes of pollutants, rate restrictions in real-world applications, and sustainability over the long term. The working principles of electrodes is shown in Figure 9.

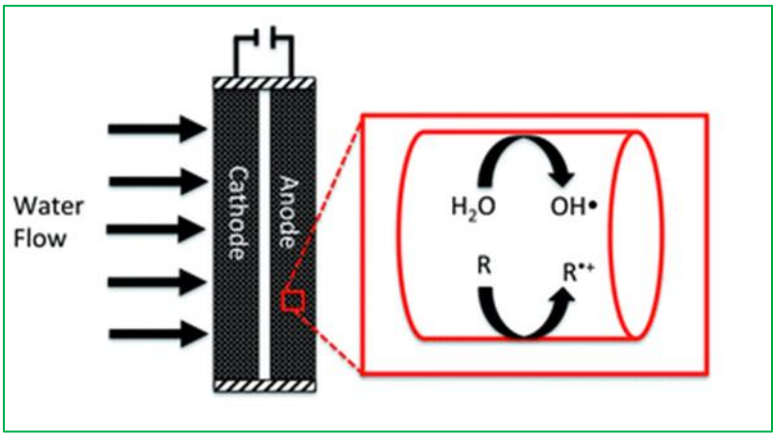

Figure 9: Schematic Diagram of Working Principles of Electrodes (Chaplin, 2014)

Brillas et al. (2021) worked on several electrochemical treatment technology. They talked about each technology's foundations as well as the primary outcomes of removing the most popular herbicides through synthetic treatments and dirt washing effluent. Sirés et al. (2014) had provided an update on the implementation of EAOPs for the treatment of waterborne organic pollutants, beginning with a review of recent research and forward planning for this technology. For Heard and Lennox (2020), the materials used to design electrodes have proliferated and increased in recent years, in line with the changes and evolution of electrode applications. To give two examples, the most commonly used metals are lead and mercury, which have very high hydrogen overpotentials (ηH) and are stable in acidic environments. This indicates that mercury can stay pure and free of impurities because it is in a liquid state and its surface is continuously renewed. During their work, Patel et al. (2013) demonstrated that platinum is usually employed in developing electrode because it leads to the electrodes' increased durability, stability during oxidation-reduction, and ease of maintenance. But the studies by Pletcher (2018) stated that because carbon-based electrodes are inexpensive, current organic electrochemistry also uses them. Thus, carbon electrodes are more appropriate and require less platinum. Harris (2004) has demonstrated that glassy carbon has been the most extensively utilized carbon material. It was actually the carbon fullerene allotrope. For Wang (1981), this carbon vitreous electroplate was shaped like an RVC foam, which has a huge surface area. Lim et al. (2017) have shown the extraordinary qualities of graphite which have made it a widely used material in the design of carbon electrodes. They came to the conclusion that graphite is used because it is less costly, highly conductive, and undergoes more chemical reactions than glassy carbon. For Cobb et al. (2018) and Lips and Waldvogel (2019), BDD is a unique material that is of tremendous efficacy. They saw this material's increasing utilization as a result of its novelty. Numerous examples have demonstrated how novel metals, alloys, and materials are being developed and used in electrode designs to effectively break down organic matter. According to Beil et al. (2018) and Gütz et al. (2015), materials being tested as electrodes in electrochemical reactions to determine the composition of organic matter include lead, bronze, tantalum, niobium, and molybdenum. Electrochemistry technology is becoming more and more interesting and research-focused. There is no doubt that other materials will be developed to optimize and make decomposition of organic matter more efficient. That is when needs arise in the electrochemical decomposition of organic matter; other electrodes will be developed. These metals can be improved. This improvement can promote their insertion and increase their efficiency. It would be very interesting to verify their resistance to industrial use. According to Ujah et al. (2020), it would be more interesting to improve the resistance of these materials to corrosion by combining them with Carbon Nanotubes (CNTs). This combination could improve the electrode's resistance to corrosive media.

5.4. Products of Electrochemical Decomposition of Organic Matter

Several types of products can be obtained during the electrochemical decomposition of organic matter. These products can vary according to the electrode material used, the current intensity, the time and above all the composition of the organic matter.

5.4.1 Useful Products

Simond et al. (1997) and Martínez-Huitle et al. (2023) have demonstrated that there are two types of electrode materials for the breakdown of organic molecules. We call these electrodes active and non-active. For Kislyi et al. (2023), with activated or regenerative anodes, the hydroxyl radicals formed are able to attack the anode material directly. The organic molecules are oxidized by the resultant oxides from this reaction. The anode material and the generated radicals do not interact in the case of inactive anodes. Trellu et al. (2018) have demonstrated that the creation of reactive OH^- species is facilitated by high oxygen evolution potential (OEP) at dormant anodes. For Garcia-Segura et al. (2018), Martínez-Huitle et al. (2018), and Oturan et al. (2018) in general, it was believed that these radicals oxidize complex organic molecules when current densities above the threshold value are supplied. This oxidation process directly leads to the fouling that is seen during water treatment. The study of Oturan et al. (2018), was to gain experience in understanding the mechanisms of OH^- oxidation in associated research areas. To achieve this, they used the reactor shown in Figure 10 to carry out all the experiments. The experiments on H_2O_2 oxidation were carried out in the same reactor, except that the electrodes were missing. Fig 11a shows the reaction time of each component using different electrode materials. They found that OH- can react with four organic compounds. This is shown in Fig 11b. They also found that each compound has its own specific reaction time. This reaction time is a function of the electrode materials used and the concentration of the electrolyte.

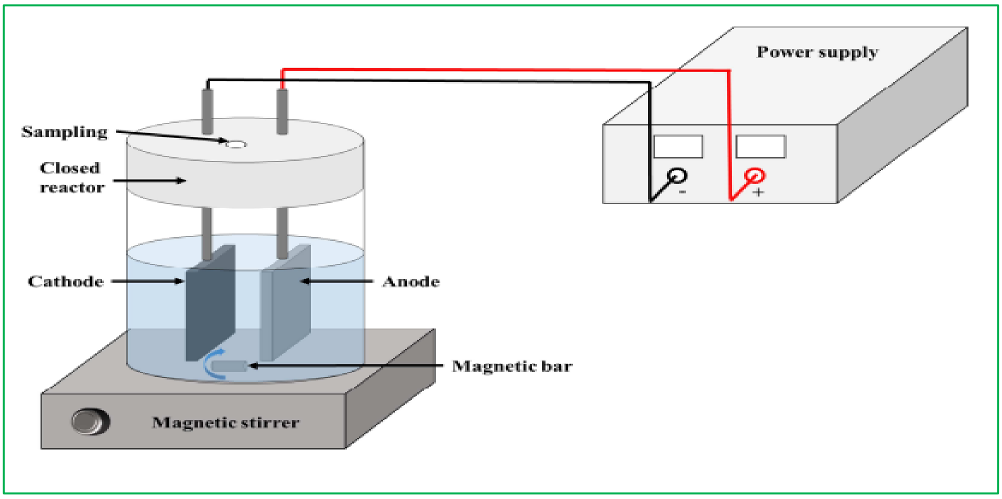

Figure 10: Experimental setup for H_2O_2 oxidation and electrolysis experiments (Oturan et al., 2018).

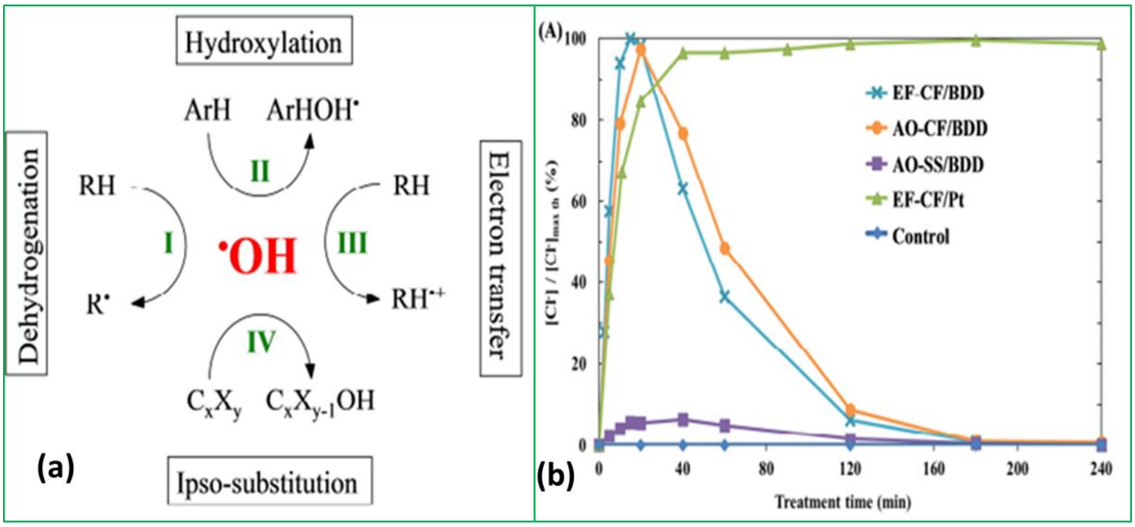

Figure 11: (a) Scheme of the 4 ways in which OH can attack organic molecules. (b) Reduction of CCl4 by AO and EF processes with various cathodes and anodes Chloride content history standardized to the theoretically maximum (Oturan et al., 2018).

For (Dean, 1992), the conversion equation that was applied to determine the effectiveness of reactions in the electrochemical decomposition of organic materials is as shown:

$$C_X H_Y^{\cdot} O_Z + nH_2O \rightarrow xCO_2 + (y+2n)H^+ + (y+2n)e^- \qquad (1)$$

$$C_6 H_6O + 11H_2O \rightarrow 6CO_2 + 28H^+ + 28e^- \qquad (2)$$

$$C_4 H_4O_4 + 4H_2O \rightarrow 4CO_2 + 12H^+ + 12e^- \qquad (3)$$

$$C_2 H_2O_4 \rightarrow 2CO_2 + 2H^+ + 2e^- \qquad (4)$$

$$HCOOH \rightarrow CO_2 + 2H^+ + 2e^- \qquad (5)$$

Using equations 2, 3, 4 and 5, Weiss-Hortala (2006) had shown the breakdown of several organic molecules, including phenol (2), and simple carboxylic acids, including maleic (3), oxalic (4), and formic (5) acids, by electrochemical means. Trasatti (1980) presented a comprehensive schematic diagram of the organic compound oxidation process. This is the most comprehensive method for utilizing metal oxide-based anodes to electrochemically oxidize organic molecules. Note that the generation of radicals remains the initial stage of manufacturing. Either physisorbed or chemisorbed radicals can be found. According to him, the physisorbed radicals enable organic compounds to react to produce CO_2 at the terminal step. Achieving the terminal stage of CO_2 is essential for the synthesis of fuels, including methane and hydrogen. Because the terminal CO_2 stage cannot be reached, the chemical bound activated oxygen participates in the formation of selectively oxidized substances.

Getting to the terminal CO_2 stage during the electrotechnical decomposition of organic matter ensures the availability of CO_2 and dihydrogen. The availability of these two compounds is very important for the rest of the process of cooking gas production. According to Moletta (2008), during methanisation, methane is obtained in two ways. The first route is the conversion of acetic acid into methane and carbon dioxide (the acetoclastic route) and the second route is the conversion of CO_2 intso methane by combining it with dihydrogen (the hydrogenophilic route). In this case, the CO_2 and dihydrogen obtained after treatment will be converted into methane.

Archaea methanogens acetoclastic:

Aceticacid → Methane + carbondioxide (6)

Archaea methanogenic hydrogenophilic:

Hydrogen+ Carbon dioxide→ Methane + water (7)

In 1902 Sabatier and Senderens (2000), discovered the methanation reactions of COx. The equations for the methanation of CO and CO_2 are as follows:

$$CO + 3H_2 \rightarrow CH_4 + H_2O \quad (8)$$

$$C0_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (9)$$

The products of equations 8 and 9 are the cooking gas called methane. Therefore, the principal processes include generation of CO and CO_2 from organic matters and then converting them into methane gas. For Inui and Takeguchi (1991), it should be noted that the methanation of CO_2 is still the thermodynamically most favorable hydroprocessing reaction for this type of molecule, when compared to the production of other hydrocarbon or alcohol. For Rihko-Struckmann et al. (2010), the heterogeneous catalyzed thermochemical reforming of CO_2 into energy products such as methanol, methane or longer hydrocarbons is well known and is as shown in Figure 12.

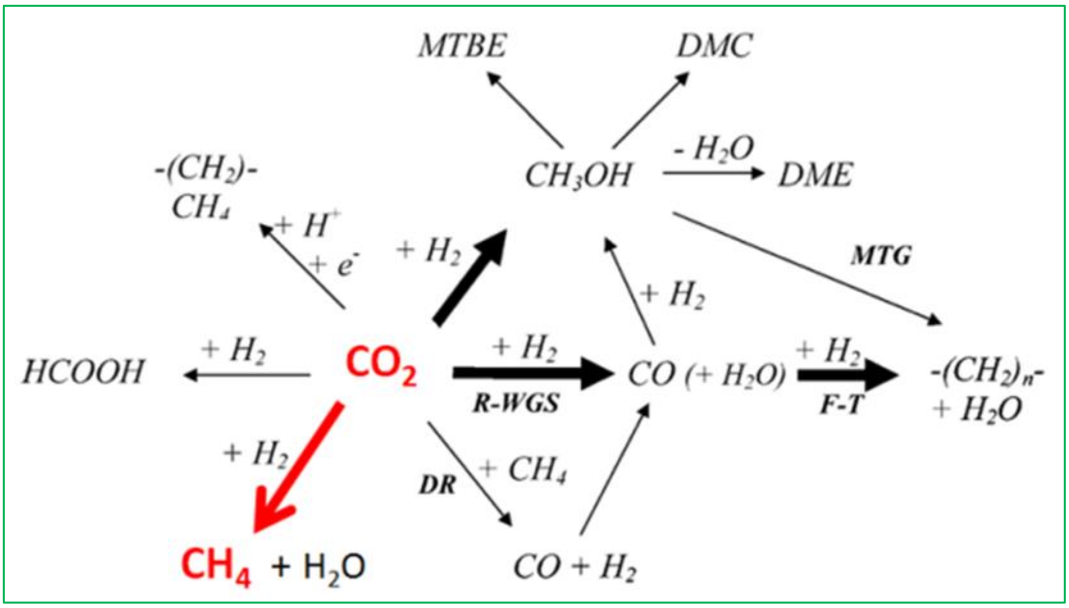

Figure 12: Principal Routes for Utility of CO_2 as an Energy Carrier Using Heterogeneous Catalysis

5.4.2. Harmful Products

During the electrochemical decomposition of organic compounds, certain intermediary products are produced. Most of these products are more toxic than the parent material. The elimination of these by-products becomes more crucial. Rusling (1994), opined that since benzoquinone is more harmful than phenol itself, it is best to get rid of it as quickly as possible as it is a step in the phenol's destruction process. According to Bureau (2004), electrochemically treated sludge contains trihalomethanes (THMs), polycyclic aromatic hydrocarbons (PACHs), and monocyclic aromatic hydrocarbons (MAHs). These compounds' concentrations, meanwhile, are too low to be deemed hazardous. The presence of trichloromethane (chloroform) and dichloromethane in the treated sludge is also noted. The work of Delatt (1981) demonstrated the enhancement of trihalomethane synthesis by chorophenol. For Savall (1995), even though phenol is the ideal model molecule for aromatic ring effluents, a little two electron exchange can alter the molecule's structure, turning phenol into hydroquinone and making it extremely difficult to reach the CO_2 terminal stage. Więckowski (1981) found out that one of the materials whose carbon-oxygen linkages are adsorbed on the working face of the sensor is platinum. Biological Structures' ability to oxidize is restricted by this absorption.

5.5. Challenges and Future Works of Electrochemical Decomposition of Organic Matters

5.5.1. Challenges

Despite the considerable advances made in the electrochemical treatment of organic matter, a number of issues remain unresolved. Radjenovic and Sedlak (2015) creating by-products is the biggest obstacle. Efficiency losses brought on by restrictions on mass transfer and unfavorable side effects are added to this. Martínez-Huitle et al. (2023) wrote an article that condensed these difficulties into seven (7) points. He claims that the following issues are still unsolved:

- There is inadequate understanding of the proportion of both direct and indirect processes
- There is little use of electrically produced oxides as an in situ or ex situ oxidation approach.
- Oxidant electrosynthesis still yields low current efficiency.
- Reactive species' stability, or half-life, is still poorly understood.

When comparing the treatment of water synthesis matrices, differences arise in the impacts of the parameters due to differences as well as the existence of oxidant interceptors.

- A few stubborn organic byproducts are produced at random.
- The varied nature of the reactive species results in limits during oxidation, depending on the anode surface or volume.

5.5.2. Future Research Works

The greatest challenge to the use and adoption of electrochemical treatment of organic matter remains the formation of by-products. Work must focus on solutions to reduce or eliminate the production of these by-products and reduce the losses or decrease in efficiency. At the same time as, or before, these corrections, the conditions under which these products are formed and their impact on human health must be determined as accurately as possible. To broaden the scope of electrochemical treatment of organic matter, further efforts should concentrate on the behavior of different electrode materials on the decomposition of pasty organic matter. These studies will make it possible to make progress in the production of gaseous fuels such as methane to meet current energy challenges. After the terminal stage of CO_2, studies must continue to be able to explore the routes available to convert $C0_2$ into methane thanks to the methanation route. Future research should address the removal of carbon from the electrochemical output of organic matter by removing carbon from oxygen to decompose the CO_2 produced or other carbon substrates present.

6. Conclusion

The use of electrochemistry is already being implemented in the treatment of used water. This technique is also used in the depollution of industrial waste to reduce their toxicity to the environment. We can note that several researches are carried out in the area of the electrochemical degradation of organic compounds. The majority of this work is carried out in the context of water treatment and the decomposition of organic compounds found in water. Whether in the choice of electrode materials, the electrolysis catalyst or the decomposition techniques used, we note a very significant advance in the technology of electrochemical decomposition of solid substances. It should be noted that the choice of electrode material is very crucial to guarantee high performance. For the application of this technique, two types of electrodes are generally used. They use electrodes made of metal oxides and diamonds doped with boron. In the literature, boron-doped diamond electrodes appear to have greater efficiency thanks to their high anodic activity. The biggest problems in using these electrodes are the high cost of their production and the production technique which is relatively more complex than those made of metal oxide. When the conditions are well met with regard to voltage, intensity, catalysis, treatment time and others, waste treatment is easier and more efficient regardless of the electrode material used. Otherwise, we see the production of certain intermediates which are more toxic and polluting than the simple material. This is for example the case of benzoquinone which is a more toxic by-product than phenol, the simple composition. In the case of normal decomposition, we reach the terminal stage of CO_2. This terminal stage is the very essential for the production of fuels. When the terminal stage of CO_2 is reached, both CO_2 and dihydrogen are produced. These two compounds are therefore used to produce methane by a hydrogenophilic route or by methanation. The methane obtained in this process is the usual cooking gas which are universally used for culinary purposes by households. For further research in the field of electrochemical treatment of organic matter, we recommend that very advanced experiments must be carried out focusing on the increasing the efficiency and quantity of cooking gas produced with the electrochemical decomposition of organic matter. Research be directed towards quantifying CO_2 and hydrogen produced from organic matter. Research should be interested in a more cost effective method of producing boron-doped diamond electrodes. Avenues should be explored for its use in the production of methane using organic materials that are pastier than what has been used before now. Research should be carried out on improving the efficiency of metal oxide electrodes

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Conflict of Interest

There is no conflict of interest to declare whatsoever

Author Contributions

RDS, COU, DVVK and GDFA conceived and developed the research; RDS, DVVK, GDFA and COU supervised, reviewed and analyzed the data; RDS, DVVK, GDFA and COU collected and analyzed the data

Data Availability Statement

The datasets generated and/or analyzed in this article are contained in it.

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