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# Lanthanum Cerium Ferrite Nanoparticles for Enhancing Voltammetric Response of a Carbon Paste Electrode to Opioid Methadone

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**Abstract**- Lanthanum cerium ferrite (LaCeFe<sub>2</sub>O<sub>4</sub>) nanomaterials were synthesized, characterized, and used for the modification of carbon paste electrodes, employed in the electrochemical determination of methadone. Methadone is one of the prescription opioid drugs which is widely used in addiction treatment programs. It is an electroactive material and can be measured through electrochemical methods. Simple co-precipitation method was the preparation route of nanomaterial synthesis. Cyclic voltammetry was applied for studying the modified electrode performance and square wave voltammetry was chosen as the detection technique. The limit of detection of the proposed method was 2.8  $\mu$ mol L<sup>-1</sup> of methadone. The method is able to detect methadone molecule in human plasma samples precisely.

**Keywords-** Cerium lanthanum ferrite nanoparticles; Carbon paste electrode; Methadone; Voltammetry; Sensor

# **1. INTRODUCTION**

Methadone-HCl (6-(dimethylamino)-4, 4-diphenyl-3-heptane hydrochloride or Dolphin, MET) is an opioid medication that has been attempted to reduce the risk of heroin overdose [1-7]. Moreover, it is a long-side-acting opioid that is being used in addiction treatment programs by replacing short-acting opioids like heroin or morphine [8]. The drug rises addicts' tolerance to opioids and also decreases their needs. However, methadone can be the reason for overdose

and finally, death, which is more probable in the first two weeks of start using or during the restart situation [9]. Therefore, in some countries doctors have to announce their prescription of MET for each person to certain centers, to prevent multiple prescriptions for one person at the same time. The prescriptive dose for each individual must be personalized by physical conditions and tolerance to opioid medicines. MET has also many side effects including anxiety, nervousness, sleep problems, weakness, dry mouth, nausea, diarrhea and in overdoses situation it causes respiratory depression, hypotension, stupor, circulatory problems and may be coma or death [10].

Many efforts have been done by researchers to make a reliable, rapid and accurate method that can be used in hospitals and forensic organizations because of the importance of methadone detection [11]. Various methods have been used to detect methadone such as UPLC/MS [12], electrophoresis [6], liquid and gas chromatography methods [13-17], Indirect flow-injection determination of methadone by atomic absorption spectrometry [18], chiral column chromatography coupled with mass spectrometric detection [19]. In addition to their high precision and accuracy, they are laborious and require high-priced apparatus and reagents, on the contrary electroanalytical methods with acceptable accuracy propose some advantages in methadone determinations such as simplicity of operation, low cost, scaling done and quick response time [20-22].

Nanomaterials and nanostructures, recently, are widely used in many applications like sensors, supercapacitors, solar cells, and water purification. Electrochemical sensors-based nanomaterials show special physical and chemical characteristics which separate them from their bulk-sized counterparts. Nanomaterials have high surface which leads to more interactions between atoms and their surroundings, also they often have electrocatalytic properties and the ability to facilitate electron transference mechanism. They are divided into different types of nanomaterials including carbon based, e.g., nano diamond, graphene, fullerene [23,24], metal based, e.g., Ag, Ni [25-27], metal oxide, e.g., TiO<sub>2</sub>, CuO, ZnO, Fe<sub>3</sub>O<sub>4</sub> [28-31] and etc. There is also another group of nanomaterials which has concerned researchers recently and are known as rare earth metal-based nanomaterials [32-44]. The characteristics which make this group unique are mostly their higher catalytic activities, lower pollution and their recyclability.

Ferrites are composed of iron oxide and one or more other metals in chemical combination. Their general formula is  $M_{1-x}N_xFe_{2-y}R_yO_4$ , where M, N and R can be transition metal ions or be a rare earth ion. They have interesting magnetic and dielectric properties which makes them a potential material for electronic and solid-state applications. A spinel ferrite with general formula MFe<sub>2</sub>O<sub>4</sub> is a composite oxide crystal in a face-centered cubic core. They can be made from the combination of a trivalent cation (Fe<sup>3+</sup>) and other metallic cation Mg, Co, Ni, Zn or lanthanide cations. Lanthanide doped ferrite nanomaterials have attracted a great attention for various application such as photocatalyst, supercapacitors or gas sensors. For example,

lanthanides doped  $CoZnFe_2O_4$  is used as photocatalyst [44], or lanthanum cerium ferrite (LaCeFe<sub>2</sub>O<sub>4</sub>) applied for supercapacitor [45].

Ferrites nanomaterials are prepared through various synthesis methods including coprecipitation, sol–gel, hydrothermal, ball milling, electrospinning, micro-emulsion, and etc [46]. Among them, co-precipitation method is low-cost, simple, fast, and ecofriendly as compare to other procedures.

Here, lanthanum cerium ferrite (LaCeFe<sub>2</sub>O<sub>4</sub>) nanomaterials were synthesized through coprecipitation method. Then, they were characterized and successfully applied for modification of a carbon paste electrode which was used in voltammetric measurement of MET.

### 2. MATERIALS AND METHODS

### 2.1. Chemicals and reagents

Cerium nitrate hexahydrate (Ce(NO<sub>3</sub>)<sub>3</sub>.6H<sub>2</sub>O), lanthanum nitrate hexahydrate (La(NO<sub>3</sub>)<sub>3</sub>.6H<sub>2</sub>O), ferric nitrate nonahydrate (Fe(NO<sub>3</sub>)<sub>3</sub>.9H<sub>2</sub>O), NaOH, acetic acid, Na<sub>2</sub>HPO<sub>4</sub>, NaH<sub>2</sub>PO<sub>4</sub>, CaCl<sub>2</sub>, KCl and NH<sub>4</sub>Cl, D-(+)-Glucose, L-cysteine, ascorbic acid and uric acid were all obtained from Merck Chemical Company. Pure methadone hydrochloride powder was obtained from Daroo pakhsh Co (Tehran, Iran). Graphite powder along with the paraffin oil for carbon paste preparation were also purchased from Merck. Human plasma sample was obtained from Iranian blood transfusion organization. All chemicals were of analytical-reagent grade and used without further purification. Stock solution of methadone hydrochloride was prepared in 0.1 M buffer solutions and diluted to prepare other concentrations. All solutions were prepared in deionized distilled water.

## 2.2. Instruments

Electrochemical voltammetric measurements were performed by a DropSens  $\mu$ Stat400 Bipotentiostat/Galvanostat (Asturias, Spain). A homemade carbon paste electrode and Ag/AgCl reference electrode (Azar Electrode, Iran) and a carbon counter electrode were used for the measurements. In order to characterize the morphology of nanomaterials and the modified surfaces was carried out with a Hitachi S4160 (Cold Field Emission) scanning electron microscope. The X-ray diffraction (XRD) measurements were performed using an EQUINOX diffract meter with u-Ka radiation (k = 1.5418 A°) at scanning angles  $0.0^{\circ}$ –100° (Intel Company).

#### 2.3. Synthesis of LaCeFe<sub>2</sub>O<sub>4</sub> nanomaterial

Primarily, three solutions were made separately by adding 0.3 mol of  $Fe(NO_3)_3.9H_2O$ , 0.05 mol of La(NO<sub>3</sub>)<sub>3</sub>.6H<sub>2</sub>O and 0.05 mol of Ce(NO<sub>3</sub>)<sub>3</sub>.6H<sub>2</sub>O in 25 mL distilled water. Then, all the solutions were mixed together while stirring at room temperature for 15 min to get a

homogeneous mixture. Next, 0.2 mol of NaOH in 25 mL distilled water was used as a precipitating reagent and added drop wise into the mixed solution through a burette while stirring at 80 °C for 4 h. A precipitate with brick red color was formed, after adding the whole NaOH solution [45]. At the end, the formed precipitates were washed fourth times with distilled water and dried in an oven at 200 °C for 24 h.

# 2.4. Preparation of the modified carbon paste electrode

The modified carbon paste electrode was made using a 1 mL syringe which the tip has been cut off and the electrical connection was obtained using a copper wire. The modified carbon paste was prepared by mixing 3% LaCeFe<sub>2</sub>O<sub>4</sub> NPs, 67% graphite and 30% paraffin oil in a 10 mL beaker with a stainless spatula on an 80° C heater to achieve a homogenous mixture. The container was filled with the mixture. The electrode was compressed and fixed on a smooth paper.

## 2.5. Preparation of the plasma sample

The plasma sample from healthy volunteers was mixed with concentrated nitric acid followed by centrifugation in order to remove proteins. Appropriate amounts of supernatant, after 10 times diluting, were spiked with 300  $\mu$ L, 500  $\mu$ L and 700  $\mu$ L of 10 mM methadone and analyzed by the modified carbon paste electrode.

### **3. RESULTS AND DISCUSSION**

### 3.1. Structure and morphology characterization of the nanocomposite

# 3.1.1. XRD studies

X-rays diffraction patterns of the synthesized CeLaFe<sub>2</sub>O<sub>4</sub> through co-precipitate method is shown in Figure 1.



Figure 1. XRD pattern of synthesis CeLaFe<sub>2</sub>O<sub>4</sub> nanomaterials

The XRD patterns has four prominent scattering peaks in the 2 theta range of 20°-80° which can correspond to the crystal planes (111), (200), (220) and (311) representing the formation of cubic cerium lanthanum ferrite structure. The XRD pattern is in agreement with previous reports [45].

# **3.2.** Electrochemical characterization of the modified carbon paste electrode with the nanocomposite

Cyclic voltammetry (CV) is an important and widely used technique for studying the redox processes and the kinetics of electron transfer in electroanalytical chemistry. In order to investigate the redox properties of the prepared nanocomposite, the electrochemical behavior of methadone was studied at both bare and modified carbon paste electrodes by cyclic voltammetry.



**Figure 3.** Cyclic voltammograms of methadone  $5 \times 10^{-4}$  mol L<sup>-1</sup> in phosphate buffer solution (pH 7) at the surface of (a) bare CPE, (b) LaCeFe<sub>2</sub>O<sub>4</sub> nanomaterial modified CPE (scan rate: 0.1 V s<sup>-1</sup>)

Figure 3 demonstrates the cyclic voltammograms of methadone in the optimized conditions at the bare and modified carbon paste electrodes. As can be seen, the electro-oxidation of methadone at the bare CPE shows an irreversible peak with a potential of 1.18 V. At the modified CPE, the peak current enhances significantly which is related to the high surface area and the facility of electron transference in the presence of the nanomaterial. These results confirm that the modified CPE with the presented nanocomposite can be a suitable device for methadone determination at low concentrations.

## 3.3. Optimization of the measurement conditions

### 3.3.1. pH study

The effect of the pH on the oxidation potential of the methadone hydrochloride was studied in different pH solutions from 5 to 8. The presence of amine group in methadone structure makes the oxidation potential strongly dependent to the pH of the drug solution. As shown in Figure 4 with increasing the pH of the solution the peak potential shifts to less positive values and the peak current increases which means that methadone oxidation is much easier in higher pH solutions. The changes in peak potential show a linear relationship with pH of the solution according to the following equation:  $E_p$ = -0.052 pH + 1.518 (R<sup>2</sup> = 0.996).



**Figure 4.** Cyclic voltammograms of methadone  $10^{-3}$  mol L<sup>-1</sup> in different pH values: pH 5 (dashdotted line), pH 6 (dotted line), pH 7 (solid line), pH 8 (dashed line) at the surface of the LaCeFe<sub>2</sub>O<sub>4</sub> nanomaterial modified CPE (scan rate: 0.1 V s<sup>-1</sup>).

The slope of -0.052 V/pH obtained in the above equation confirms that the equal number of protons and electrons are involved in methadone amine group oxidation. The large variations in peak current and peak potential by increasing the pH of the solution are up to pH 7, after that increasing the pH does not show significant effect on the peak current and potential. Additionally at pH 7, methadone has positive charge ( $pk_a=8.94$ ) which increases its adsorption on the negative surface of the modified carbon paste electrode. Therefore, by consideration of the methadone determination in physiological conditions (pH=7.4), the pH of the 7 was selected as the optimum value for simulating with real samples.

### 3.3.2. The potential scan rate

The effect of the potential scan rate on the electrochemical oxidation of methadone at the surface of modified carbon paste electrode was investigated by cyclic voltammetry in  $5.0 \times 10^{-4}$  mol L<sup>-1</sup> drug solution (prepared in phosphate buffer (pH 7)) in the range of 10 to 100 mV s<sup>-1</sup>. The results of such studies can be used for understanding the mechanism (diffusion or adsorption control) of the methadone oxidation at the modified CPE. As can be seen in Figure 5 the oxidation peak current of methadone shows a good relationship with scan rate (v) with a linear regression equation of I<sub>p</sub> ( $\mu$ A) = 0.6541v (mV s<sup>-1</sup>) + 12.624 (R<sup>2</sup> = 0.9909). This indicated that the oxidation of methadone at the surface of the electrode is controlled by an adsorption process.



**Figure 5.** (a) Cyclic voltammograms of methadone  $5 \times 10^{-4}$  mol L<sup>-1</sup> in phosphate buffer solution (pH 7) at different scan rates, (a) 10, (b) 25, (c) 50, (d) 75, (e) 100, (f) 125 and (g) 150 mV s<sup>-1</sup> on LaCeFe<sub>2</sub>O<sub>4</sub> nanomaterial modified CPE (b) Plot of current *vs.* scan rate. (c) Plot of potential *vs.* logarithmic function of scan rate

The dependence of the peak potential on the logarithmic function of scan rate also shows a good relationship with the correlation coefficient of 0.9951 according to the following equation:  $E_p(V) = 0.0888 \log v (V \text{ s}^{-1}) + 1.2788$ . According to Laviron, for an irreversible and adsorption-controlled process, the following equation is considered [47]:  $E_p=E^{0'+}$  (2.303RT/anF) log (RTk<sub>0</sub>/anF) + (2.303RT/anF) log v, where a is the transfer coefficient, k<sub>0</sub> the standard heterogeneous rate constant of the reaction, n the number of electrons transferred, v the scan rate, and  $E^{0'}$  is the formal redox potential. The value of an can be calculated from the slope of  $E_p vs$ . log v. Considering the slope of 0.0888, an is calculated about 0.66. According to Bard and Faulkner [48], a can be given by the following equation:  $E_{p/2}-E_p = 1.857(RT/aF)$ ,

where  $E_{p/2}$  is the potential where the current is at half the peak value. From this equation the value of  $\alpha$  was obtained 0.28, hence, the number of electron transferred at the surface of modified electrode was calculated about 2.35 (n=2.35 $\approx$ 2).

### 3.4. Analytical features of the method

The LaCeFe<sub>2</sub>O<sub>4</sub> modified carbon paste electrode, at the adjusted conditions, was used for calibration curve plotting. The calibration curve was obtained after analyzing each concentration of methadone hydrochloride with square wave voltammetry at the modified electrode surface. The linear range, regression equation and correlation coefficient of the proposed sensor were 10 to 1000  $\mu$ mol L<sup>-1</sup>, I ( $\mu$ A) = 0.1261 Conc. ( $\mu$ mol L<sup>-1</sup>) +15.935 and 0.998, respectively (Figure 6). The limit of detection (LOD) and the relative standard deviation (RSD) of the method were obtained 2.8  $\mu$ mol L<sup>-1</sup> and 3.7 %, respectively.



**Figure 6.** (a) Square wave voltammograms containing some concentrations of methadone, (a) 0, (b) 10, (c) 100, (d) 300, (e) 500, (f) 700, (g) 1000  $\mu$ M in phosphate buffer solution at LaCeFe<sub>2</sub>O<sub>4</sub> nanomaterial modified CPE. (b) Linear calibration curve of proposed sensor toward methadone

## 3.5. Interferences

One of the most important features of an analytical method is its selectivity. In order to investigate the selectivity of the proposed modified CPE toward methadone, the effect of the common species such as ascorbic acid, uric acid, D-(+)-glucose, L-cysteine, Ca<sup>2+</sup>, K<sup>+</sup> and NH<sub>4</sub><sup>+</sup> at high concentrations were tested on the electrochemical behavior of methadone at the given conditions. The results showed that the presence of these species has no significant effect on the methadone response even at 1:100 methadone to interference species ratio. From the obtained results it is obvious that the proposed sensor can be used effectively for methadone determination in biological complex matrixes containing the possible mentioned interferences.

## 3.6. Performance of the LaCeFe<sub>2</sub>O<sub>4</sub> modified CPE in analysis of methadone in plasma

Performance of the propose electrode was assessed through methadone determination in plasma matrix. Test solution was made as described in experimental section. The results are presented in Table 1. As it can be seen the recovery amount of methadone is very close to 100% that can confirm the applicability of the method in direct low concentrations detection of methadone in plasma.

Table 1.	Recoveries	obtained fo	r the detern	nination of	of methadon	e in plasma	sample at r	nodified
CPE								

Plasma Sample number	Added amount of MET (µM)	Found amount of MET (µM)	Recovery (%)	RSD (%) (n=3)
1	0	-	-	-
2	300	274.9	91.6	2.07
3	500	498.6	99.7	1.09
4	700	695.2	99.3	0.4

## 4. CONCLUSION

Recently, lanthanoid doped nanomaterials, due to their unique electronic properties, have attracted the attention of the researches in the field of photocatalysts, sensors, batteries and supercapacitors. Their various oxidation states and active surfaces, they can catalyze many chemical reactions. Here, lanthanum cerium ferrite (LaCeFe<sub>2</sub>O<sub>4</sub>) nanomaterials were applied for the improvement of the carbon paste electrodes in the electrooxidation of methadone, as a widely used opioid medication. The nanomaterials were synthesized through co-precipitation method. Using square wave voltammetry as the detection technique, a limit of detection of 2.8  $\mu$ mol L<sup>-1</sup> of methadone was obtained. Finally, performance of the method was tested in human plasma matrix which the recovery results were acceptable.

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### REFERENCES

- [1] A.J. Cotton, L.J. Shipley, L.H. Glynn, J. Tracy, and A.J. Saxon, The American Journal on Addictions 26 (2017) 50.
- [2] C.S. John, L.M. Savitsky, J. Fowler, and A.B. Caughey, American Journal of Obstetrics & Gynecology 216 (2017) S449.
- [3] L.A. Dervan, B. Yaghmai, R.S. Watson, and F.M. Wolf, Pedi. Anesth. 27 (2017) 228.

- [4] A. Smith, K. Jensen, J. Li, Y. Nunez, L. Farrer, H. Hakonarson, S. Cook-Sather, H. Kranzler, and J. Gelernter, Molecular Psychiatry 22 (2017) 346.
- [5] J.D. Livingston, E. Adams, M. Jordan, Z. MacMillan, and R. Hering, Substance Use & Misuse 53 (2018) 334.
- [6] S. Hamidi, M. Khoubnasabjafari, K. Ansarin, V. Jouyban-Gharamaleki, and A. Jouyban, Current Pharm. Anal. 12 (2016) 137.
- [7] A.R. Winstock, T. Lea, and J. Sheridan, Int. J. Drug Policy 19 (2008) 450.
- [8] C. Vignali, C. Stramesi, L. Morini, F. Pozzi, and A. Groppi, Forensic Sci. Int. 257 (2015) 172.
- [9] M.C. Buster, G.H. van Brussel, and W.V.d. Brink, Addiction 97 (2002) 993.
- [10] C. Moore, F. Guzaldo, M.J. Hussain, and D. Lewis, Forensic Sci. Int. 119 (2001) 155.
- [11] A. Shafaat, and F. Faridbod, Anal. Bioanal. Electrochem. 14 (2022) 319.
- [12] P.-P. Pan, S.-H. Wang, J. Wang, J. Luo, P.-W. Geng, Y.-F. Zhou, and G.-X. Hu, Chromatographia 79 (2016) 601.
- [13] G. Achilli, G. Cellerino, G.M. d'Eril, and F. Tagliaro, J. Chromatography A 729 (1996) 273.
- [14] A. Taghvimi, H. Hamishehkar, and M. Ebrahimi, J. Separation Sci. 39 (2016) 2307.
- [15] F. Chiadmi, and J. Schlatter, Anal. Chem. Insights 10 (2015) 17.
- [16] M. Khoubnasabjafari, K. Ansarin, V. Jouyban-Gharamaleki, V. Panahi-Azar, A. Shayanfar, L. Mohammadzadeh, and A. Jouyban, J. Pharmacy Pharm. Sci. 18 (2015) 207.
- [17] K.M. Ara, and F. Raofie, Talanta 168 (2017) 105.
- [18] R. Montero, M. Gallego, and M. Valcarcel, Anal. Chim. Acta 234 (1990) 433.
- [19] R. George, M. Lobb, A. Haywood, S. Khan, J. Hardy, P. Good, S. Hennig, and R. Norris, Talanta 149 (2016) 142.
- [20] S. Khalil, and A. Kelzieh, J. Pharm. Biomed. Anal. 31 (2003) 601.
- [21] M. Amiri-Aref, J.B. Raoof, and R. Ojani, Colloids and Surfaces B 109 (2013) 287.
- [22] M. Ardeshiri, and F. Jalali, Mater. Sci. Engin. C 63 (2016) 30.
- [23] S. Kurbanoglu, and S.A. Ozkan, J. Pharm. Biomed. Anal. 147 (2018) 439.
- [24] K. Scida, P.W. Stege, G. Haby, G.A. Messina, and C.D. García, Anal. Chim. Acta 691 (2011) 6.
- [25] S.W. Wijnhoven, W.J. Peijnenburg, C.A. Herberts, W.I. Hagens, A.G. Oomen, E.H. Heugens, B. Roszek, J. Bisschops, I. Gosens, and D. Van De Meent, Nanotoxicology 3 (2009) 109.
- [26] H. Cheshideh, and F. Nasirpouri, J. Electroanal. Chem. 797 (2017) 121.
- [27] E.L. Dreizin, Progress Energy Comb. Sci. 35 (2009) 141.
- [28] M. Runowski, T. Grzyb, and S. Lis, J. Nanoparticle Res. 14 (2012) 1188.
- [29] O. Bondarenko, K. Juganson, A. Ivask, K. Kasemets, M. Mortimer, and A. Kahru, Archives of Toxicology 87 (2013) 1181.

- [30] Y. Ma, X. Wang, Y. Jia, X. Chen, H. Han, and C. Li, Chem. Rev. 114 (2014) 9987.
- [31] D.R. Miller, S.A. Akbar, and P.A. Morris, Sens. Actuators B 204 (2014) 250.
- [32] Y. Liu, K. Ai, J. Liu, Q. Yuan, Y. He, and L. Lu, Angewandte Chemie International Edition 51 (2012) 1437.
- [33] F. Wang, R. Deng, and X. Liu, Nature Protocols 9 (2014) 1634.
- [34] D. Girija, H.S.B. Naik, C. Sudhamani, and B.V. Kumar, Arch. Appl. Sci. Res. 3 (2011) 373.
- [35] J.C. Dumke, B. El-Zahab, S. Challa, S. Das, L. Chandler, M. Tolocka, D.J. Hayes, and I.M. Warner, Langmuir, 26 (2010) 15599.
- [36] A.L. Sanati, and F. Faridbod, Anal. Bioanal. Electrochem. 14 (2022) 510.
- [37] S.A. Mousavifar, M.R. Ganjali, F. Faridbod, and P. Norouzi, J. Mater. Sci. Mater. Electron. 32 (2021) 8535.
- [38] T. Alizadeh, M.R. Ganjali, M. Akhoundian, and P. Norouzi, Microchim. Acta 183 (2016) 1123.
- [39] L. Anvari, S.M. Ghoreishi, F. Faridbod, and M.R. Ganjali, Anal. Lett. 54 (2021) 2509.
- [40] M. Shoghi-Kalkhoran, F. Faridbod, P. Norouzi, and M.R. Ganjali, J. Mater. Sci. Mater. Electron. 29 (2018) 20.
- [41] H. Beitollahi, Z. Dourandish, S. Tajik, M.R. Ganjali, P. Norouzi, and F. Faridbod, J. Rare Earth 36 (2018) 750.
- [42] A. Sobhani-Nasab, H. Naderi, M. Rahimi-Nasrabadi, and M.R. Ganjali, J. Mater. Sci. Mater. Electron. 28 (2017) 8588.
- [43] M. Aghazadeh, and M.R. Ganjali, J. Mater. Sci. 53 (2018) 295.
- [44] S.M. Peymani-Motlagh, N. Moeinian, M. Rostami, M. Fasihi-Ramandi, A. Sobhani-Nasab, M. Rahimi-Nasrabadi, M. Eghbali-Arani, M.R. Ganjali, T. Jesionowski, H. Ehrlich, M.A. Karimi, and N. Ajami, J. Rare Earth 37 (2019) 1288.
- [45] W. Raza, G. Nabi, A. Shahzad, N. Malik, and N. Raza, J. Mater. Sci. Mater Electron. 32 (2021) 7443.
- [46] A. Soufi, H. Hajjaoui, R. Elmoubarki, M. Abdennouri, S. Qourzal, and N. Barka, Applied Surf. Sci. Adv. 6 (2021) 100145.
- [47] E. Laviron, J. Electroanal. Chem. Interfacial Electrochem. 101 (1979) 19.
- [48] A.J. Bard, and L.R. Faulkner, J. Leddy, C.G. Zoski, Electrochemical Methods: Fundamentals and Applications: Wiley New York (1980).