



A Novel Approach to Brewery Effluent Treatment: Adsorption, Electrochemical Oxidation, and in Situ Regeneration for Efficient Nitrogenous Pollutants Removal

Romuald Teguia Doumbi · Koutou Allahossem · Djonga Weldi Gnowe · Lys Carelle Motue Waffo · Ebio Nko'o Guillaume · Jean Marie Dikdim Dangwang · Tinda Domga · Benguene Ngobtchok · Eric Noubissié · Guy Bertrand Noumi · Marcio Assolin Correa

Received: 13 November 2025 / Accepted: 21 March 2026 / Published online: 26 March 2026
© The Author(s) 2026

Abstract Nitrogenous pollutants from wastewater pose a serious environmental concern and have to be managed by an efficient treatment technique. In this context, the main objective of this study was to remove nitrogenous pollutants (NH_4^+ , NO_3^- , and NO_2^-) from real brewery effluent using an adsorption (AD) process and to regenerate the saturated adsorbent through a direct anodic oxidation (DAO) process. The regeneration aimed at enabling the reuse of the adsorbent for additional applications. The experiments were conducted on brewery effluent sampled in N'Djamena (Chad). Adsorption tests were performed in batch mode by mixing a volume of effluent with a specific amount of activated carbon (AC) prepared from the core shell of *Balanites*

Aegyptiaca. Based on the characterization results, the activated carbon exhibited an amorphous graphitic structure with the main functional groups (O–H, C–O, C=O), and a micro- and mesoporous structure showing a specific surface area of $153 \text{ m}^2 \text{ g}^{-1}$. DAO was employed to enhance adsorption efficiency and to regenerate the active sites of the AC that had been previously saturated with pollutants. The maximum adsorption capacities for NH_4^+ , NO_3^- , and NO_2^- ions were 40.16, 34.13, and 28.82 mg/g, respectively. The adsorption kinetics followed a pseudo-second-order model. Thermodynamic analysis revealed that the adsorption is endothermic with low enthalpy values ($\Delta H^\circ = 3.40\text{--}9.02 \text{ kJ/mol}$), confirming that the adsorption mechanism is predominantly governed

R. T. Doumbi (✉) · M. A. Correa
Postgraduate Program in Materials Science
and Engineering, Federal University of Rio Grande Do
Norte, Natal, RN 59078-970, Brazil
e-mail: romuald.teguia.048@ufrn.edu.br

R. T. Doumbi · M. A. Correa
Department of Physics, Federal University of Rio Grande
Do Norte, Natal, RN 59078-970, Brazil

R. T. Doumbi · K. Allahossem · D. W. Gnowe ·
E. N. Guillaume · B. Ngobtchok · G. B. Noumi
Department of Chemistry, Faculty of Science, University
of Ngaoundere, PO Box. 454, Ngaoundere, Cameroon

L. C. M. Waffo
Department of Chemistry, Faculty of Science, University
of Douala (UD), PO Box. 24157, Douala, Cameroon

J. M. D. Dangwang
Department of Chemistry, Faculty of Science, University
of Maroua, PO Box. 814, Maroua, Cameroon

T. Domga
Department of Chemical Engineering, School of Chemical
Engineering and Mineral Industries (EGCIM), University
of Ngaoundere, PO Box. 454, Ngaoundere, Cameroon

E. Noubissié
Department of Chemical Engineering, University Institute
of Technology, University of Ngaoundere (UN), PO
Box 455, Ngaoundere, Cameroon

by physisorption involving Van der Waals forces and electrostatic interactions. The regeneration efficiency of saturated activated carbon via the DAO process was 84.29%, 88.57%, and 40.83% for NH_4^+ , NO_2^- , and NO_3^- ions, respectively. Based on these findings, coupling AD and DAO processes is a viable method for treating effluents containing nitrogenous pollutants and effectively regenerates AC.

Keywords Adsorption · Activated carbon · Brewery effluent · Direct anodic oxidation · Nitrogenous pollutants · Regeneration

1 Introduction

Water is an essential resource for all living beings and is highly used in human activities. With continued population growth, global water demand has risen steadily. Rapid urbanization, together with the expansion of industrial and agricultural sectors, has further intensified pressure on water resources. As a result, increasing volumes of wastewater are generated, contributing over time to the deterioration of water quality (Sun et al., 2025). In the beverage manufacturing industry, water plays multiple roles, including use in production, packaging, rinsing, cleaning, cooling, and sanitation processes. Freshwater consumption in this sector is substantial, with estimates of approximately 3.0 L of water required per liter of soft drink produced and about 7.5 L per liter of beer manufactured (Nascimento et al., 2025; Pettigrew et al., 2015). Consequently, beverage production generates large volumes of wastewater on a daily basis, often containing a diverse mixture of organic and inorganic pollutants (Pettigrew et al., 2015). The diversity of raw materials used, such as sugars, starches, ethanol, colorants, and fatty acids, combined with variations in rinsing operations for tanks and bottles, as well as facility cleaning procedures, leads to significant variability in effluent composition and characteristics (Arumugam et al., 2025; Zapata-Martínez et al., 2024).

Contamination of brewery effluents often arises from nitrogen and phosphorus inputs found in detergents and disinfectants, alongside the presence of pathogenic and non-pathogenic organisms (Gnowe Djonga et al., 2021). Water pollution threatens rivers, seas, groundwater, and lakes, primarily through the discharge of untreated or inadequately treated

wastewater, which triggers ecosystem degradation (Zapata-Martínez et al., 2024). These discharges introduce substantial quantities of organic matter and nutrients (nitrogen and phosphorus) into surface waters, disrupting the natural equilibrium of aquatic ecosystems (Machida et al., 2019). The most apparent consequence of this pollution is the eutrophication of rivers and lagoons, characterized by excessive algal blooms, increased turbidity, and distinct colour changes (Innes et al., 2021). Furthermore, the resulting oxygen depletion poses a significant mortality risk to aquatic life. Numerous studies have established a direct correlation between nutrient concentrations, specifically phosphate and nitrogen, and eutrophication (Ji et al., 2024; Raza et al., 2025). Consequently, reducing phosphate or nitrate inputs would limit primary production. From this perspective, phosphorus and nitrogen act as the primary limiting factors in these ecosystems; thus, targeting them is an effective strategy to combat eutrophication (S et al., 2023; Zapata-Martínez et al., 2024). Given that wastewater is the principal source of nitrogen loading, denitrification represents a promising method for mitigating eutrophication and safeguarding water resources.

To eliminate or reduce pollution caused by nitrogenous compounds, a range of depollution techniques has been developed in recent years (Gnowe et al., 2020; Li et al., 2025a, 2025b; Zouaoui et al., 2025). Incineration, physicochemical treatments, and conventional chemical oxidation methods present several drawbacks in terms of feasibility for biorefractory organic pollutants, overall effectiveness, and cost (Doumbi et al., 2022; Farghali et al., 2024). Although some physicochemical and biological purification processes can be highly efficient, many merely transfer pollution to another phase through the generation of sludge. Other treatment approaches include filtration, electrocoagulation, indirect anodic oxidation, and adsorption (Guo et al., 2025; Li et al., 2026; Namla et al., 2025; Wang et al., 2025). More recently, adsorption has attracted considerable attention among researchers (Jafarinejad & Esfahani, 2021; Jathan & Marchand, 2024; Namla et al., 2025; Wang et al., 2025). Adsorption may be defined as the accumulation of a substance at the solid–liquid interface, whereas desorption refers to the release of molecules previously retained on a solid surface (Jalilian et al., 2026).

Adsorption using activated carbon (AC) is widely applied in the treatment of industrial aqueous effluents, particularly for the removal of toxic, refractory, and non-biodegradable compounds (Abia et al., 2019). Once the adsorbent becomes saturated, it is typically destroyed by incineration or disposed of in a landfill, both of which are costly from economic and environmental perspectives (Takigami et al., 2014). To overcome this limitation, reactivation techniques have been developed to enable the reuse of adsorbents, including activated carbons (Quimada et al., 2024). While most conventional studies have focused on thermal or chemical regeneration using commercial activated carbons or traditional biomass precursors (such as coconut shells and rice husks), there remains a clear need to investigate sustainable, locally available biomass sources combined with cleaner regeneration technologies.

While conventional studies have primarily focused on thermal or chemical regeneration methods using commercial activated carbons or conventional biomass precursors (coconut shells, rice husks), there remains a critical need to explore sustainable, locally available biomass sources coupled with cleaner regeneration technologies. Within this context, the core shell of *Balanites aegyptiaca* (BA), which is abundantly available in northern Cameroon, is one potential candidate for activated carbon. To date, *Balanites aegyptiaca* shells have been underutilized as an activated carbon precursor for wastewater treatment applications, despite their local abundance and potential as a sustainable, zero-waste biomass resource. *Balanites aegyptiaca* appears as a sustainable adsorbent precursor with zero damage to the environment and has already demonstrated good performance in the removal of organic and inorganic pollutants from the adsorption process (Adam & Al-Shammari, 2023; Kada et al., 2024; Magaji et al., 2020).

The technique adopted in this work is based on coupling adsorption–desorption with a direct anodic oxidation (DAO) using a graphite electrode. The DAO process is an advanced oxidation process based on the *in-situ* generation of hydroxyl radicals, which possess a very high oxidation potential. Unlike previous studies that have examined adsorption and electrochemical regeneration separately, using synthetic wastewater or single-pollutant model solutions, the present work provides the first systematic integration of bio-based activated carbon adsorption with DAO

regeneration specifically applied to the treatment of real brewery effluent.

This combined approach enables the removal of pollutants initially adsorbed onto the activated carbon (AC), followed by their electrochemical oxidation to nitrogen gas, while simultaneously restoring the adsorption sites of the AC (Alabi et al., 2018; Gahrouei et al., 2024; Mirshafiee et al., 2024). The investigation of such a system, therefore, requires kinetic measurements during both the adsorption stage and the subsequent desorption–electrochemical regeneration phase. DAO represents a clean and suitable option for wastewater depollution, as it does not require the addition of chemical oxidants and produces minimal secondary by-products that would otherwise necessitate further treatment (Motue Waffo et al., 2022; Tegui Doumbi et al., 2023).

Moreover, to the best of our knowledge, the literature still lacks studies that comprehensively address the integrated approach proposed here. In particular, the use of *Balanites aegyptiaca* shells as a sustainable and locally abundant precursor for the production of activated carbon targeting the removal of nitrogenous pollutants from industrial wastewater remains largely unexplored. Although bio-based adsorbents have been widely investigated, their application to real effluents with complex chemical matrices, rather than simplified synthetic solutions, has received limited attention. In this context, the present work introduces an innovative coupling between bio-derived activated carbon adsorption and direct anodic oxidation for the treatment of real brewery effluent. This integrated strategy goes beyond conventional adsorption studies by considering the synergistic interaction between adsorption and electrochemical regeneration under realistic operating conditions. Such an approach is scarcely reported in the literature and addresses a critical gap between laboratory-scale demonstrations and practical wastewater treatment applications. Furthermore, the systematic evaluation of regeneration efficiency and adsorbent reusability over multiple adsorption/desorption cycles provides industrially relevant evidence of process sustainability, an aspect frequently overlooked or only superficially discussed in previous studies. Finally, the comprehensive physicochemical characterization presented herein enables mechanistic insight into both the adsorption behavior and the electrochemical regeneration process in real wastewater systems.

Taken together, these aspects highlight the originality and relevance of this study, as they combine sustainable material development, treatment of real complex effluents, process integration, and long-term performance assessment, elements that are not simultaneously addressed in the current literature and therefore justify the present investigation.

The objective of this work is to investigate the removal of nitrogenous ions from real brewery effluent through the combined application of adsorption and direct electrooxidation processes for activated carbon regeneration.

2 Materials and Methods

2.1 Chemical, Sampling, and Characterization of the Brewery Effluent

All chemicals used in this study were analytical grade and were used without further purification. Hydrochloric acid (HCl, 36.5%), sulfuric acid (H₂SO₄, 98.0%), sodium hydroxide (NaOH, 99.5%), silver nitrate (AgNO₃, 98.5%), and phosphoric acid (85.0%) were from Sigma-Aldrich. Deionized water was used for all the experiments.

The effluent was sampled from the N'Djamena brewery (Chad). The sampling was done by collecting water from four distinct wastewater discharge points within the factory. Each sample was mixed and filtered to remove suspended solids. The samples were mixed and homogenized to get a representative brewery effluent sample. The pH, temperature, conductivity, and turbidity of the effluent were measured in situ at the sampling site using a multi-parameter (PCE-PHD). The turbidity was measured using the Hanna brand turbidimeter. The samples were put in polyethylene bottles and kept in a cooler at 4 °C before the analyses and treatment study. The chemical characterization of the brewery effluent consisted of the determination of the concentrations of ammoniacal nitrogen (NH₄⁺), nitrite (NO₂⁻), nitrate (NO₃⁻), chloride (Cl⁻), sulphate (SO₄²⁻), and chemical oxygen demand (COD) following the methods described by Rodier (2016). To ensure the reproducibility of the measurements, the procedures were conducted three times.

2.2 Preparation of Adsorbent Material

The biomass used for producing the adsorbent is the core shell of *Balanites Aegyptiaca*. These shells were collected in the Maroua market in the Far North region of Cameroon. Figure 1 summarizes the main steps involved in preparing the adsorbent material. The fruits were first peeled, and then the core shells were collected and washed thoroughly with deionized water. They were then dried at room temperature for 5 days. Thereafter, they were crushed to separate the hulls from the core. The hulls were crushed using a ball mill and then sieved using a sieve to retain only particles with a particle size of less than 200 µm. The substrate (300 g) retained was impregnated in 1.2 L of a solution of phosphoric acid (2 N) with a ratio of 1 g per 4 mL. The mixture was stirred at room temperature for 24 h, then filtered through filter paper and finally dried in an oven at 105 °C for 24 h. The chemically activated substrate subsequently underwent carbonization at 550 °C (5 °C/min) for 2 h in a muffle furnace (Nabertherm brand). The obtained activated carbon (AC) was washed 10 times with deionized water to remove the excess H₃PO₄ until pH stabilization. After washing, the AC was dried in an oven at 105 °C for 24 h (Gueye et al., 2014; Machida et al., 2019).

2.3 Physicochemical Characterizations of the Adsorbent

FTIR spectroscopy was used to determine the functional groups present on the adsorbent surface. The FTIR spectrophotometer (Agilent FTIR 51420) was employed. The thermal stability of the adsorbent was evaluated using the Thermogravimetry analysis associated with differential thermal analysis (DTG-60H simultaneous DTA-TG instrument). The structural properties of the adsorbent were determined by the X-ray diffraction analysis using the Bruker D8 Advance X-ray Diffractometer. The Cu Kα target ($\lambda = 1.5406 \text{ \AA}$) was employed within a 2θ range of 15° to 70°. Field emission scanning electron spectroscopy coupled to the X-ray energy dispersive spectroscopy (FESEM-EDS, FEG-SEM Zeiss Supra 35-Vp) was used to study the morphological properties of the activated carbon and its chemical composition. A laser Raman microscope (LabRam

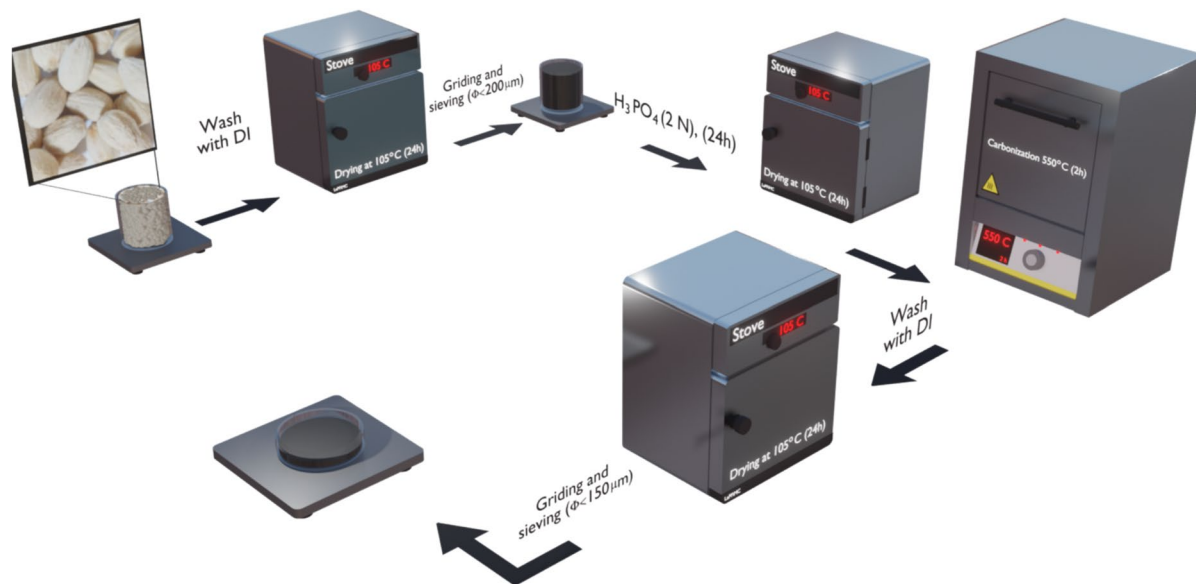


Fig. 1 Schematic diagram describing the main steps carried out for the synthesis of activated carbon (AC): starting from the pre-treatment of the precursors following by the chemical activation in H_3PO_4 (2N) and the thermal treatment at 550 °C

HR, Horiba) with a 633 nm wavelength has been employed to record the Raman spectra. The specific surface area of the catalyst was measured using the Brunauer–Emmett–Teller (BET) method with the BELSORP Mini-II instrument.

The iodine index (IN) is one of the methods for measuring the adsorption capacity of an adsorbent while indicating its microporosity. It is the number of milligrams of iodine adsorbed per gram of adsorbent at a residual concentration of 0.02 N. It was determined by bringing 1 g of activated carbon previously dried at 105 °C in contact with 10 mL HCl (0.01 M), stirring slowly, and bringing to a boil for 30 s. In the following, 100 mL of the iodine solution was added to the mixture and maintained under stirring for 4 min. After filtration, 50 mL was taken to determine the residual concentration of iodine by titration with a sodium thiosulfate solution (Dehmani et al., 2025). The iodine index was calculated according to the following equation:

$$\text{Iodine index (mg/g)} = \frac{[1269.1 - (V' \times 27.92)] \times D}{m} \quad (1)$$

where D is the correction factor given by,

$$D = \left(\frac{0.01}{R} \right)^{0.165} \quad (2)$$

and R , the molarity described as:

$$R = \frac{0.001 \times V'}{2} \quad (3)$$

m (g) is the mass of the AC and V' the volume (mL).

The pH point of zero charge (pH_{PZC}) is defined as the pH at which the positive charge on the surface of an adsorbent is equal to the negative charge. To determine the pH_{PZC} , we prepared sodium chloride solutions (0.1 M NaCl) at different pH (2, 4, 6, 8, 10). The pH values were adjusted through a pH meter using sodium hydroxide (0.1 M) and hydrochloric acid (0.1 M) solutions. In the following, 0.1 g of AC was brought into contact with 20 mL of each solution. The mixture was stirred magnetically for 24 h. The suspension was filtered through filter paper, and the pH of the filtrate was measured, which made it possible to draw the curve $\Delta\text{pH} = f(\text{pH}_i)$ (Abia et al., 2019; Tebeje et al., 2022).

2.4 Study of the Adsorption of Nitrogenous Pollutants from Brewery Effluent

The adsorption study was carried out in batch mode, and this makes it possible to determine the adsorption mechanisms (pollutant-adsorbent interaction) and the adsorption effects on which the adsorption capacity of the activated carbon depends. The parameters indicating the adsorption performance of the AC obtained from *Balanites Aegyptiaca* shells were investigated by dispersing the adsorbent in 100 mL of brewery effluent under stirring at 250 rpm. The operational factors were the contact time, the initial concentration of the brewery effluent, pH, and the temperature of the medium. For all adsorption tests, the AC was removed after equilibrium by filtration. The residual concentrations of ammonium, nitrite, and nitrate were analysed by spectrophotometry. The quantities of ions adsorbed at equilibrium and the removal efficiencies were calculated according to the relationships (5) and (6), respectively.

$$Q_{ads} = \frac{(C_0 - C_e) \times V}{m} \quad (4)$$

$$R(\%) = \frac{(C_0 - C_e)}{C_0} \times 100 \quad (5)$$

where Q_{ads} is the adsorbed quantity (mg/g), C_0 the initial concentration of the ions (mg. L⁻¹), C_e the equilibrium concentration (mg. L⁻¹), m the mass of adsorbent (g), and V the volume of the effluent (L).

2.5 Kinetic Study of the Nitrogen Pollutants' Adsorption on Activated Carbon

In the case of the pseudo-first-order reaction, the rate constant is deduced from the model established by Lagergren. This mathematical model was chosen due to its simplicity and application in the field of the adsorption of compounds on different adsorbents (Santos et al., 2025; Milakin et al., 2025). The adsorption rate is proportional to $(q_e - q_t)$ and can therefore be described by the following relationship,

$$\frac{dq_t}{dt} = k_1(q_e - q_t) \quad (6)$$

where q_e (mg g⁻¹) is the quantity of the pollutant adsorbed at equilibrium, q_t (mg g⁻¹) is the quantity

adsorbed at time t , k_1 is the Lagergren rate constant, and t is the contact time.

The integration of Eq. (7) between 0 and t for the time and between 0 and q_t for the adsorbed quantity makes it possible to obtain the linear form of Lagergren:

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad (7)$$

$$\log(q_e - q_t) = \log q_e - \log \frac{k_1}{2.303} t \quad (8)$$

Plotting the curve $\ln(q_e - q_t)$ as a function of t makes it possible to determine the constant k_1 and the quantity adsorbed at equilibrium q_e (David Léonce et al., 2023).

The rate of the pseudo-second order reaction depends on the quantity adsorbed on the surface of the adsorbent and the quantity adsorbed at equilibrium. The pseudo-second-order kinetics equation obeys the following relationship (David Léonce et al., 2023),

$$\frac{dq_t}{dt} = k_2(q_e - q_t)^2 \quad (9)$$

where q_e (mg/g) is the quantity of the pollutant adsorbed at equilibrium, q_t (mg/g) is the quantity adsorbed at time t , and k_2 is the rate constant of the second-order kinetic model (mg g⁻¹ min⁻¹). The integration of equation (Eq. 10) between 0 and t for time and between 0 and q_t for the adsorbed quantity makes it possible to obtain the linear form of the pseudo-second-order model, given by,

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \left(\frac{1}{q_e} \right) \quad (10)$$

From this analysis, it is possible to determine the constant K_2 and the quantity adsorbed at equilibrium q_e .

2.6 Modelling of Adsorption Isotherms of Nitrogenous Pollutants from Brewery Effluent on AC

Several laws (models) have been proposed for the study of the adsorption process. They express the relationship between the quantity adsorbed and the solution concentration of the pollutant at a given

temperature. The models used in this work were the Langmuir (Eq. 12), the Freundlich (Eq. 14), and the Temkin (Eq. 15) models (Zheng et al., 2024),

$$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{K_L q_m} \quad (11)$$

With q_e the adsorbed quantity of the solute at equilibrium and q_m the maximum adsorption capacity expressed in mg/g, C_e the concentration of the solute at equilibrium in (mg/L), and K_L the Langmuir constant expressed in $\text{L} \cdot \text{mg}^{-1}$.

The R_L ratio (Eq. 13) is a unitless quantity indicating whether the adsorption is all the more favourable as R_L tends towards zero ($R_L \rightarrow 0$) and all the more unfavourable as R_L tends towards unity ($R_L \rightarrow 1$) (Adam & Al-Shammari, 2023),

$$R_L + \frac{1}{1 + K_L C_0} \quad (12)$$

where C_0 is the initial concentration of the pollutant expressed in (mg L^{-1}),

$$\log q_e = \log k_f + \frac{1}{n_f} \log C_e \quad (13)$$

where q_e is the quantity adsorbed per gram of the adsorbent, C_e is the concentration of the adsorbate at equilibrium, K_f and $1/n_f$ are the Freundlich constants characterizing the effectiveness of a given adsorbent with respect to a given solute. If $n > 1$, then the adsorption is quantitatively greater, and if $n < 1$, the adsorption is weak (Magaji et al., 2020),

$$q_e = B \ln(A) + B \ln(C_e) \quad (14)$$

with $B = (RT)/b$, where R is the ideal gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$), T is the absolute temperature (K), A is the Temkin constant ($\text{L} \cdot \text{mg}^{-1}$), and b is the heat adsorption (J mol^{-1}).

2.7 Study of Regeneration of Adsorption Sites on the Surface of Activated Carbon

The electrochemical regeneration of adsorbents saturated with pollutants was studied in an electrochemical cell with a graphite rod as the working electrode and counter electrode with an effective surface area of 12.058 cm^2 . Desorption experiments were carried out on activated carbon saturated with nitrogenous

pollutants (NH_4^+ , NO_2^- , NO_3^-) following the adsorption of nitrogenous pollutants from brewery effluent. The study consisted of monitoring the desorption kinetics and evaluating the regeneration rate of the adsorption sites on the surface of the activated carbon. Thus, 0.15 g of adsorbent saturated with pollutants is brought into contact with 100 mL of an aqueous solution of Na_2SO_4 with a concentration of 0.1 M (pH=3), serving as a support electrolyte for the regeneration of the AC by electrolysis, and the sample is continuously stirred at room temperature until reaching the equilibrium. When the desorption equilibrium was reached, a sample was taken to determine the pollutant concentration at the desorption equilibrium, which also corresponded to the initial concentration of the electrochemical oxidation step. This process is called simple desorption. A constant current intensity is then applied, and samples are taken at regular time intervals, filtered, and analysed. The current intensity is applied by using an adjustable DC power supply unit, LW LONGWEI LK-K30100-China. It should be noted that after carrying out a first electrochemical regeneration, the adsorbent is recovered by filtration, washed, and then dried in an oven at 105°C before undergoing a second adsorption cycle. The efficiency of regeneration of the adsorbent noted (E), by electrolysis on a graphite electrode, was defined as the ratio between the adsorption capacity of the adsorbent after regeneration (Q_r) (mg/g), and the initial adsorption capacity (Q_i) (mg/g) (Teguia Doumbi et al., 2023):

$$E = \frac{Q_r}{Q_i} \times 100 \quad (15)$$

The removal of nitrogenous charge by direct anodic oxidation is influenced by several operating parameters, including current intensity, electrolysis time, the concentration of the supporting electrolyte (Na_2SO_4), and the pH of the medium. The pH of the medium was kept at 3. The following formula, therefore, calculates the elimination rate (TE) of nitrogenous ions (Teguia Doumbi et al., 2023):

$$TE = \frac{C_0 - C_f}{c_0} \times 100 \quad (16)$$

with C_0 and C_f , the initial and final concentrations, respectively.

3 Results and Discussion

3.1 Physicochemical Characterization of the Adsorbent

Figure 2 depicts the scanning electron microscopy (SEM) of the activated carbon. The micrograph reveals the porous structure of the adsorbent. This porosity could be due to the interaction between the activating agent and the biomaterial, leading to the release of most organic volatiles during the synthesis process. At this stage, it can also be observed that the amorphous graphitic structure of the activated carbon. To highlight this issue, Fig. 2b shows details of the pores, which present different sizes. This feature provides an improvement of adsorption sites for the nitrogenous pollutants. The elemental chemical composition of the activated carbon was carried out by EDS analysis, as depicted in Fig. 2c–e. From the results, a uniform distribution of carbon (Fig. 2c), oxygen (Fig. 2d), and nitrogen (Fig. 2e) on the surface of the activated carbon was observed. To confirm this texture and chemical composition, the FTIR, Raman, BET, and XRD analyses have been done, and the results are presented in the following.

The TGA/DTA analyses were used to determine the thermal stability of the adsorbent. The TGA analysis, depicted in Fig. 3a, shows a main loss mass at around 59–150 °C, which is related to the moisture and water removals. The second mass loss happens at a temperature range of 290–361 °C. This should be related to the degradation of hemicellulose and cellulose. The DTA curve shows an endothermic event at 355 °C, associated with this reaction. From 361 to 1000 °C, we notice a low mass loss, which could be due to the degradation of the lignin and formation of carbon material (Louarrat et al., 2019). The decomposition of the lignin is done at a slow rate due to the complexity of the material.

FTIR spectroscopy was used to identify the chemical groups on the sorbent's surface. The FTIR spectrum is shown in Fig. 3b where it is possible to observe a strong peak around 3425 cm⁻¹, which could be associated to the OH stretching vibration from hydroxyl groups. The absorption band at 1100 cm⁻¹, attributed to the asymmetric stretching vibration of C–O in aromatic ethers, esters, and phenols, confirms the presence of hydroxyl groups on the catalyst. The vibrations around 1620 and 1501 cm⁻¹ likely

originate from C=C stretches in aromatic rings present in biomass (Adam & Al-Shammari, 2023). The peak observed at around 1725 cm⁻¹, corresponds to the stretching vibration of the C=O carbonyl group of lignin and hemicellulose. The deformation band near 615 cm⁻¹ can be assigned to C–H bonds (Lékéné et al., 2018).

Figure 3c shows the Raman spectroscopy employed to characterize the activated carbon. It can be observed from these results that the spectrum shows two main peaks, denoted D and G bands, around 1332 and 1600 cm⁻¹, respectively (Ali et al., 2020; Costa E Silva et al., 2018). The broad D-band is attributed to a defective or disordered carbon structure, while the narrower G-band refers to the ordered sp²-bonded carbon atoms in a two-dimensional hexagonal lattice or graphitic structure. The intensity ratio (I_D/I_G) of the D to G bands of the activated carbon is around 0.90. Successful carbonization during heat treatment can be observed through the presence of the main graphite peaks in the structure of the AC.

The XRD pattern of the prepared activated carbon is presented in Fig. 3d. From this figure, it is observed that AC shows two main diffraction peaks located at around 23° and 43°, which can be indexed to the (002) and (100) lattice planes of graphitic carbons (JCPDS No 75–1621), respectively (Shiryaev et al., 2023). The calculated interlayer spacing from Bragg's law for the (002) peak is 0.331 nm. However, it is important to note that the peak around $2\theta \approx 23^\circ$ is broad, indicating that the AC possesses a lower degree of graphitization and high disorder. This can be due to the activation of the precursor material and the carbonization at low temperature. In conclusion, we can notice that the as-prepared activated carbon has a structure close to carbonaceous phase domain sizes and exhibits an amorphous graphitic phase (Ray et al., 2023).

Figure 3e shows the BET results for the studied AC. According to the IUPAC classification, the adsorbent exhibited an IV-type isotherm, which relates to the micro- and mesoporosity of the material, resulting in good nitrogen adsorption at very low relative pressure (Jalilian et al., 2026). This confirms the results obtained from the iodine number measurement, as shown below. The specific surface area of the activated carbon was 153 m²/g. The average pore diameter (3.93 nm), measured using the Barrett-Joyner-Halenda (BJH) method, is shown in Fig. 3f. It

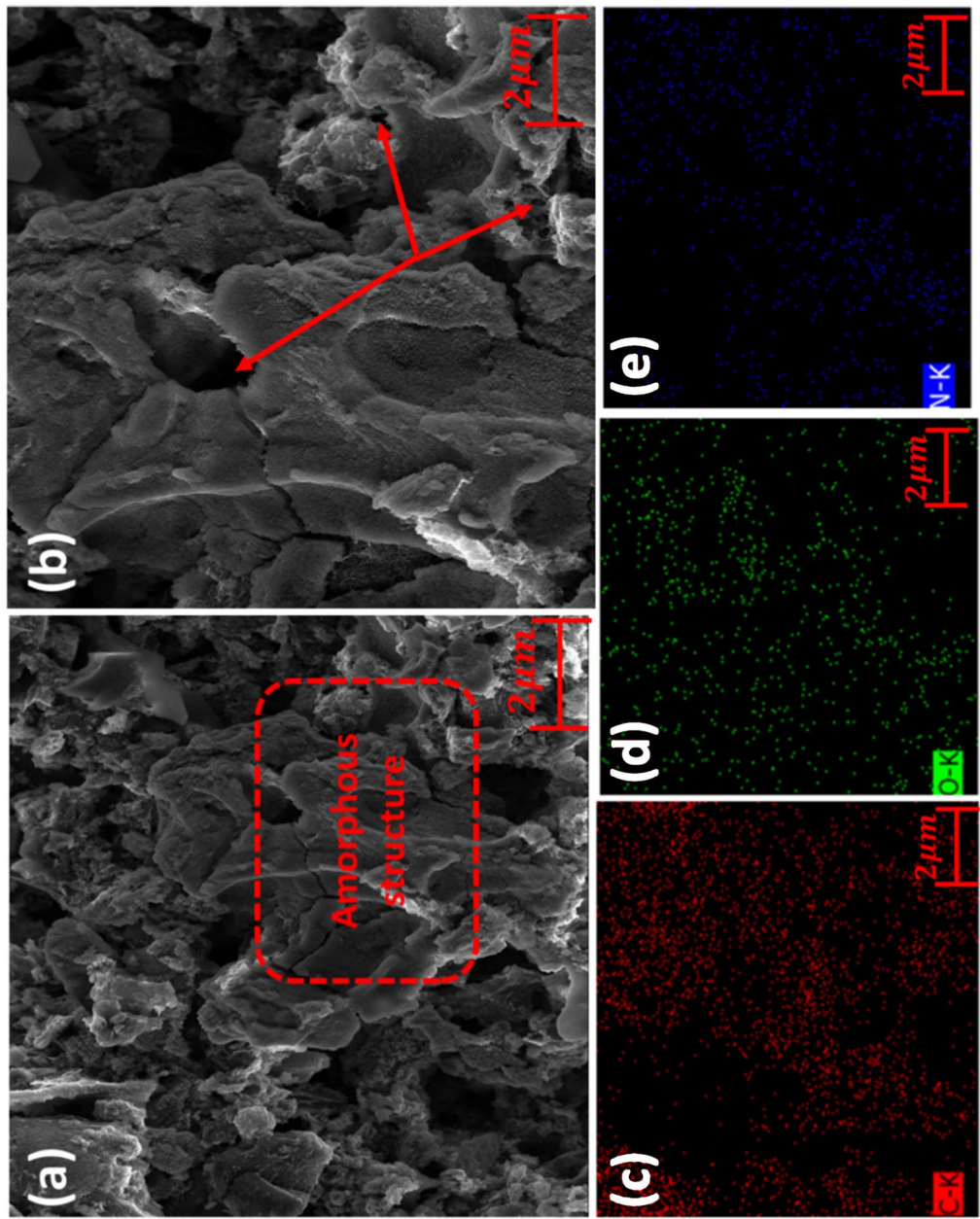


Fig. 2 SEM images $4000 \times$ **a**, $8000 \times$ **b**, carbon distribution **c**, oxygen distribution **d**, and nitrogen distribution **e** of the activated carbon

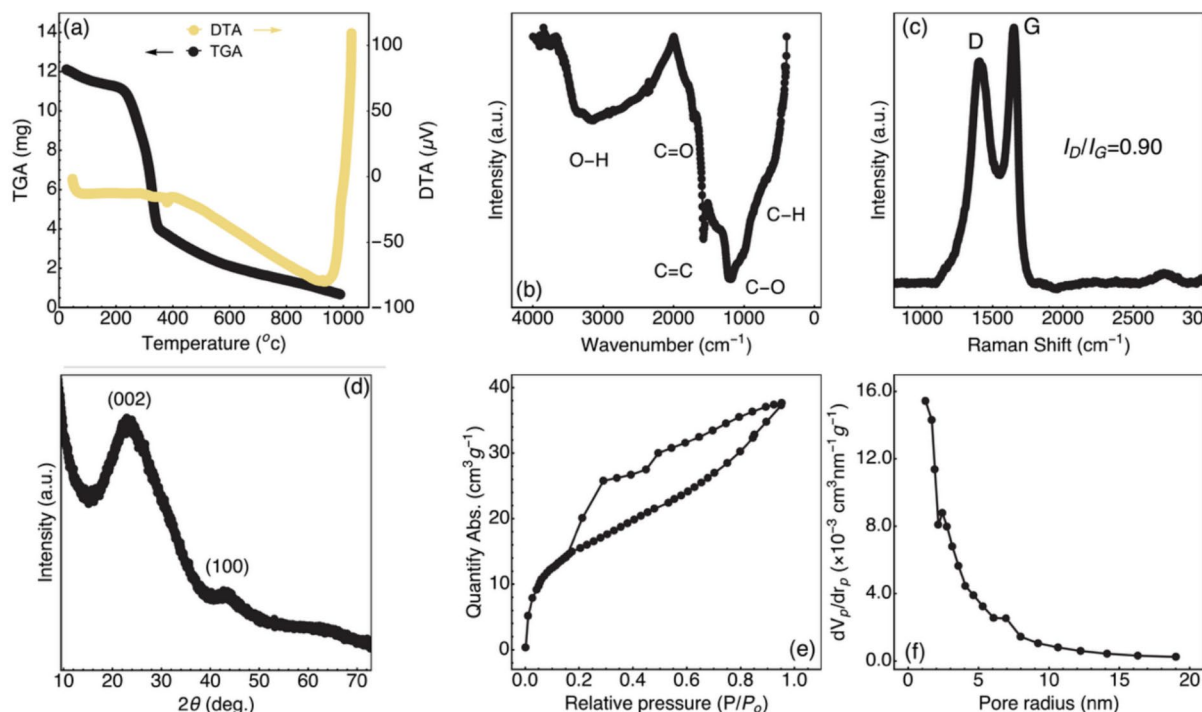


Fig. 3 TGA and DTA plots **a**, FTIR curve **b**, Raman spectroscopy **c**, XRD pattern **d**, Nitrogen adsorption/desorption isotherm **e**, and size distribution curve **f** of the activated carbon

is clearly evident that the activated carbon has micro- and mesoporous structures. The total pore volume was $0.058 \text{ cm}^3/\text{g}$. The high specific surface area and favorable pore size enhance the adsorption process by providing more adsorption sites and increasing the adsorption rate. Therefore, the activating agent played a significant role in creating porous structures within the carbon matrix. Additionally, the BET results support the textural features observed in the SEM analysis.

The iodine index is a fundamental parameter for characterizing the performance of activated carbon. The iodine index provides a good indication of the total surface area available for the adsorption of low molecular weight compounds (micropores) (David Léonce et al., 2023). The activated carbon prepared in this work exhibited an iodine index of $1108.68 \pm 2.12 \text{ mg/g}$, indicating that the biomaterial activated by H_3PO_4 develops micropores on its surface and thus a high internal surface area, enabling it to adsorb smaller particles. This high iodine index value could be due to the use of a high concentration of H_3PO_4 and a high carbonization temperature,

which are recommended for preparing activated carbon with excellent catalytic activity (Nzetchuen Kouahou et al., 2023). However, high concentration promotes contact between the activating agent and the biomaterial, leading to pore formation. In contrast, the work conducted by Lékéné et al. (2018) recommended using an H_3PO_4 concentration in the range of 2 N – 8 N, because at very low concentrations, incomplete reaction between the activating agent and the precursor decreases the iodine index. At excessively high concentrations, pore development may be hindered by pore blockage due to excessive activation agent. Based on these physicochemical characteristics, *Balanites aegyptiaca* is a good precursor for producing high mesoporous activated carbon, which could be applied for the removal of pollutants from wastewater.

3.2 Physico-Chemical Characteristics of Brewery Effluent

Table 1 presents the concentration of some pollutant parameters in brewery effluent. The basic pH of the

Table 1 Physicochemical characterization of raw brewery effluent

Parameters	Non treated	Treated	WHO values
pH	7.18 ± 0.21	6.95 ± 0.15	5.5–9
Temperature (°C)	25.7 ± 0.3	25.4 ± 0.4	20–30
Conductivity (ms/cm)	0.57 ± 0.08	0.021 ± 0.008	1.20
Turbidity (NTU)	210 ± 5	19.5 ± 1.3	-
Ammoniacal nitrogen (mg/L)	137.56 ± 5.15	3.27 ± 0.11	0.5
Nitrite (mg/L)	41.04 ± 1.23	11.21 ± 0.63	0.5
Nitrate (mg/L)	97.68 ± 2.55	19.41 ± 1.71	50
Chlorure (mg/L)	113.42 ± 4.21	14.21 ± 1.05	1000
Sulfate (mg/L)	78.53 ± 6.05	11.55 ± 1.23	-
COD (mg O ₂ /L)	684 ± 9.54	98.28 ± 2.66	250

effluent could be due to the use of alkaline compounds during cleaning. The high electrical conductivity (0.57 mS/cm) can be explained using chemical salts and justified by the presence of Cl^- and SO_4^{2-} ions.

The high concentration of chemical oxygen demand (COD) can be due to the presence of organic matter from dyes used during the production process of beverages. The results reveal that the brewery effluent from N'Djamena (Chad) presents high concentrations of ammoniacal nitrogen, nitrate, and nitrite, which were superior to the permissible concentrations recommended by the World Health Organization (WHO) (Doumbi et al., 2022). Therefore, this brewery effluent poses a growing threat to the environment, particularly to the aquatic ecosystem, and therefore, it is imperative to subject it to further treatment before its release into nature.

3.3 Point of Zero Charge (pH_{PCN}) and Study of the Parameters Influencing Adsorption

Figure 4a shows the pH at the point of zero charge of the prepared AC. From these results, it appears that the point of zero-charge of the as-prepared AC is 4.3. This pH value indicates the point at which the sum of the positive and negative charges on the activated

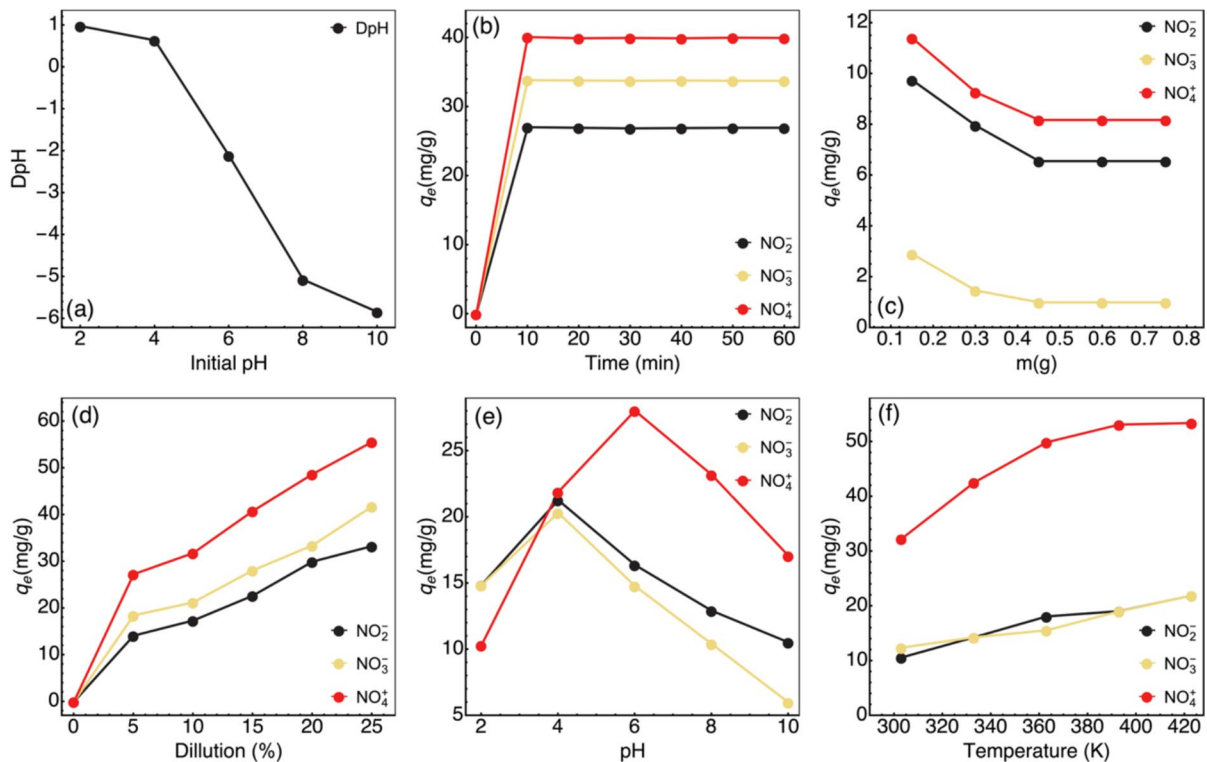


Fig. 4 pH at the point of zero charge of the activated carbon **a**, adsorption kinetics of nitrogenous charges **b**, influence of the mass of the AC **c**, influence of the dilution factor **d**, influence of the pH of the effluent **e**, and influence of the temperature **f** of the effluent

carbon's surface is zero. It highlights how the adsorbent's charge varies depending on the environment. Thus, when the pH is less than 4.3, the surface of the AC becomes positively charged. On the other hand, when the pH is greater than 4.3, it becomes negatively charged, while at pH 4.3, the surface charge is neutral. Similar results were observed by Djonga et al. (2021), when preparing the from Ayous sawdust for the removal of nitrogen and phosphate pollutants from slaughterhouse effluent.

The adsorption kinetic study aimed to determine the maximum amount of nitrogen loads that could be fixed on the AC. Figure 4b illustrates how the interaction time affects the surface interaction with the ions in solution. This figure shows that the curves for nitrogen adsorption are nearly identical. A rapid increase in retention occurs within the first 10 min for all three ions studied. This suggests that the reaction is spontaneous and requires minimal energy to initiate. The active sites of the adsorbent are quickly occupied at the start of the experiment, with the highest nitrogen retention achieved within the initial 10 min of contact. The quick fixation is explained by the great affinity of the carbon matrix for the retention of nitrogenous charges, by better diffusion of the substrate through the pores of this adsorbent, and by the huge number of free sites. After reaching the saturation value in 10 min of contact, a steady step is obtained. Activated carbon has presented a remarkable performance in the adsorption of NH_4^+ , NO_2^- , and NO_3^- ions with the maximum retention capacities of 34.93, 27.05, and 33.87 mg/g, respectively. This performance of the activated carbon could be due to the presence of functional groups on its surface, which can facilitate the interaction between nitrogenous charge and the sorbent surface. Based on these results, the duration of the process was 10 min, which was taken as the equilibrium time in subsequent AC adsorption experiments. Similar results were obtained by Battas et al. (2019), with a similar equilibrium time being observed during the elimination of nitrogen and phosphate loads from wastewater by adsorption on zeolites, bentonites, and other local clays.

The analysis of Fig. 4c showed that when the mass of the AC increased, the quantity of NH_4^+ , NO_2^- , and NO_3^- ions adsorbed decreased. This is explained by the fact that at low quantities of AC, nitrogenous loads easily access the adsorption sites on the AC, leading to a rapid increase in the amount adsorbed

with the mass of AC. The reduction in the ultimate adsorption capacity as a function of the AC mass is due to the formation of agglomerations of AC particles at high dosages. There is a steric hindrance at this point; only a few particles on the periphery of the spheres formed participate in adsorption. Steric hindrance also reduces the total accessible surface area, resulting in decreased adsorption capacity with higher AC mass and a constant adsorption level at very high adsorbent masses. For larger masses, strong interactions develop between the adsorbent molecules due to the increased quantity, which can lead to desorption of the nitrogen charges (NH_4^+ , NO_2^- , and NO_3^-) from adsorption sites. The bulk of the adsorbent particles blocks active sites, thereby reducing the contact surface of the material. Adsorption capacity is inversely proportional to the mass.

Figure 4d presents the results of nitrogen load adsorption as a function of effluent dilution. The adsorption rate increases with effluent dilution. This can be explained by the fact that the more the effluent is diluted, the lower the concentration of pollutants in the environment, leading to a slowdown in the amount adsorbed. These findings are consistent with those obtained in previous works (Djonga et al., 2021; Fito et al., 2023).

In Fig. 4e, we observe the growth and decrease of the curves reflecting nitrogen charge fixation on the surface of the material, influenced by the pH of the effluent. Indeed, the initial pH of the effluent strongly influences the adsorption of the studied pollutants. This influence varies depending on the pollutant load, the adsorbent, and the pH at the point of zero charge, which is 4.3. For pH values lower than pH_{PZC} ($\text{pH} < \text{pH}_{\text{PZC}}$), the surface of the material is positively charged, but above $\text{pH}=4.3$, it carries negative charges. The reduction of positive sites favors the adsorption of NO_2^- and NO_3^- ions, likely due to the increase in pH of the medium. We observe an increasing adsorption capacity of anions from 14.89 mg/g (pH 2) to 27.72 and 34.67 mg/g (pH 4) for NO_2^- and NO_3^- ions, respectively. The adsorption of anions is slow in a very acidic environment (low pH values) because of a competition phenomenon between hydronium H_3O^+ ions and the positive charge of the material. However, the anions form more bonds with protons, H^+ , than with the charge of the material. The adsorption capacity of anions decreases sharply after pH 4.3 because, beyond this pH, the surface of the

AC is negatively charged, creating electrostatic repulsion with the anions (Nascimento et al., 2025). Furthermore, the adsorption capacity of ammonium ions increases up to pH 6, but remains very low at acidic pH due to electrostatic repulsion between similarly charged species. However, above pH 6, the adsorption capacity decreases because in basic environments, OH^- ions are produced, competing with the negatively charged species for binding sites. This results in NH_4^+ ions being more likely to bond with hydroxide ions than with the material's charge. Battas et al. (2019) suggested that the adsorption of nitrate ions on quartz-based local clays strongly depends on pH. The maximum adsorption capacity was observed at pH 2 from local clays. Thus, this result is because the further the pH of a solution moves away from the pH_{PZC} at lower values, the more positively charged the overall AC becomes, increasing its affinity for negatively charged species.

As shown in Fig. 4f, the curves reflecting nitrogen load adsorption increase, indicating an increase in removal efficiency with rising temperature. This is because higher temperatures reduce the viscosity of the reaction medium, promoting the diffusion of ions into the internal pores of the AC. The temperature increase thus enhances ion mobility, causes the AC structure to swell, and allows ions to penetrate deeper (Menkiti et al., 2014). This can be explained by an increased diffusion rate of ions in the pores, which accounts for the endothermic nature of the diffusion-controlled adsorption process. These findings align with those of Adam and Al-Shammari (2023), who observed that higher temperatures led to increased adsorption of herbicide on *Balanites aegyptiaca*-based adsorbent.

3.3.1 Adsorption Kinetic Studies

The pseudo-first-order and pseudo-second-order models were used to better explain the adsorption mechanism of nitrogenous pollutants on activated

carbon. From the kinetic study results presented in Fig. 4b, the kinetic model constants were extracted and summarized in Table 2. This table shows that the correlation coefficients for the pseudo-first-order kinetic model are low. Therefore, this model is not suitable for explaining the adsorption of NH_4^+ , NO_2^- , and NO_3^- ions from brewery effluent on activated carbon. On the other hand, the pseudo-second-order kinetic model, with correlation coefficients all greater than 0.95, is the most appropriate model for describing nitrogen ion adsorption in this study. Additionally, the theoretical values of the adsorbed quantities calculated from the pseudo-second-order kinetic model ($q_{\text{NH}_4^+} = 34.843$; $q_{\text{NO}_2^-} = 26.954$; $q_{\text{NO}_3^-} = 33.898$ mg/g) closely match the experimental results ($q_{\text{NH}_4^+} = 34.936$; $q_{\text{NO}_2^-} = 26.751$; $q_{\text{NO}_3^-} = 33.876$ mg/g). Thus, the sorption mechanism of nitrogenous pollutants on the AC surface occurs in two stages: i) An initial diffusion phase of NH_4^+ , NO_2^- , and NO_3^- toward the AC surface. ii) an interaction phase between the ions and the surface of the activated carbon (Chinoune et al., 2024). The good fit to the pseudo-second-order model can suggest the chemisorption or physisorption process involving electron exchange or electrostatic interactions at the interface between the AC and the ions.

3.3.2 Adsorption Isotherm Models

The main adsorption isotherm models studied in this work were Langmuir, Freundlich, and Temkin isotherms. The modelling was carried out based on the results obtained from the effect of the adsorbent mass study (Fig. 4c), and the results are presented in Tab. 3. From this table, it can be observed that, for all isotherm models applied to the adsorption of the three nitrogen forms from the brewery effluent onto the AC, the Langmuir and Temkin models exhibit very high correlation coefficients, both close to unity ($R^2 > 0.95$). These isotherm models are the most

Table 2 Constant values of the pseudo-first and pseudo-second-order kinetic models

Pollutants	Pseudo-first-order model			Pseudo-second-order model		
	q_e (mg/g)	K_1	R^2	q_e (mg/g)	K_2	R^2
NH_4^+	34.9362	0.0538	0.9627	34.8432	1.1767	0.9999
NO_2^-	27.0509	0.0513	0.6329	26.9541	-6.8820	0.9999
NO_3^-	33.8761	0.1027	0.8529	33.8983	2.9008	0.9999

Table 3 Constant values of the Langmuir, Freundlich, and Temkin isotherms

Models	Parameters	NH ₄ ⁺	NO ₂ ⁻	NO ₃ ⁻
Langmuir	Q _m (mg/g)	40.161	34.130	28.818
	K _L (L/mg)	0.9764	73.2501	0.7096
	R ²	0.9922	0.9999	0.9812
Freunlich	K _f	2.190	18.403	9.517
	n _f	0.8892	3.6624	0.6932
	R ²	0.7252	0.0136	0.9785
Temkin	B (J/mol)	-3.207	-13.675	21.618
	A (L/mg)	1.4 × 10 ⁻⁸	0.00053	0.014
	R ²	0.9971	0.9949	0.9957

appropriate for describing the adsorption mechanism of NH₄⁺, NO₂⁻, and NO₃⁻ ions contained in the Chad brewery effluent on the AC prepared from *Balanites aegyptiaca* shells. On the other hand, the Freundlich model presents a weak correlation below 0.95, except in the case of the NO₃⁻, where the R² > 0.95. This explains that the adsorption of these inorganic ions takes place in a monolayer on a homogeneous surface made up of energetically equivalent sites (Raji et al., 2023). Once the first surface layer is completed, a new layer caused by the interaction between the adsorbed particles and the surface charge is formed in the case of NO₃⁻ (Santos et al., 2025). This is a multilayer adsorption confirmed by the Temkin model, including the energy of adsorption of pollutant loads, which decreases linearly with the surface coverage. Therefore, we can say that the adsorption of NH₄⁺, NO₂⁻, and NO₃⁻ from brewery effluent on AC made from *Balanites aegyptiaca* core shells is better described by the Langmuir and Temkin models.

3.3.3 Thermodynamic Studies

Determining thermodynamic parameters is essential for understanding the energetic mechanism during

the adsorption process. This involves applying Van't Hoff's law, expressed as follows (Nogueira et al., 2023). The thermodynamic parameters, Gibbs free energy (ΔG° , kJ mol⁻¹), standard enthalpy (ΔH° , kJ mol⁻¹), and standard entropy (ΔS° , kJ mol⁻¹ K⁻¹), for removing nitrogenous ions at different temperatures are shown in Fig. 4f and summarized in Tab. 4. Here, the Gibbs free energy was calculated using the following equations (Eq. 18,19):

$$\Delta G^\circ = -RT \ln(k_d) \quad (17)$$

The equilibrium constant k_d (mL g⁻¹) was calculated using the ratio ΔS° :

$$k_d = \frac{q_e}{C_e} \quad (18)$$

where q_e and C_e are the adsorbed amount (mg/g) and the equilibrium concentration of the nitrogenous ions in the effluent (mg/L), respectively. ΔH° (Eq. 20) and ΔS° (Eq. 21) were calculated from the following equations called the Van't Hoff formula (Neolaka et al., 2020):

$$\ln(k_d) = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT} \quad (19)$$

with

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ \quad (20)$$

The plot of $\ln(k_d)$ as a function of T^{-1} of the Van't Hoff equation could be used to find ΔH° and ΔS° from the slope $\frac{\Delta H^\circ}{R}$ and the intercepts $\frac{\Delta S^\circ}{R}$, respectively. R and T were the gas constant (8.314 J K⁻¹ mol⁻¹) and temperature (K), respectively.

It appears in Tab. 4 that the values of the parameter ΔG° for the NH₄⁺ and NO₂⁻ ions decrease when the temperature increases. This indicates that the adsorption process is more favorable at higher temperatures. The negative values of ΔG° for NH₄⁺ and NO₂⁻ ions show the spontaneity nature of the

Table 4 Thermodynamic parameters

Ions	ΔH° (kJ mol ⁻¹)	ΔS° (kJ mol ⁻¹ K ⁻¹)	ΔG° (kJ mol ⁻¹)					R ²
			303 K	333 K	363 K	393 K	423 K	
NH ₄ ⁺	3.40	10.48	-6.54	-6.89	-7.26	-7.52	-7.78	0.991
NO ₂ ⁻	5.63	-3.36	-4.54	-4.60	-4.52	-4.22	-4.18	0.986
NO ₃ ⁻	9.02	-31.05	-3.93	1.25	2.37	3.11	4.11	0.996

adsorption process, while the positive values of ΔG° obtained for NO_3^- indicate non-spontaneity and the presence of an energy barrier in the adsorption process on these ions at low temperatures (Cavalcanti et al., 2021). The positive enthalpy values ($\Delta H^\circ > 0$) suggest the endothermic nature of the adsorption process. These positive ΔH° values indicate that all retention reactions by the AC are endothermic, whatever the nature of the charge of the ions. Physical and chemical adsorption can be classified, to some extent, by the magnitude of the enthalpy change. The relatively low enthalpy values ($\Delta H^\circ = 3.40$, 5.63, and 9.02 kJ mol⁻¹ for NH_4^+ , NO_2^- , and NO_3^- , respectively) indicate that the adsorption process is predominantly governed by physisorption, involving weak Van der Waals forces and electrostatic interactions rather than chemical bonding. These values are well below the typical threshold for chemisorption (> 80 kJ mol⁻¹), confirming the physical nature of the adsorption process. Furthermore, the positive value of ΔS° for NH_4^+ suggests an increase in the randomness of the adsorption process (Raji et al., 2023). Therefore, each nitrogenous pollutant can possess different thermodynamic affinities with the AC due to the unique electronic configurations and charge densities. It is important to note that the decisive evidence for the adsorption mechanism comes from the

thermodynamic parameters, particularly the enthalpy values, which clearly indicate physisorption in this study. The good fit to the pseudo-second-order model suggests that the rate-limiting step involves surface interaction, but the low activation energies confirm that these interactions are physical in nature.

3.4 In Situ Regeneration of Active Sites by the Direct Anodic Oxidation Process

The desorption of nitrogenous pollutants previously adsorbed on AC was carried out to regenerate the occupied sites with the help of a direct anodic oxidation process. Figure 5a shows the influence of time on the desorption of nitrogenous species. It appears from Fig. 5a that a particular observation could be made on the desorption speed of the ions initially adsorbed on the AC. However, in the first minutes of the experiment, the desorption speed is fast, then it decreases with contact time. This is because the ions in solution tend to reoccupy the active sites of the adsorbent, and we note a competition between adsorption and desorption. In addition, the current intensity applied during the process contributes to the electrochemical transformation of the inorganic ions present in solution. The most probable reactions are based on thermodynamic considerations and previous

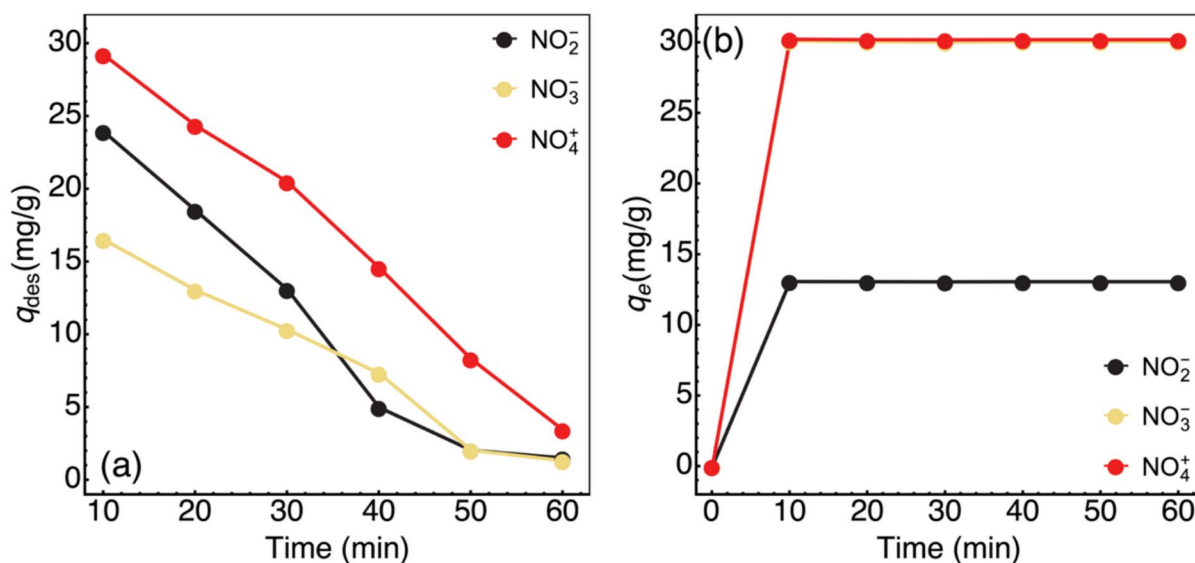


Fig. 5 Desorption kinetics of nitrogenous load adsorbed on the AC **a**, $m=0.30$ g; $v=250$ trs/min; $V=100$ mL; $T=25$ °C; $[\text{Na}_2\text{SO}_4]=0.1$ M and Re-adsorption of nitrogenous ions on the regenerated AC **b**

Table 5 Values of the quantities adsorbed and desorbed, as well as the desorption yield of the nitrogenous pollutants

Adsorbates	Q_{ads} (mg/g)	Q_{des} (mg/g)	Desorption yield (%)
NH_4^+	34.93	29.44	84.28
NO_2^-	27.05	23.96	88.57
NO_3^-	33.87	16.54	40.83

electrochemical studies (Martínez-Huitle & Ferro, 2006) (Tables 3 and 4).

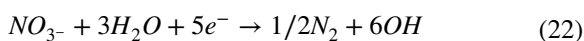
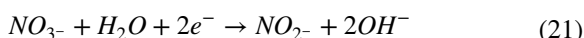


Table 5 illustrates the percentage of nitrogenous compounds desorbed as a function of time (10 min). These desorption results show that the ions would be fixed on the surface of the AC in several forms. In particular, the NO_3^- is strongly adsorbed, while NO_2^- and NH_4^+ are weakly adsorbed. This result is in accordance with the enthalpies of the adsorption reaction. Although all enthalpy values indicate physisorption, the relative magnitude of ΔH° for NO_3^- (9.02 kJ mol⁻¹) compared to NH_4^+ (3.40 kJ mol⁻¹) and NO_2^- (5.63 kJ mol⁻¹) suggests relatively stronger physical interactions for NO_3^- , which is consistent with the lower desorption efficiency observed. Then, the desorbed percentage of ions varied from the deeply to weakly bonded on the surface of *Balanites aegyptiaca* shells-based AC. Also, the highest desorption efficiency in the case of NO_2^- ions could arise from the electrochemical reduction of NO_3^- ions (Eq. 22), contributing to the increase in the quantity of NO_2^- desorbed.

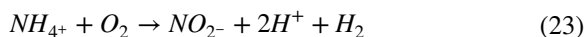
3.5 Influence of Time on the Re-Adsorption of Nitrogenous Ions on the Regenerated Activated Carbon

To test the AC regeneration efficiency, an experiment of the re-adsorption of nitrogenous ions was performed with the electrochemically regenerated AC. As previously observed for non-regenerated AC, Fig. 5b shows that the adsorption rate of NH_4^+ , NO_2^- , and NO_3^- ions on the regenerated AC is also accelerated by the availability of free sites during the first 10 min and attains

the saturation limit, indicating that adsorption equilibrium was reached. However, for all studied ions, the quantity adsorbed during re-adsorption is lower than that obtained during the first adsorption tests (Fig. 4a). This is explained by the fact that certain sites were still occupied by adsorbate molecules/ions after the electrochemical desorption process.

3.6 Evaluation of Adsorbent Regeneration Efficiency

The efficiency of regeneration of the adsorbent, denoted E , was defined as the ratio between the adsorption capacity of the adsorbent after regeneration (Q_r), expressed in mg/g, and the initial adsorption capacity (Q_i), expressed in mg/g. Table 6 gives the values of the AC regeneration efficiency (E) after a first adsorption and re-adsorption by the regenerated material. Table 6 shows that the calculated AC regeneration efficiency is 74.33%, which represents the average of the regenerated sites. This value shows that there are modifications in the properties of the AC after contact with Na_2SO_4 during the desorption stages. These results are close to those obtained by Berenguer et al. (2010), who obtained a regeneration efficiency of the AC saturated with phenol molecules of 73%. Thus, from this result, we note that the regenerated AC has an appreciable capacity for subsequent adsorption. From Table 5, it is observed that the percentage of desorption of NO_2^- is 88.57%, while after the electrochemical oxidation, the regeneration rate efficiency is 48.42%. This could be because during the DAO, NO_3^- could be reduced to NO_2^- (Eq. 22) through cathodic reduction, while NH_4^+ could potentially undergo anodic oxidation to NO_2^- (Eq. 24) according to established nitrification pathways.

**Table 6** Regeneration rate efficiency of AC

Adsorbates	Q_i (mg/g)	Q_r (mg/g)	E (%)
NH_4^+	40.11	29.91	85.62
NO_2^-	27.05	13.10	48.42
NO_3^-	33.87	30.13	88.95

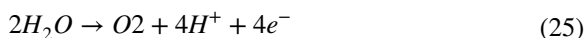
Q_i (mg/g): initial adsorption capacity; Q_r (mg/g): adsorbed quantity after regeneration

3.6.1 Influence of the Applied Current on the Removal of Nitrogenous Pollutants

The imposed current intensity is one of the most influential factors for the generation of oxidizing species by the electrochemical processes (Rodríguez-Narváez et al., 2021). In this study, the effect of current intensity on the removal of nitrogenous loads from brewery effluent was evaluated. To show the effect of current intensity on the removal efficiency of nitrogenous ions, experiments were done for current intensities of 200, 300, and 400 mA. The experiments were carried out under the following conditions: pH was adjusted to 3, with a supporting electrolyte Na_2SO_4 (0.1 M), and an inter-electrode distance of 1 cm to avoid energy consumption.

Figure 6a shows that the rate of elimination of ammoniacal nitrogen increases with the increase in the applied current, ranging from 200 (67.18%) to 300 mA (97.62%), and decreases after a current intensity of 400 mA. This result shows a similarity with the two other ions studied, NO_2^- (65.03, 72.69, and 69.63%) (Fig. 6b) and NO_3^- (71.78, 80.13, and 78.46%) (Fig. 6c). These results can be explained by the generation of hydroxyl radicals on the anode surface through the oxidation of water, which leads to the oxidation of nitrogen forms into gaseous nitrogen (N_2), which is harmless to the environment. However, increasing the current beyond 300 mA did not bring any positive effect on the removal efficiency; rather, a drop in the removal efficiency was observed during the treatment. This could be explained by the fact that the excess current favors an increase in the speed of the reaction, and in this case, the electrodes will be attacked more quickly, leading to a fast consumption of the electrodes and the

loss of energy. The decrease in removal efficiency at high current intensities is attributed to the intensification of parasitic reactions, such as hydrogen evolution at the cathode (Eq. 25) and oxygen evolution at the anode (Eq. 26) (Martínez-Huitle & Ferro, 2006),



At the optimal current intensity (300 mA), hydroxyl radicals generated at the anode surface (Eq. 27) are believed to oxidize nitrogenous species (Panizza & Cerisola, 2009):



The transformation of NH_4^+ , NO_2^- , and NO_3^- into less harmful nitrogen species (potentially N_2) likely occurs through a combination of direct electrochemical oxidation and indirect oxidation by $\bullet\text{OH}$ radicals (Yao et al., 2019).

After the electrochemical oxidation process, the remaining concentrations of NO_2^- , NO_3^- , and NH_4^+ in the brewery effluent were 11.21, 19.41, and 3.27 mg/L, respectively. The concentrations of the other physicochemical characteristics were reported in Table 1. It could be noticed that the effluent was significantly decontaminated from the system used in this work. Table 7 reports the comparison between the removal efficiency of nitrogenous pollutants from different effluents by some techniques. From this table, we could notice that the removal efficiencies of NO_3^- , NO_2^- , and NH_4^+ are comparable to those reported previously. The remarkable performance of

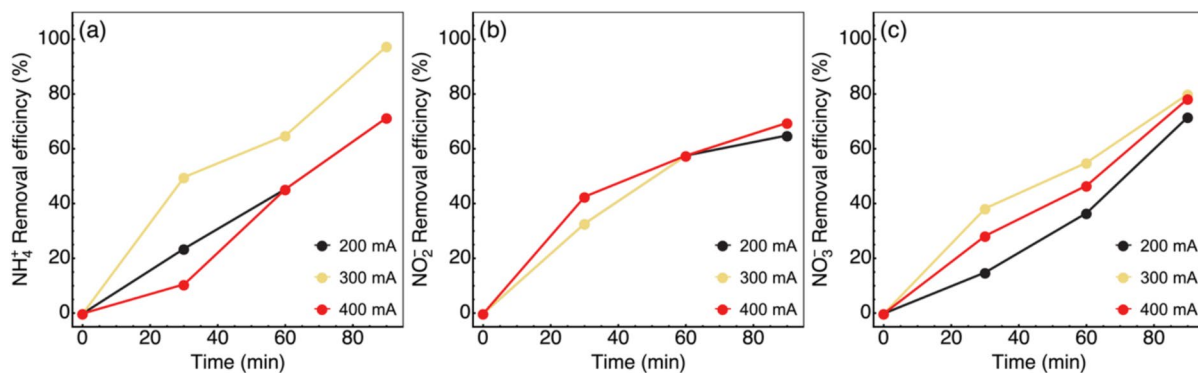


Fig. 6 Effect of the current intensity on the removal efficiency of NH_4^+ **a**, NO_2^- **b** and NO_3^- **c**

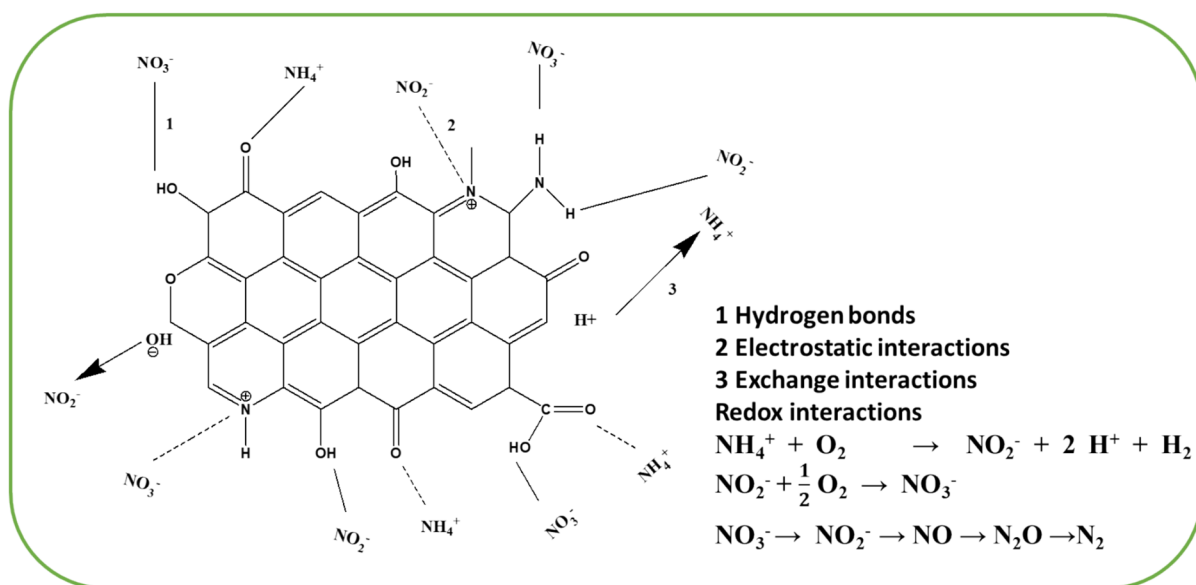
Table 7 Comparison between the removal efficiency of nitrogenous pollutants from some techniques

Pollutants	Effluent	Method	Removal efficiency (%)	Reference
NO_3^-	Brewery	Electrocoagulation	98.02	(Garomsa et al., 2024)
NO_3^- NH_4^+	Synthetic wastewater	Photocatalysis and biodegradation	54.45 42.47	(Lu et al., 2023)
NO_3^- NO_2^- NH_4^+	Slaughterhouse	Biological treatment	57 57 57	(Gnowe et al., 2020)
NO_3^-	Synthetic effluent	Adsorption	59.8	(Dos Santos et al., 2025)
NO_3^-	Synthetic effluent	Electricity-assisted adsorption	80	(Li et al., 2025a, 2025b)
NO_3^- NH_4^+	Pharmaceutical effluent	Biological process	91.1 98.5	(Yang et al., 2019)
NO_3^- NO_2^- NH_4^+	Brewery	Adsorption and direct anodic oxidation	80.13 72.69 97.62	This work

the system could be assigned to the micro- and mesoporosity of the activated carbon, which provides a more accessible location for nitrogenous ions and facilitates their interaction with the functional groups on the adsorbent surface (Li et al., 2025a, 2025b). In addition, the anodic oxidation process not only contributes to regenerating the active sites of the sorbent but also contributes to oxidizing the pollutants, leading to enhancing the removal efficiency.

3.7 Plausible Mechanism of Sorption/Oxidation of Nitrogenous Pollutants on the Adsorbent Surface

It is well-known that basic and acidic functions coexist at the surface of the activated carbon prepared from biomass (Raji et al., 2023). According to the results presented in the kinetic and isotherm studies, the functional groups and the structural property of the activated carbon, we have proposed a plausible mechanism of

**Fig. 7** Plausible mechanism for in situ removal of nitrogenous pollutants by the adsorption and direct anodic oxidation processes

adsorption and oxidation of nitrogenous pollutants, as shown in Fig. 7. We could notice the presence of three main interactions, such as hydrogen bonding, electrostatic interaction, ion exchange, and redox reactions. The electrostatic interaction can occur between the proton of the ammonium and the negative charge of the adsorbent, justifying the physisorption mechanism observed during the process. This results in a strong bond. However, during the in-situ generation of the AC, the efficiency was found in an acidic medium. These protons present in the medium could also contribute to the electrostatic interaction between nitrate and nitrite ions, forming hydrogen bonds. Furthermore, we could notice the ion exchange interaction, resulting from negatively charged nitrogen groups attracting protons present in the reaction medium (Santos et al., 2025). Redox reactions could also appear during the process. Thus, we could observe some redox reactions between the different nitrogenous species and the oxidizing species that could be electro-generated during the process. The generation of oxygen during the treatment could initiate successively the oxidation of ammonium to nitrite, nitrite to nitrate, and nitrate to nitrogen in the medium as summarized in the reaction below (Eq. 28–30).

4 Conclusion

Brewery industries generate large volumes of wastewater containing mineral pollutants such as nitrogen compounds. This study aimed to evaluate the effectiveness of activated carbon (AC) derived from plant biomass (core shell of *Balanites aegyptiaca*) for removing nitrogenous pollutants from brewery effluent and regenerating the AC through electrochemical oxidation. Iodine number, SEM, and BET analyses confirmed the micro- and mesoporous structure of the activated carbon, with a high specific surface area. TGA and TDA results helped to find the thermal stability of the adsorbent material. FTIR spectroscopy identified the main functional groups on the adsorbent's surface, which help improve adsorption efficiency by facilitating interactions between pollutants and the sorbent. Raman and XRD analyses revealed that the as-prepared carbon material corresponds to a model of disordered graphitic carbon crystallites embedded in an amorphous carbon matrix.

The results indicated that maximum adsorption efficiency was achieved at 10 min and increased with

temperature, indicating an endothermic process. The optimal pH for nitrate and nitrite ions adsorption was pH=4, while for ammonium ions it was pH=6. It was also observed that the amount adsorbed is inversely proportional to the AC mass. Kinetic studies showed that the pseudo-second-order model best described the adsorption process. Thermodynamic analysis revealed low enthalpy values ($\Delta H^\circ = 3.40, 5.63, \text{ and } 9.02 \text{ kJ mol}^{-1}$ for NH_4^+ , NO_2^- , and NO_3^- , respectively), confirming that the adsorption mechanism is predominantly governed by physisorption involving Van der Waals forces and electrostatic interactions. The average regeneration efficiency of the AC was 74.33%, demonstrating that the regenerated material maintained a good capacity for subsequent adsorption, consistent with the reversible nature of physical adsorption. Ultimately, the highest removal efficiencies for nitrogen pollutants via the direct anodic oxidation process were achieved at 300 mA, with the removal efficiency of 97.62%, 72.69%, and 80.13% for NH_4^+ , NO_2^- , and NO_3^- ions, respectively. Furthermore, coupling the two processes not only regenerated the AC after adsorption but also significantly reduced nitrogen pollutants in the brewery effluent. These removal efficiencies, confirmed after the DAO process, demonstrated effective decontamination of the wastewater. The introduction of agricultural waste-based AC into a combined adsorption-oxidation treatment process for industrial wastewater offers a promising, sustainable alternative to address environmental challenges.

Acknowledgements The authors would like to thank Mr Max Nyamsi for his technical help for the analysis of the concentration of nitrogenous ions.

Author Contributions Romuald T.D.: Conceptualization, data curation, formal analysis, methodology, validation, Writing – original draft, writing review & editing. Koutou: Conceptualization, Formal analysis, methodology, Writing – original draft, writing review & editing. Djonga W.G.: Conceptualization, Formal analysis, Writing – original draft, writing review & editing. Lys C.M.W.: Conceptualization, Formal analysis, Writing – original draft, writing review & editing. Ebio N.G.: Conceptualization, Formal analysis, Writing – original draft, writing review & editing. Jean M.D.D.: Conceptualization, Formal analysis, Writing – original draft, writing review & editing. Domga: Conceptualization, Formal analysis, Writing – original draft, writing review & editing. Benguene N: Formal analysis, Writing – original draft, writing review & editing. Eric N.: Conceptualization, Writing – original draft, writing review & editing. Guy B.N: Conceptualization, Writing – original draft, writing review & editing. Marcio A.C.: Conceptualization, Writing – original draft, writing review & editing.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614).

Data Availability The data and materials presented in this research are available upon request from the corresponding author.

Declarations

Ethics Approval Not applicable. This study does not involve human subjects.

Consent for Publication All authors have given their approval to the publication of this manuscript.

Competing Interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abia, D., Domga, R., Domga, D., Daouda, A., Tokodne Honore, A., Guy Bertrand, N., & Richard, D. (2019). Adsorption of Rhodamine B onto Orange Peel Powder. *American Journal of Chemistry*, 5, 142–149. <https://doi.org/10.5923/j.chemistry.20190905.02>
- Adam, O. E. A. A., & Al-Shammari, A. S. (2023). Preparation and characterization of activated carbon from *Balanites aegyptiaca* seed shell for the removal of 2, 4-dichlorophenoxyacetic acid herbicide from aqueous solution. *Desalination and Water Treatment*, 315, 314–326. <https://doi.org/10.5004/dwt.2023.30138>
- Alabi, A., AlHajaj, A., Cseri, L., Szekely, G., Budd, P., & Zou, L. (2018). Review of nanomaterials-assisted ion exchange membranes for electromembrane desalination. *Npj Clean Water*, 1, 1–22. <https://doi.org/10.1038/s41545-018-0009-7>
- Ali, R., Aslam, Z., Shawabkeh, R. A., Asghar, A., & Hussein, I. A. (2020). BET, FTIR, and Raman characterizations of activated carbon from waste oil fly ash. *Turkish Journal of Chemistry*, 44(2), 279–295. <https://doi.org/10.3906/KIM-1909-20>
- Arumugam, T., Dhandapani, B., & Iyyappan, J. (2025). Photocatalytic activity of calcined chicken bone waste doped with TiO₂/MnO/SDS towards brewery wastewater treatment and hydrogen production—a circular economy-based approach. *Biomass Conversion and Biorefinery*, 15, 19505–19524. <https://doi.org/10.1007/s13399-025-06623-4>
- Battas, A., El Gaidoumi, A., Ksakas, A., & Kherbeche, A. (2019). Adsorption study for the removal of nitrate from water using local clay. *The Scientific World Journal*, 2019, 1–10. <https://doi.org/10.1155/2019/9529618>
- Berenguer, R., Marco-Lozar, J. P., Quijada, C., Cazorla-Amorós, D., & Morallón, E. (2010). Comparison among chemical, thermal, and electrochemical regeneration of phenol-saturated activated carbon. *Energy & Fuels*, 24(6), 3366–3372. <https://doi.org/10.1021/ef901510c>
- Cavalcanti, J. V. F. L., da Fonseca, C. C., da Silva, G. M., Santiago, I. T., Tenório, L. L., da Motta Sobrinho, M. A., & Baraúna, O. S. (2021). Adsorption of textile dye and textile effluent using organoclay from Northeast of Brazil. *Cerâmica*, 67(383), 277–283. <https://doi.org/10.1590/0366-6913202167383094>
- Chinoune, K., Mekki, A., Boukoussa, B., Mokhtar, A., Sardi, A., Hachemaoui, M., Iqbal, J., Ismail, I., Abboud, M., & Aboneama, W. A. (2024). Adsorption behavior of MB dye on alginate-sepiolite biocomposite beads: Adsorption, kinetics, and modeling. *Inorganic Chemistry Communications*, 165, Article 112558. <https://doi.org/10.1016/j.inoche.2024.112558>
- Costa E Silva, D. L., Pires Kassab, L. R., dos Santos, A. D., & Pillis, M. F. (2018). Evaluation of carbon thin films using Raman spectroscopy. *Materials Research*, 21(4), 745–756. <https://doi.org/10.1590/1980-5373-MR-2017-0787>
- David Léonce, K., Yapo Hermann Aristide, Y., Djedjess Essoh Jules-César, M., Kacou Alain Paterne, D., Djamatché Paul Valery, A., Brou, D., Kouamé Bini, D., & Karim Sory, T. (2023). Contribution to the Modeling of a Biosorbent Derived from Cocoa Pod Shells on the Methylene Blue Index. *American Journal of Applied Chemistry*. <https://doi.org/10.11648/j.ajac.20231102.11>
- Dehmani, Y., Franco, D. S. P., Georgin, J., Mghaiouini, R., Mohammed, B. B., Kacimi, R., Lamhasni, T., Lima, E. C., El Messaoudi, N., & Sadik, A. (2025). Towards a deeper understanding of the adsorption of methyl orange on a commercial activated carbon: Study of impact factors, isotherm and mechanism. *Environmental Surfaces and Interfaces*, 3, 103–111. <https://doi.org/10.1016/j.esi.2025.02.002>
- Djonga, W. G., Noubissié, E., & Noumi, G. B. (2021). Removal of nitrogen, phosphate and carbon loads from slaughterhouse effluent by adsorption on an adsorbent based on Ayous sawdust (*Triplochyton scleroxylon*). *Case Studies in Chemical and Environmental Engineering*, 4, Article 100120. <https://doi.org/10.1016/j.cscee.2021.100120>
- Dos Santos, L. G., Machado, L. F. L., Andrade, L. S., Xavier, G. T. M., Mandelli, D., & Carvalho, W. A. (2025). Glycerol-based modified carbons as adsorbents for efficient and sustainable nitrate removal from wastewater. *Energy*

- & *Environmental Sustainability*, 1(3), Article 100031. <https://doi.org/10.1016/j.eesus.2025.100031>
- Doumbi, R. T., Bertrand Noumi, G., Ngobtchok, B., & Domga. (2022). Tannery wastewater treatment by electro-Fenton and electro-persulfate processes using graphite from used batteries as free-cost electrode materials. *Case Studies in Chemical and Environmental Engineering*, 5, 100190. <https://doi.org/10.1016/j.cscee.2022.100190>
- Elabbas, S., Oumani, A., Lazrak, A., Hannoun, G., & Mandi, L. (2023). Treatment of Tannery Effluent Using Combined Electrocoagulation and Adsorbent of Powdered Marble. *International Journal of Water and Wastewater Treatment*, 9(1), 1–11. <https://doi.org/10.16966/2381-5299.187>
- Farghali, M., Chen, Z., Osman, A. I., Ali, I. M., Hassan, D., Ihara, I., Rooney, D. W., & Yap, P. S. (2024). Strategies for ammonia recovery from wastewater: A review. *Environmental Chemistry Letters*, 22, 2699–2751. <https://doi.org/10.1007/s10311-024-01768-6>
- Fito, J., Abewaa, M., & Nkambui, T. (2023). Magnetite-impregnated biochar of *parthenium hysterophorus* for adsorption of Cr(VI) from tannery industrial wastewater. *Applied Water Science*, 13(3), 25–39. <https://doi.org/10.1007/s13201-023-01880-y>
- Gahrouei, A. E., Vakili, S., Zandifar, A., & Pourebrahimi, S. (2024). From wastewater to clean water: Recent advances on the removal of metronidazole, ciprofloxacin, and sulfamethoxazole antibiotics from water through adsorption and advanced oxidation processes (AOPs). *Environmental Research*, 252, Article 119029. <https://doi.org/10.1016/j.envres.2024.119029>
- Garomsa, F. S., Mehari, Y., Desta, W. M., Bidira, F., & Asaithambi, P. (2024). Removal of NO_3^- , PO_4^{3-} , and color from brewery wastewater by the use of indigenous bio-coagulant-assisted electrocoagulation. *Progress in Engineering Science*, 1(4), Article 100032. <https://doi.org/10.1016/j.pes.2024.100032>
- Gnowe, W. D., Noubissié, E., & Noumi, G. B. (2020). Influence of time and oxygenation on the degradation of organic matter, nitrogen and phosphates during the biological treatment of slaughterhouse effluent. *Case Studies in Chemical and Environmental Engineering*. <https://doi.org/10.1016/j.cscee.2020.100048>
- GnoweDjonga, W., Noubissié, E., & Bertrand Noumi, G. (2021). Removal of organic, nitrogen and phosphate pollutants from slaughterhouse effluent by a process combining biodegradation with adsorption. *Journal of Energy, Environmental & Chemical Engineering*, 6(2), 31. <https://doi.org/10.11648/j.jeece.20210602.11>
- Gueye, M., Richardson, Y., Kafack, F. T., & Blin, J. (2014). High efficiency activated carbons from African biomass residues for the removal of chromium(VI) from wastewater. *Journal of Environmental Chemical Engineering*, 2(1), 273–281. <https://doi.org/10.1016/j.jeece.2013.12.014>
- Guo, Y., Wang, R., Ren, L., Li, Y., Wang, X., Jiang, Y., Wang, L., & Wang, Z. (2025). Harnessing singlet oxygen for advanced electrochemical treatment of coking wastewater. *Energy & Environmental Sustainability*, 1(3), Article 100033. <https://doi.org/10.1016/j.eesus.2025.100033>
- Innes, P., Chang, S., & Rahaman, M. S. (2021). Treatment of effluent of upflow anaerobic sludge blanket bioreactor for water reuse. *Water (Basel)*, 13(15), 555–564. <https://doi.org/10.3390/w13152123>
- Jafarinejad, S., & Esfahani, M. R. (2021). A review on the nanofiltration process for treating wastewaters from the petroleum industry. *Separations*, 8(11), Article 8110206. <https://doi.org/10.3390/separations8110206>
- Jalilian, M., He, Q. S., & Hu, Y. (2026). Synthesis of bime-tallic biocomposite materials prepared from activated hydrochar/biochar for methylene blue removal via Fenton oxidation coupled with adsorption. *Chemical Engineering Science*, 320, Article 122514. <https://doi.org/10.1016/j.ces.2025.122514>
- Jathan, Y., & Marchand, E. A. (2024). Enhanced coagulation for removal of dissolved organic nitrogen in water: A review. *Chemosphere*, 366, Article 143429. <https://doi.org/10.1016/j.chemosphere.2024.143429>
- Ji, J., Yan, S., Zhou, Z., Gu, Y., Liu, C., Yang, S., Wang, D., Xue, Y., & Tang, C. (2024). High-surface area active boron nitride nanofiber rich in oxygen vacancies enhanced the interface stability of all-solid-state composite electrolytes. *Journal of Materials Science & Technology*, 15, 85–94. <https://doi.org/10.1016/j.jmst.2024.07.051>
- Kada, D., Domga, D., Asobo, C., Taybe, N., & Kowe, J. (2024). Adsorption of iron (II) from aqueous solution by activated carbon from Desert Date Seed Shells. *World Journal of Applied Chemistry*, 9(3), 44–55. <https://doi.org/10.11648/j.wjac.20240903.12>
- Lékéné, R. B. N., Nsami, J. N., Rauf, A., Kouotou, D., Belibi, P. D. B., Bhanger, M. I., & Mbadcam, J. K. (2018). Optimization conditions of the preparation of activated carbon based Egusi seed shells for nitrate ions removal from wastewater. *American Journal of Analytical Chemistry*, 09(10), 439–463. <https://doi.org/10.4236/ajac.2018.910034>
- Li, X., Cheng, Q., Kang, Y., Gu, Z., Bao, H., Wang, N., Liu, Y., Hu, C., & Qu, J. (2025a). Synergistic adsorption and removal of nitrate in an electrically polarized column packed with AlCl_3 -modified activated carbon. *Separation and Purification Technology*, 364, Article 132570. <https://doi.org/10.1016/j.seppur.2025.132570>
- Li, Y., Li, Y., Ni, B. J., Li, Y. Z., & Ni, S. Q. (2025b). Towards scalable anammox: Mechanistic insights and emerging strategies. *Trends in Biotechnology*, 8, 558–569. <https://doi.org/10.1016/j.tibtech.2025.08.013>
- Li, Z., Tang, L., Tang, M., Zhan, P., Ouyang, K., & Wu, Z. (2026). Efficient adsorption of antibiotic Levofloxacin using KOH-activated bamboo biochar. *Water, Air, & Soil Pollution*, 237(10), Article 581. <https://doi.org/10.1007/s11270-026-09286-7>
- Louarrat, M., Enaïme, G., Baçaoui, A., Yaacoubi, A., Blin, J., & Martin, L. (2019). Optimization of conditions for the preparation of activated carbon from olive stones for application in gold recovery. *Journal of the Southern African Institute of Mining and Metallurgy*, 119(3), 297–306. <https://doi.org/10.17159/2411-9717/2019/v119n3a9>
- Lu, Y., Zhang, H., & Li, Y. (2023). Coupling FeMgAl-LDH and sludge biofilm for simultaneous and effective removal of nitrate and ammonium in water. *Journal of Water Process Engineering*, 56, Article 104285. <https://doi.org/10.1016/j.jwpe.2023.104285>

- Machida, M., Yoo, P., & Amano, Y. (2019). Adsorption of nitrate from aqueous phase onto nitrogen-doped activated carbon fibers (ACFs). *SN Applied Sciences*, 1(4), 961–972. <https://doi.org/10.1007/s42452-019-0333-7>
- Magaji, B., Maigari, A. U., Abubakar, U. A., Sani, M. M., & Maigari, A. U. (2020). Batch Adsorption of Safranin Dye from an Aqueous Solution of Balanites aegyptiaca Seed Coats. *Asian Journal of Physical and Chemical Sciences*, 48–54. <https://doi.org/10.9734/ajopacs/2020/v8i130109>
- Martínez-Huitle, C. A., & Ferro, S. (2006). Electrochemical oxidation of organic pollutants for the wastewater treatment: Direct and indirect processes. *Chemical Society Reviews*, 35(12), 1324–1340. <https://doi.org/10.1039/b517632h>
- Menkiti, M. C., Aneke, M. C., Ejikeme, P. M., Onukwuli, O. D., & Menkiti, N. U. (2014). Adsorptive treatment of brewery effluent using activated *Chrysophyllum albidum* seed shell carbon. *Springerplus*, 3(1), 1–19. <https://doi.org/10.1186/2193-1801-3-213>
- Milakin, K. A., Taboubi, O., Lhotka, M., Hromádková, J., Hodan, J., Pop-Georgievski, O., & Bober, P. (2025). Impact of aniline-to-pyrrole ratio on the adsorption performance of polyaniline/polypyrrole aerogels towards anionic dyes. *Emergent Materials*, 8, 6439–6451. <https://doi.org/10.1007/s42247-025-01130-8>
- Mirshafiee, A., Nourollahi, M., & Shahriary, A. (2024). Application of electro oxidation process for treating wastewater from petrochemical with mixed metal oxide electrode. *Scientific Reports*, 14(1), 555–568. <https://doi.org/10.1038/s41598-024-52201-5>
- Motue Waffo, L. C., Dangwang Dikdim, J. M., Noumi, G. B., Domga, T. D., Kaichouh, G., Sieliechi, J. M., Haji, I., Guessous, A., & El Karbane, M. (2022). Electrochemical production of sulfate radicals for degradation of Tenofovir in aqueous solution. *Case Studies in Chemical and Environmental Engineering*, 6, Article 100235. <https://doi.org/10.1016/j.csee.2022.100235>
- Namla, D., Oves, M., Alshaeri, M. A., Al-Maaqar, S. M., Issa, H. N. Y., & Mangse, G. (2025). Nanofiltration as an advanced wastewater treatment technique: A comprehensive review. *Discover Applied Sciences*, 7(4), 125–134. <https://doi.org/10.1007/s42452-025-06576-3>
- Nascimento, I. G., de Lima, E. S. A., de Oliveira, C. C. L., do Amaral Sobrinho, N. M. B., da Fonseca Bre, F. A., de Campos, D. V. B., & Pinheiro, É. F. M. (2025). Adsorption of cadmium by brewery waste. *Bioresource Technology Reports*, 30, Article 102108. <https://doi.org/10.1016/j.biteb.2025.102108>
- Neolaka, Y. A. B., Lawa, Y., Naat, J. N., Riwu, A. A. P., Iqbal, M., Darmokoeseomo, H., & Kusuma, H. S. (2020). The adsorption of Cr(VI) from water samples using graphene oxide-magnetic (GO-Fe₃O₄) synthesized from natural cellulose-based graphite (kusambi wood or *Schleichera oleosa*): Study of kinetics, isotherms and thermodynamics. *Journal of Materials Research and Technology*, 9(3), 6544–6556. <https://doi.org/10.1016/j.jmrt.2020.04.040>
- Nogueira, DAdER., Zanela, T. M. P., Machado, M. V., Almeida, C. A. P., & Marangoni, R. (2023). Adsorption process of Methyl Orange dye onto Zinc Hydroxide Nitrate: Kinetic and thermodynamic studies. *Colorants*, 2(3), 565–577. <https://doi.org/10.3390/colorants2030028>
- Nzetchuen Kouahou, G., Fotsop, C. G., Adoum Amola, L., Donlifack Atemkeng, C., Kamdem Tamo, A., Teikam Kenda, G., Tiegam Tagne, R. F., & Kamgaing, T. (2023). Optimized preparation of activated carbon with high porosities based on puck shells (*Afrostryax lepidophyllus*) by response surface methodology and physico-chemical characterization. *Royal Society Open Science*, 10(12), Article 230911. <https://doi.org/10.1098/rsos.230911>
- Panizza, M., & Cerisola, G. (2009). Direct and mediated anodic oxidation of organic pollutants. *Chemical Reviews*, 109(12), 6541–6569. <https://doi.org/10.1021/cr9001319>
- Pettigrew, L., Blumenhofer, V., Hubert, S., Groß, F., & Delgado, A. (2015). Optimisation of water usage in a brewery clean-in-place system using reference nets. *Journal of Cleaner Production*, 87(1), 583–593. <https://doi.org/10.1016/j.jclepro.2014.10.072>
- Quimada, N. E., Sioson, A. S., Sutopo, F., & Mabayo, V. I. F. (2024). Response surface optimization of the efficiency of ZnCl₂-impregnated activated carbon from residual coffee grounds in the removal of Eriochrome Black T dye-contaminated wastewater. *Biomass Conversion and Biorefinery*, 14(6), 7555–7567. <https://doi.org/10.1007/s13399-023-04090-3>
- Raji, Z., Karim, A., Karam, A., & Khalloufi, S. (2023). Adsorption of heavy metals: Mechanisms, kinetics, and applications of various adsorbents in wastewater remediation—a review. *Waste*, 1(3), 775–805. <https://doi.org/10.3390/waste1030046>
- Ray, S. K., Pant, B., Park, M., & Bastakoti, B. P. (2023). Rice husk-derived sodium hydroxide activated hierarchical porous biochar as an efficient electrode material for supercapacitors. *Journal of Analytical and Applied Pyrolysis*, 175, Article 106207. <https://doi.org/10.1016/j.jaap.2023.106207>
- Raza, B., Ramzan, M. N., & Yang, W. (2025). A review: Improving aquaculture rearing water quality by removal of nutrients using microalgae, challenges and future prospects. *Aquaculture*, 598, Article 741959. <https://doi.org/10.1016/j.aquaculture.2024.741959>
- Rodier, J. (2016). *L'Analyse de l'eau - 10^e Ed. - eaux naturelles, eaux résiduaires, eau de mer*. DUNOD. 7658–7711
- Rodríguez-Narváez, O. M., Picos, A. R., Bravo-Yumi, N., Pacheco-Alvarez, M., Martínez-Huitle, C. A., & Peralta-Hernández, J. M. (2021). Electrochemical oxidation technology to treat textile wastewaters. *Current Opinion in Electrochemistry*, 29, Article 100806. <https://doi.org/10.1016/j.coelec.2021.100806>
- Shiryayev, A. A., Pré, P., Pardanaud, C., Murzin, V., Averin, A., Rouzaud, J.-N., & Frumkin, A. N. (2023). Microporosity and nanostructure of activated carbons: Characterization by X-ray diffraction and scattering, Raman spectroscopy and transmission electron microscopy. *Adsorption*, 10, 88–99. <https://doi.org/10.1007/s10450-023-00406>
- Sun, W., Ju, X., Wang, H., Sun, H., Zhao, C., & Shi, B. (2025). Dimethyl phthalate removal through synergistic adsorption-oxidation process of citrus peel biochar coupled with electrochemical system. *Journal of Environmental Chemical Engineering*, 13(3), Article 116739. <https://doi.org/10.1016/j.jece.2025.116739>

- Takigami, H., Watanabe, M., & Kajiwar, N. (2014). Destruction behavior of hexabromocyclododecanes during incineration of solid waste containing expanded and extruded polystyrene insulation foams. *Chemosphere*, 116, 24–33. <https://doi.org/10.1016/j.chemosphere.2014.01.082>
- Tebeje, A., Worku, Z., Nkambule, T. T. I., & Fito, J. (2022). Adsorption of chemical oxygen demand from textile industrial wastewater through locally prepared bentonite adsorbent. *International Journal of Environmental Science and Technology*, 19(3), 1893–1906. <https://doi.org/10.1007/s13762-021-03230-4>
- Tegui Doumbi, R., Noumi, G. B., & Domga. (2023). Synthesis of Ti/SnO₂-Sb electrode modified by nitrogen and sulfur co-doped graphene for optimization the electrooxidation of neutral red and methyl orange dyes. *Environmental Engineering Research*, 28(5). <https://doi.org/10.4491/eeer.2022.378>
- Wang, L., Sun, Z., Shi, J., Li, H., Fu, T., Xu, Y., Xiao, K., & Zhao, H. (2025). Selective oxidation of nitrogenous heterocyclic compounds by heat/peroxymonosulfate in phenol-rich wastewater. *Water Research*, 269, Article 122804. <https://doi.org/10.1016/j.watres.2024.122804>
- Yang, J. R., Wang, Y., Chen, H., & Lyu, Y. K. (2019). Ammonium removal characteristics of an acid-resistant bacterium *Acinetobacter* sp. JR1 from pharmaceutical wastewater capable of heterotrophic nitrification-aerobic denitrification. *Bioresource Technology*, 274, 56–64. <https://doi.org/10.1016/j.biortech.2018.10.052>
- Yao, J., Mei, Y., Xia, G., Lu, Y., Xu, D., Sun, N., Wang, J., & Chen, J. (2019). Process optimization of electrochemical oxidation of ammonia to nitrogen for actual dyeing wastewater treatment. *International Journal of Environmental Research and Public Health*, 16(16), 88–97. <https://doi.org/10.3390/ijerph16162931>
- Zapata-Martínez, O., Villa-Gomez, D., Tapia-Tussell, R., Dominguez-Maldonado, J., Hernández-Zárate, G., España-Gamboa, E., Valdez-Ojeda, R., & Alzate-Gaviria, L. (2024). Craft brewery wastewater treatment in a scalable microbial fuel cell stack. *Beverages*, 10(1), Article 10020. <https://doi.org/10.3390/beverages10010020>
- Zheng, T., Wu, H., Han, Z., Chen, L., Tang, B., Cui, P., Liu, H., Chao, Y., Zhu, W., & Liu, Z. (2024). Boron nitride modified CuZn-calcinated layered double hydroxides as efficient adsorbents for tetracycline removal. *Separation and Purification Technology*, 340, Article 126648. <https://doi.org/10.1016/j.seppur.2024.126648>
- Zouaoui, F., Moreira, V. R., Amaral, M. C. S., Biard, P. F., & Fourcade, F. (2025). Treatment of membrane concentrates using anodic oxidation process: A review. *Chemical Engineering and Processing - Process Intensification*, 214, Article 110357. <https://doi.org/10.1016/j.cep.2025.110357>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.