# The effect of chemical modification procedure on corrosion behaviour of pure magnesium in simulated body fluid: A comparison study

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#### Abstract

The corrosion behaviour of pure Mg in simulated body fluid (SBF) and the effect of chemical modification on the anticorrosion property of the metal was investigated using DEIS (dynamic electrochemical impedance spectroscopy), EIS (electrochemical impedance spectroscopy), PDP (potentiodynamic polarization), SEM (scanning electron microscopy), AFM (atomic force microscope), and pH measurement techniques for 30 h. NaOH and H2O2 were utilized for the chemical modification. The DEIS was used for the first time in the investigation of Mg corrosion in SBF.

Results gotten indicate that, the chemical modification benefitted the anticorrosion property of the metal immensely. The charge transfer resistance of the Mg was raised from 387.80  $\Omega$  cm<sup>2</sup> to 775.10  $\Omega$  cm<sup>2</sup> and 1393.20  $\Omega$  cm<sup>2</sup> at 30 h of immersion. The DEIS results revealed that the protective layer formed upon NaOH modification collapsed and lost its effectiveness after 2 h of immersion in the tested medium. H<sub>2</sub>O<sub>2</sub> modified surface demonstrated superior corrosion resistance and the pH of the SBF solution containing the H<sub>2</sub>O<sub>2</sub> modified specimen stood at 7.58 after 30 h of immersion. The results from both the electrochemical and the surface analysis techniques were consistent.

#### **Keywords:**

Magnesium; Chemical modification; Dynamic Electrochemical Impedance Spectroscopy (DEIS)

## **Introduction**

Magnesium and magnesium alloys were used in biomedical applications more than a long time but progress was unrecorded because corrosion of magnesium in vivo environment could not be solved sufficiently [1]. Due to the clinical needs for biodegradable metallic implants, there has been resurgence in developing Mg-based biomedical implants [2]. However, some of the disadvantages of using magnesium and Mg alloys are that it has a high rate of corrosion along with hydrogen gas release and an increase in the alkalinity of body fluids, all of which limit its clinical applicability [3]. In addition to this, an ideal implant has to be non-toxic to the organism, provide adequate mechanical support to surrounding tissues until the tissues are completely healed, and degrade without causing serious inflammatory or immunological response [4-7]. Although Mg and its alloys satisfy some of these requirements, they are inclined to corrosion in physiological environment and this often leads to lost of mechanical strength and implant failure [8,9]. Another limitation to the use of Mg and its alloys as biodegradable implant is the evolution of hydrogen gas at a rate that the body cannot regulate leading to subcutaneous hydrogen accumulation [10].

When a magnesium-based implant is placed in an in-vivo environment, corrosion occurs on the implant-tissue interface and biological reaction between the implant and tissue is determined by the interaction on the surface. For this reason, alloy design, anodization [11], ion implantation [12], phosphatation [13], microarc oxidation [14], laser surface treatments [15] and surface modification [16] methods are used to increase corrosion resistance and to extend the use of magnesium-based implants in biomedical applications. Of all these surface modification methods, chemical treatment is the simplest, inexpensive, and produces a uniform and well adhered porous network structure. Commonly used reagents for chemical treatments are NaOH and  $H_2O_2$  [16,17].

The present work aims to examine the corrosion behavior of chemical treatment using NaOH and  $H_2O_2$  solutions on the electrochemical behavior of pure magnesium in simulated body fluid solution. Dynamic electrochemical impedance spectroscopy (DEIS), electrochemical impedance spectroscopy (EIS), open circuit potential (OCP) and potentiodynamic polarization (PDP) were used for the electrochemical studies, while surface characterization was done with the aid of scanning electron microscopy (SEM) and atomic force microscope (AFM).

# 2. Material and experimental methods

# 2.1. Specimen preparation

Commercially available pure magnesium (99.9%) (Goodfellow Cambridge Limited, England) with surface area of 1 cm<sup>2</sup> and with chemical composition presented in Table 1 were used for this study. The exposed surface area of the working electrodes in the solution was  $0.5 \text{ cm}^2$ . Electrical conductivity was provided by a copper wire. The working electrode was first prepared using 400-2000 grade abrasive paper, and following this procedure, it was washed with distilled water and degreased with acetone.

Table 1. Chemical composition of pure Mg in (wt %)									
Sample	Al	Zn	Mn	Si	Cu	Fe	Ca	Ni	Mg
Pure Mg	-	-	0.017	-	-	0.028	-	-	99.955

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2.2. Surface treatment

Alkali-hydrogen peroxide treatment was performed by immersing the specimens in 20 mL mixture of 10 M NaOH and 4.5 M  $H_2O_2$  at 60 °C in an oven for 1 h and the specimens were washed with distilled water and dried at 40 °C in an air atmosphere [18]. The specimens were

afterwards heat treated in an electric furnace at 250 °C for 4 h and cooled to room temperature in the furnace. Finally, the specimens were ultrasonically cleaned to remove the loosely attached particles over the surface of the specimens.

## 2.3. Electrochemical characterization

A traditional three electrode cell system was used to measure electrochemical experiments. A saturated Ag/AgCl electrode act as reference electrode, platinum served as counter electrode and test specimens pure Mg (99.9%) as the working electrode. SBF used as electrolyte is prepared according to Kokubo procedure [19]. The chemical compositions of SBF CaCl<sub>2</sub> 0.292 g mL<sup>-1</sup>, KCl 0.225 g mL<sup>-1</sup>, K<sub>2</sub>HPO<sub>4</sub>.3H<sub>2</sub>O 0.231 g mL<sup>-1</sup>, MgCl<sub>2</sub>.6H<sub>2</sub>O 0.311 g mL<sup>-1</sup>, NaCl 8.035 g mL<sup>-1</sup>, NaHCO<sub>3</sub> 0.355 g mL<sup>-1</sup>, Na<sub>2</sub>SO<sub>4</sub> 0.072 g mL<sup>-1</sup>, into distilled water and buffered at pH 7.4 with TRIS (tris-hydroxymethyl aminomethane) and HCl. The human blood plasma and SBF solution ion concentrations are presented in Table 2. A Gamry potentiostat/galvanostat/ZRA (Reference 600) instrument was used for EIS and PDP studies. The potential change OCP due to the interaction between the working electrode (99.9% Mg) and SBF was measured for 30 h. To ensure repeatability of the experimental data, all the measurements were repeated under the same experimental conditions. In PDP experiments, the working electrode was scanned at a constant sweep rate of 1 mV/s at -300 to +300 mV interval with reference to corrosion potential. EIS measurements were performed with a frequency ranging from 100 kHz to 0.1 Hz and amplitude signal of 10 mV peak-to-peak voltage. The results obtained from the EIS experiments were analyzed using Echem Analyst 6.32 program. The DEIS method has a National Instruments Measurement Ltd. PCI-4461digital analogue card and Potantiostat/Galvanostat device that produces perturbation signal in the working system [20]. The same card was used for impedance measurement of current perturbation and voltage response signals with a sampling frequency of 12.8 kHz [21]. The perturbation signal was in the range of 4.5 kHz-700 MHz and the duration of measurement were 6, 12, 18, 24 and 30 h respectively.

Table 2. Ionic concentrations of SBF and the organic part of human blood plasma (mmol  $1^{-1}$ )

Ions	$Na^+$	$\mathbf{K}^+$	$Mg^{2+}$	Ca <sup>2+</sup>	Cl	HCO <sub>3</sub> <sup>-</sup>	HPO <sub>4</sub> <sup>-</sup>	$SO_4^{2-}$	pН
Plasma	142.0	3.6-5.5	1.0	2.12-2.6	95-107	27.0	0.65-1.45	1.0	7.3-7.4
SBF	142.0	5.0	1.0	2.5	131.0	5.0	1.0	1.0	7.4

## 2.4. Surface characterization

The surface analysis of the pure Mg (99%) samples exposed to before experiment, SBF solution and surface treatment in SBF solution for 6, 12, 18, 24 and 30 h respectively were scanned using SEM (FEI, Model: Quanta FEG 250) with an EDAX probe (accelerator voltage 20 keV), AFM (Park System X-100E) were investigated by means of after DEIS measurements.

# 2.5. pH measurements

pH measurements were made before and after the DEIS method. Initially, the pH value of the SBF solution was measured as 7.4 in accordance with the literature. After 6, 12, 18, 24 and 30 h respectively, pH measurements were made with ISOLAB hand type pH meter at room temperature.

# 3. Result and Discussion3.1. Surface characterization

SEM- EDS Analysis: The SEM micrographs obtained for pure Mg metal surface was smooth (Figure 1(a)) in the polished state and contained a considerable amount of Mg (100%). Upon exposure to the SBF solution, the metal surface suffered noticeable damage, as is evident in the coarseness of the surface in Figure 1(f). Large deposits of corrosion products can also be seen on the metal surface. Furthermore, it should also be noted that Mg, which is composition of metal, is corroded in SBF solution. The high rate of O in the EDAX spectrum shows (Fig.1 (f)) the formation of magnesium hydroxide on the surface [22]. Figure 3.1 (b) shows corrosion products on the surface of the metal exposed to the SBF medium for 6 h. When it is seen that the amount of Mg in the metal which increases the amount of Ca, P and O on the metal surface decreases (Table 3). Figure 3.1 (c) shows the presence of magnesium hydroxide layer on the surface of the metal exposed to SBF medium for 12 h and the EDS spectrum of P, Ca elements to the surface. Figure 3.1 (c), (d), (e) EDS results show that the magnesium metal is corroded as time increases and in the EDS spectrum Mg element is 33.01% in 12 h, 19.57% in 18 h, 15.72% in 24 h. Magnesium metal was observed in EDS spectra where the Ca and P elements in the SBF solution were adsorbed onto the magnesium surface. Fig. 1 (f), it is observed that the rate of mg in Metal decreases with increasing Ca, P and O on metal surface. The EDAX results show that magnesium metal is corroded and the Mg element is 11.37% at the end of 30 h. While magnesium metal was corroded, it was observed in the EDAX spectrum that Ca and P elements in the SBF solution were adsorbed to the magnesium surface.

Metal condition	Elemental composition (%)							
	Mg	0	Ca	Р	Cl			
Before expriment	100	-	-	-	-			
бh	48.02	36.88	5.75	4.66	0.65			
12h	33.01	41.07	11.23	9.10	0.29			
18h	19.57	46.04	11.92	15.66	3.39			
24h	15.72	39.98	14.15	16.58	0.66			
30h	11.37	42.59	17.43	17.87	1.65			
NaOH 30h	14.06	40.16	16.49	18.00	1.79			
$H_2O_2$ 30h	32.58	30.25	10.44	16.10	2.31			

Table 3. Elemental composition of pure magnesium before and after corrosion in SBF solution and NaOH and H<sub>2</sub>O<sub>2</sub> treatment at 25°C.

Fig.1 (g, h) shows fracture appears in the morphology of the structure formed on metal surface due to dehydration process during heat treatment while the surface modification process is performed [23]. In Fig.1 (g,h), the percentages of Mg, Ca, P, O elements were compared as a result of  $H_2O_2$  and NaOH chemical surface modification. As a result of surface modification is covered by the surface of the metal and EDAX spectrum is observed the amount of Mg is 32.58% and the amount of O is 30.25% in Fig.1 (g). The fact that these data are close to each other suggests that  $H_2O_2$  chemical surface modification makes a better improvement on the metal surface. In Table 3, the amount of Mg is 14.06% and the amount of O is 40.16%. This indicates that the NaOH chemical surface modification shows improvement on the metal surface but that the corrosion products are excessive.



Figure 1. SEM images for pure Mg in (a) abraded state, (b, c, d, e, f) exposed to SBF solution, (g) exposed to SBF solution containing H<sub>2</sub>O<sub>2</sub> surface treatment, (h) exposed to SBF solution containing NaOH surface treatment after 30 h of immersion at 25 °C.

**AFM** Analysis: Figure 2 presents the 3D AFM images for pure magnesium unexposed (a), after exposure to SBF solution for 30 h at 25 °C (b), exposed to SBF solution containing NaOH surface treatment after 30 h of immersion at 25 °C (c) and exposed to SBF solution containing H<sub>2</sub>O<sub>2</sub> surface treatment 30 h at 25 °C (d). Prior to the experiments (Fig. 2 (a)), the  $R_{\rm a}$  (mean of a set of independent measurements of surface peaks and valleys) was 12.938– 16.015  $\mu$ m while  $R_z$  (the root mean square average of profile height deviations from the mean line) stood at 52.969- 59,352 µm. These values infer a relatively smooth surface. Upon exposure to the SBF solution for 30 h (Fig. 2(b)), the  $R_a$  values increased significantly to 36.838-38.092  $\mu$ m and the  $R_z$  values to 140.661-141.157  $\mu$ m. Exposed to SBF solution containing NaOH surface treatment after 30 h (Fig. 2 (c)), the  $R_a$  values increased significantly to 22.127-37.081  $\mu$ m and the  $R_z$  values to 68.368-146.225  $\mu$ m. Exposed to SBF solution containing  $H_2O_2$  surface treatment 30 h (Fig. (d)), the  $R_a$  values increased significantly to 13.108-21.093  $\mu$ m and the  $R_z$  values to 78.392-88.703 $\mu$ m. The results of H<sub>2</sub>O<sub>2</sub> chemical surface modification yielded the lowest measurement results for  $R_a$  and  $R_z$  values. This decreases the roughness of the metal surface and the morphological changes of the metal surface as a result of corrosion of the H<sub>2</sub>O<sub>2</sub> chemical surface modification method.



Figure 2. 3D AFM images for pure Mg in (a) abraded state, (b) exposed to SBF solution after 30h, (c) exposed to SBF solution containing NaOH surface treatment, (d) exposed to SBF solution containing H<sub>2</sub>O<sub>2</sub> surface treatment after 30 h of immersion at 25 °C.

#### **3.2. Electrochemical measurements**

Fig. 3 shows the EIS Nyquist spectra that were taken at the corrosion potential of Mg after its immersion in SBF solutions and exposed to SBF solution containing NaOH and  $H_2O_2$ surface treatment, respectively for 30 hours. Although the Nyquist diagrams are usually semi-circle, it is seen that there is a deviation from the half circle in figure 3.1. The deflection of the Nyquist diagrams from a complete semi-circle is usually due to the frequency distribution [24], the uneven and roughness of the working electrode surface [25], fracture structures [26], the adsorption of ions in solution to the metal surface over time [27], and the load transfer process [28]. The Nyquist diagrams clearly show that when NaOH and  $H_2O_2$  surface modifications are applied to the magnesium metal surface, the size of the nyquist curves is increased.



Figure 3. Nyquist, bode and phase angle diagram of magnesium metal in SBF solution and exposed to SBF solution containing NaOH, H<sub>2</sub>O<sub>2</sub> surface treatment after 30 h of immersion at 25 °C.

### **Dynamic Electrochemical Impedance Spectroscopy (DEIS):**

DEIS method is an instant and dynamic process as is the most suitable method for corrosion research [32-36]. In particular, during in vitro experiments of biodegradable implants, instant measurements and data are of great importance. The DEIS method provides a great advantage to determine the immediate corrosion mechanism of the implants in the body and to observe the effect of the H<sub>2</sub> gas that will be released. It is thought that a protective layer is formed on the surface of magnesium metal after application of H<sub>2</sub>O<sub>2</sub> and NaOH chemical surface modification. When the surface modification method shown in Figure 4 is compared with the 3D DEIS result of magnesium, it is observed that the magnesium metal increases in the size of the impedance spectra after the application of H<sub>2</sub>O<sub>2</sub> and NaOH chemical surface modification. The reason for this increase is due to the improvement of the surface of the H<sub>2</sub>O<sub>2</sub> and NaOH chemical surface modification.



Figure 4. The DEIS 3D graphs of magnesium metal in SBF solution at 25  $^{\circ}$  C are obtained by (a) 30 hours, (b) exposed to SBF solution containing NaOH, (c) H<sub>2</sub>O<sub>2</sub> surface treatment after 30 h of immersion at 25  $^{\circ}$ C.

## 4. Conclusions

The corrosion behaviour of pure Mg in simulated body fluid (SBF) and the effect of chemical modification on the anticorrosion property of the metal have been studied for 30 h and the following conclusions drawn:

-Pure Mg dissolves rapidly in simulated body fluid and the pH of the medium can reach 7.92 after 30 h of immersion hence not suitable for implant.

-Chemical modification using NaOH or H2O2 is beneficial and can increase the corrosion resistance of Mg by 50% and 72% respectively even at long immersion duration.

-According to the DEIS results, Mg surface modified with NaOH is most effective within 2 h and gradually lost its effectiveness thereafter.

-H<sub>2</sub>O<sub>2</sub> is a better modification agent for Mg than NaOH.

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## References

[1] F. Witte, The history of biodegradable magnesium implants: A review, Acta Biomaterialia, vol. 6, pp. 1680-1692, 2010.

[2] G. Wu, J. M. Ibrahim and P. K. Chu, Surface design of biodegradable magnesium alloys - A review, Surface & Coatings Technology, vol. 233, pp. 2-12, 2013.

[3] F. Witte, V. Kaese, H. Haferkamp, E. Switzer, A. Meyer-Lindenberg, C. J. Wirth, H. Windhagen, In vivo corrosion of four magnesium alloys and the associatedbone response, Biomaterials, vol. 26, pp. 3557–3563, 2005.

[4] M. Ascencio, M. Pekguleryuz, S. Omanovic, An investigation of the corrosion mechanisms of WE43 Mg alloy in a modified simulated body fluid solution: The influence of immersion time, Corrosion Science, vol. 87, pp. 489-503, 2014.

[5] J. Gan, L. Tan, K. Yang, Z. Hu, Q. Zhang, X. Fan, Y. Li, W. Li, Bioactive Ca–P coating with self-sealing structure on pure magnesium, J. Mater. Sci. Mater. Med., vol. 24 pp. 889–901, 2013.

[6] H. Zhang, R. Luo, W. Li, J. Wang, M. F. Maitz, J. Wang, G. Wan, Y. Chen, H. Sun, C. Jiang, R. Shen, N. Huang, Epigallocatechin gallate (EGCG) induced chemical conversion coatings for corrosion protection of biomedical MgZnMn alloys, Corrosion Science, vol. 94, pp. 305-315, 2015.

[7] M. C. Zhao, P. Schmutz, S. Brunner, M. Liu, G. Song, A. Atrens, An exploratory study of the corrosion of Mg alloys during interrupted salt spray testing, Corrosion Science, vol. 51, pp. 1277-1292, 2009.

[8] C. Wen, S. Guan, L. Peng, C. Ren, X. Wang, Z. Hu, Characterization and degradation behavior of AZ31 alloy surface modified by bone-like hydroxyapatite for implant applications, Applied Surface Science, vol. 255, pp. 6433-6438, 2009.

[9] M. P. Staiger, A. M. Pietak, J. Huadmai, G. Dias, Magnesium and its alloys as orthopedic biomaterials: A review, Biomaterials, vol. 27, pp.1728–1734, 2006.

[10] A. Atrens, G. L. Song, M. Liu, Z. Shi, F. Cao, M. S. Dargusch, Review of Recent Developments in the Field of Magnesium Corrosion, Advanced Engineering Materials, vol. 17, pp. 400-453, 2015.

[11] G. Song, Control of biodegradation of biocompatable magnesium alloys, Corrosion Science, vol. 49, pp. 1696-1701, 2007.

[12] Y. Z. Wan, G. Y. Xiong, H. L. Luo, F. He, Y. Huang and Y. L. Wang, "Influence of zinc ion implantation on surface nanomechanical performance and corrosion resistance of biomedical magnesium–calcium alloys", *Applied Surface Science*, vol. 254, no. 17, pp. 5514–5516, 2008.

[13] L. Xu, F. Pan, G. Yu, L. Yang, E. Zhang, K. Yang, In vitro and in vivo evaluation of the surface bioactivity of a calcium phosphate coated magnesium alloy, Biomaterials, vol. 30, pp. 1512-1523, 2009.

[14] S. F. Fischerauer, T. Kraus, X. Wu, S. Tangl, E. Sorantin, A. C. Hänzi, J. F. Löffler, P. J. Uggowitzer, A. M. Weinberg, In vivo degradation performance of micro-arc-oxidized magnesium implants: A micro-CT study in rats, Acta Biomaterialia, vol. 9, pp. 5411-5420, 2013.

[15] F. Xie, X. He, Y. Lv, M. Wu, X. He, X. Qu, Selective laser sintered porous Ti–(4–10)Mo alloys for biomedical applications: Structural characteristics, mechanical properties and corrosion behaviour, Corrosion Science, vol. 95, pp. 117-124, 2015.

[16] Y. Sasikumar, M. M. Solomon, L. O. Olasunkanmi, E. Ebenso, Effect of surface treatment on the bioactivity and electrochemical behavior of magnesium alloys in simulated body fluid, Materials and Corrosion, vol. 9999, pp. 1-15, 2017.

[17] A. K. Shukla, R. Balasubramaniam, Effect of surface treatment on electrochemical behavior of CP Ti, Ti–6Al–4V and Ti–13Nb–13Zr alloys in simulated human body fluid, Corrosion Science, vol. 48, pp. 1696-1720, 2006.

[18] Y. Sasikumar and N. Rajendran, "Influence of surface modification on the apatite formation and corrosion behavior of Ti and Ti-15Mo alloy for biomedical applications," *Materials Chemistry and Physics*, vol. 138, pp. 114-123, 2013.

[19] T. Kokubo, and H. Takadama, "How useful is SBF in predicting in vivo bone bioactivity?," *Biomaterials*, vol. 27, pp. 2907-2915, 2006.

[20] J. Orlikowski and K. Darowicki, "Investigations of pitting corrosion of magnesium by means of DEIS and acoustic emission," *Electrochimica Acta*, vol. 56, pp. 7880-7884, 2011.

[21] H. Gerengi, G. Bereket, M. Kurtay, "A morphological and electrochemical comparison of the corrosion process of aluminum alloys under simulated acidrain conditions," *J. Taiwan Inst. Chem. Eng.*, vol. 58, pp.509–516,2016.

[22] R. Rettig and S. Virtanen, "Composition of corrosion layers on a magnesium rare earth alloy in simulated body fluids," *Journal of Biomedical Materials Research Part A*, vol. 88, pp. 359–369, 2008.

[23] A. K. Shukla and R. Balasubramaniam, "Effect of surface treatment on electrochemical behavior of CP Ti, Ti 6Al–4V and Ti–13Nb–13Zr alloys in simulated human body fluid," *Corrosion Science*, vol. 48, pp. 1696-1720, 2006.

[24] M. M. Solomon and S. A. Umoren, "In-situ preparation, characterization and anticorrosion property of polypropylene glycol/ silver nanoparticles composite for mild steel corrosion in acid solution", *J. Colloid Interface Sci.*, vol. 462, pp. 29–41, 2016.

[25] M. Yadav, L. Gope, N. Kumari and P. Yadav, "Corrosion inhibition performance of pyranopyrazole derivatives for mildsteel in HCl solution: Gravimetric, electrochemical and DFT studies", *J. Mol. Liq.*, vol. 216, pp. 78–86, 2016.

[26] W. H. Mulder and J. H. Sluyters, "An explanation of depressed semicircular arcs in impedanceplots for irreversible electrode reactions", *Electrochemical Acta*, vol. 33, pp. 303–310, 1998.

[27] A. O. Yüce, E. Telli, B. D. Mert, G. Kardaş and B. Yazıcı, "Experimental and quantum chemical studies on corrosion inhibitioneffect of 5,5 diphenyl 2-thiohydantoin on mild steel in HCl solution", *J. Mol. Liq.*, vol. 218, pp. 384–392, 2016.

[28] M. Erbil, "The determination of corrosion rates by analysis of AC impedance diagrams", *Chim. Acta Turc.*, vol. 1, pp. 59–70, 1988.

[29] S. Mao, T. Xie, B. Zheng, F. Huang, Z. Song, Y. Li, Structures and properties of sintered NdFeB coated with IBAD-Al/Al<sub>2</sub>O<sub>3</sub> multilayers, Surface & Coatings Technology, vol. 207, pp. 149-154, 2012.

[30] H. M. Mousa, K. H. Hussein, H. R. Pant, H. M. Woo, C. H. Park, C. S. Kim, In vitro degradation behavior and cytocompatibility of a bioceramicanodization films on the biodegradable magnesium alloy, Colloids and Surfaces A: Physicochem. Eng. Aspects, vol. 488, pp. 82-92, 2016.

[31] E. M. Sherif, Corrosion Behavior of Magnesium in Naturally Aerated Stagnant Seawater and 3.5% Sodium Chloride Solutions, Int. J. Electrochem. Sci., vol. 7, pp. 4235-4249, 2012.

[32] H. Gerengi, H. Goksu, and P. Slepski, "The inhibition effect of mad honey on corrosion of 2007- type aluminium alloy in 3.5% NaCl solution", *Materials Research*, vol. 17, pp. 255–264, 2014.