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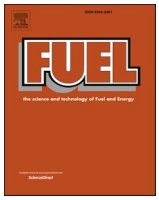

Catalytic electro-oxidation of hydrazine by thymol based-modified glassy carbon electrode

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ABSTRACT

In the present, thymol based new organic compounds (**4A**, **4B** and **4C**) are designed and synthesized via Steglich Esterification Reactions and Pd-catalyst Sonogashira Coupling Reactions. After isolation and characterization, thymol based hybrid molecules are used for hydrazine (N_2H_4) electrooxidation reactions as anode catalysts. A variety of metal based anode catalyst have been reported in literature, but this study may be the first study for thymole based hybrid molecules as an anode catalyst in fuel cells. The performance of hybrid molecules was investigated via cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) in hydrazine solution. Hybrid 2-isopropyl-5-methylphenyl-4-oxo-4-(5-(p-tolylethynyl)thiophen-2-yl)butanoate (**4C**) gives the highest performance as 3.66 $mAcm^{-2}$ (17.24 $mAmg^{-1}$). Our results displayed that natural products like thymol derivatives may be new generation anode catalyst for fuel cells, and they may be alternative for expensive Pd and Pt based metal anode catalyst.

1. Introduction

Energy is an essential component for human life. Increasing worldwide energy demand associated with fossil resources creates the energy crisis in the next two or three decades [1]. Fossil energy has been become expensive and scarce, while fossil fuels are not environmentally friendly, and they also cause the climate change due to greenhouse gases. At the present time, existing fossil energy sources are not abandoned, but renewable energy sources are reduced or eliminated their environmental impact [2–3]. New technologies may help to discover new clean energy sources to decrease the greenhouse gase effects in the next few decades [4–5]. Nowadays, scientists are trying to new ways to produce the clean energy by using solar cells [6–7], wind power, hydroelectric power and nuclear plants [8]. In addition, alternative methods including fuel cells [9,10], batteries [11], biomass [12] and hydrogene sources have been used for the producing energy [13].

Fuel cells convert the chemical energy to cleanly and efficiently electricity. There are the variety of potential applications of fuel cells; they can be used not only plants for industrial applications, but also small electronic devices like labtops. Fuel cells have many advantages such as; the efficiency (higher than 60 %), ii) lower carbon dioxide emissions, iii) environmentally friendly technologies due to the only water was formed as side product. Moreover, hydrazine fuel cells do not cause the air pollutants [14,15]. Fuel cells produce electricity and heat without run down and recharging. Fuel cell consists of two electrodes; an anode (or negative electrode) and a cathode (or positive electrode). When hydrogen is used as fuel in cells, hydrogen molecules form protons and electrons in anode catalyst surface. The electrons create a flow of electricity. At the same time, the protons move to the cathode to form the water and heat.

Although fuel cells are considered to be next generation clean energy sources, but there are some key challenge (cost, performance, and durability) for fuel cell development [16–19]. Metals like platinum, gold, palladium are mainly used as anode catalyst in direct hydrogen fuel cells, so new catalyst sytems are designed to decrease the cost. For example, polymer membrane fuel cell was used to reduce the content of heavy metals, or metal-free polymers were investigated as anode catalyst for fuel cell applications. Secondly, improving fuel cell efficiency and performance is the very important to design of new catalysts for future applications. In addition, lifetime of fuel cell is also main

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Table 1
The anode catalysts performance of hydrazine electro-oxidation in fuel cells.

Catalyst	Preparation	Maximum Peak ($mA*cm^{-2}$)	Reference
PPY/NOCB/900	polymerization	1.84	[34]
Wash-CN_{Cu}	Dope	1.94	[35]
Benzothiophene	organic synthesis	4.95	[31]
$NiFe_2O_4$-rGO	hydrothermal method	18.9	[36]
(PpPD/ZnO)	Dope	0.172	[37]

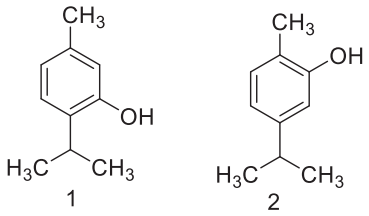

Fig. 1. Structure of Thymol (**1**) and Carvacrol (**2**).

problems under realistic operating conditions. Therefore, many scientist focused on investigate new materials for the chemical and mechanical stability.

Hydrazine [20], glucose [21], formic acid [22], ethanol [23], and methanol [24,25] are the well known fuel sources in cells. Hydrazine, N_2H_4, has very critical roles in industrial applications, explosive materials, propellants and other applications [26]. Hydrazine are also important for the producing energy in direct hydrazine fuel cells. Hydrazine is not expensive, has high energy density. In addition, it has higher performance, and it can be easily storage [27]. However, kinetically oxidation of hydrazine is not easy, so it needs special or modified electrodes in fuel cell [28]. The electrooxidation reactions of hydrazine in alkaline medium can be written as the following equations:

Anodereaction: $N_2H_4 + 4OH^- \rightarrow N_2 + 4H_2O + 4e^-$.

Cathodereaction: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$.

Overallreaction: $N_2H_4 + O_2 \rightarrow N_2 + 2H_2O$.

To increasing efficiencies of cells, metals including platinum, silver, gold and cobalt were modified and tested as electrocatalyst for hydrazine oxidation [29,30]. Recently, organic catalyst consisting of benzothiophenes were used for hydrazine electrooxidation, and the activitity was reported as 3.22 $mAcm^{-2}$ with lowest charge transfer resistance [31]. They improved that organic compounds can be used as anode catalyst in fuel cells instead of expensive metal catalsyts (Pt, Pd and Au) [32,33]. Recently, PPY/NOCB/900 [34], Wash-CN_{Cu} [35], $NiFe_2O_4$-rGO [36] and (PpPD/ZnO) [37] catalyst systems were prepared for fuel cell as anode catalysts. Interestingly, the best performance was obtained from $NiFe_2O_4$ catalysts system with 18.9 $mAcm^{-2}$ (Table 1).

Lastly, different kinds of organic compounds have been tested for the formation of clean energy including solar cells and electrochromic devices. Organic molecules are preferred for material chemistry due to their important properties such as flexibility, lower molecular weight, charge transfer capacities, and high electrochemical stability [38–40].

Thymol [41,42] (5-methyl-2-isopropyl phenol) is the member of phenols, and isolated from thyme (*Thymus vulgaris*), oregano (*Origanum vulgare*), ajowan (*Trachyspermum ammi*), and other plants (Fig. 1) [41,43]. Thymol and its derivatives have been played very important in medicines, food, and cosmetic applications [44]. Carvacrol is the other isomer of thymols. In literature, a variety of thymol and carvacrol derivatives were synthesized for the investigation of biological properties. They have been used as anticancer, antifungal, antimicrobial, antiparasitic and antioxidant agents. Moreover, they have been used as herbicides [45]. Recently, Rajkumar *et al.* was investigated electronic properties, ionization potential, thermodynamic properties and electron affinities, inter-molecular interactions of thymole structure [46]. They found that the energies of molecular orbital, obtained excitation from HOMO to LUMO, displayed π-π* transition.

In the present study, novel thymol based hybrid molecules are designed and synthesized by using esterification reactions and coupling reactions. Then, thymol hybrid molecules were tested as anode catalysts for hydrazine electrooxidation. In literature, variety of metal based anode catalyst have been used for the producing clean energy in fuel cells, but there are not any study including thymole and thymole derivatives as an anode catalyst. Therefore, this study could be created new generation anode catalyst system for future applications in fuel cells. Thymol and derivatives may be alternative anode catalyst for the producing electricity in direct hydrazine fuel cells.

2. Results and discussion

2.1. Synthesis

Initially, the reaction between 2 and iodothiophene and succinic anhydride gave the Friedel-Crafts reaction at room temperature to form the 4-(5-iodothiophen-2-yl)-4-oxobutanoic acid which was used directly for esterification reactions due to stability problems (SI). Then, Steglich reaction was applied for the formation of 1-(5-iodothiophen-2-yl)-4-(2-isopropyl-5-methylphenyl)butane-1,4-dione **(3).** When thymol was allowed to react with the intermediate in the presence of EDCI/DMAP catalyst medium, desired product **3** was obtained. After characterization of compound **3**, Pd(II)-catalyzed Sonagashira coupling reaction was used for the formation of final thymol based hybrid molecules **(4A-C).** The **4A**, **4B** and **4C** hybrid molecules are obtained as 79 %, 89 % and 90 % yields, respectively **(**Fig. 2**)**. The proton and carbon NMR spectra of thymol derivatives have characteristics thymol's peaks, so they were easily identified. For example, tymol's protons can be identified easily in aromatic region. There are two different methyl peaks in proton NMR spectra, and there are two carbonyl's peaks around 190 ppm and 171 ppm at ^{13}C NMR spectra.

2.2. Electrochemical evaluation

The electrochemical behaviors of catalysts were achieved by cyclic voltammetry analysis (potential: 0.0 and 0.8 V; scan rate: 50 mVs^{-1}). The CV analyses of catalysts in KOH (1 M) and KOH (1 M) + hydrazine (0.5 M) were shown in Fig. 3(**a-c**). Since the catalysts were organic-based and did not contain precious metals such as Pd, Pt, Au, it was

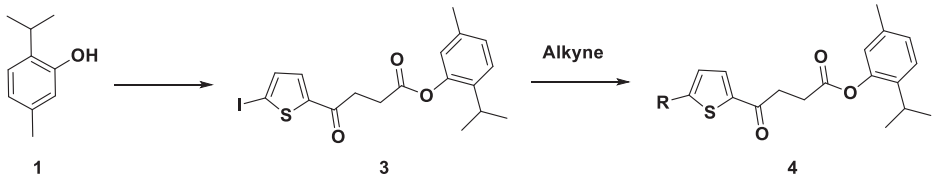

Fig. 2. Synthesis thymol based hybrid molecules (**4**).

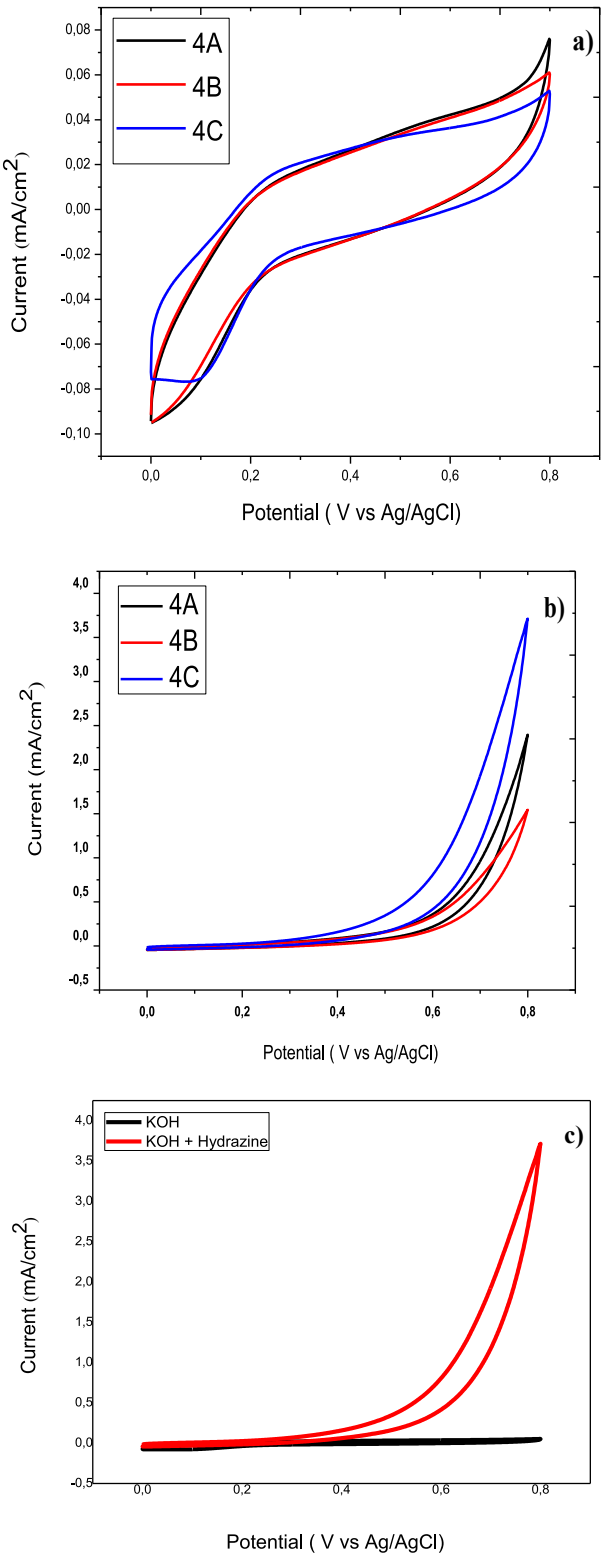

Fig. 3. Cyclic voltammetry results (a) 1 M KOH; (b) 1 M KOH + 0.5 M hydrazine; (c) comparison of 1 M KOH and 1 M KOH + 0.5 M hydrazine. (Scan rate: 50 mV s^{-1}).

seen that oxidation peaks were not formed in hydrazine electrooxidation. Therefore, thymol based hybrid catalysts were calculated on the total current (Table 2**)**. In the present study, the catalytic activities of the hybrid molecules were found by using the total current values in KOH and hydrazine mixture. It was seen in Fig. 3**b** and Table 2, the

Table 2
The electrochemical results from the hydrazine electrooxidation.

Hybrid	Total current ($mA.cm^{-2}$)			Mass Activity ($mA.mg^{-1}$ catalyst)	Onset Potential (V)
	KOH	Hydrazine	Normal		
Hybrid A	0.077	2.41	2.33	10.96	0.30
Hybrid B	0.061	1.54	1.48	6.96	0.31
Hybrid C	0.053	3.71	3.66	17.24	0.27

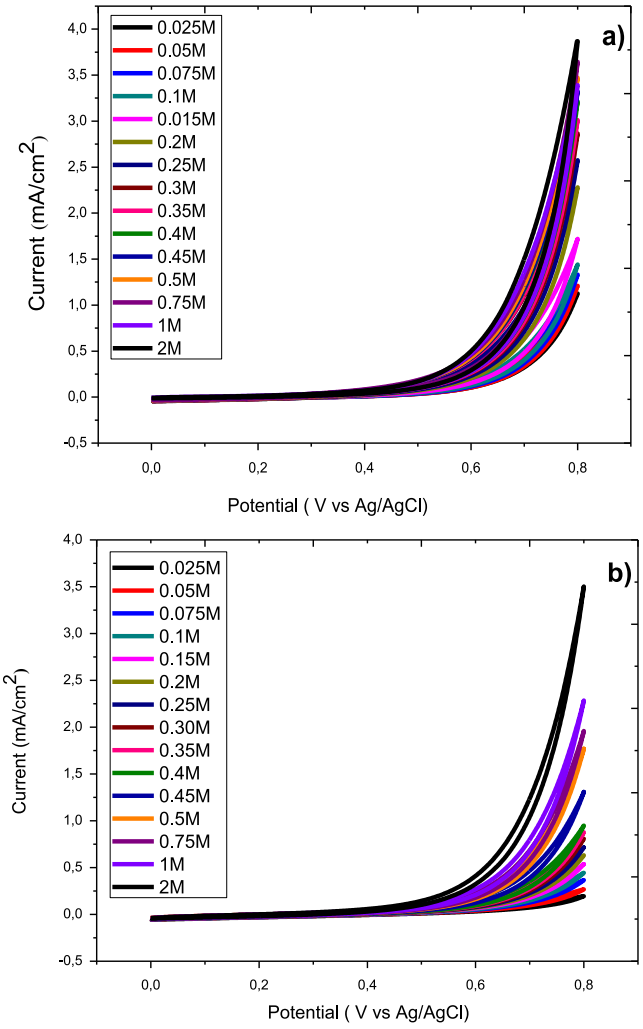

Fig. 4. CV analysis (a) different KOH concentrations with 0.5 M Hydrazine; (b) different hydrazine concentrations with 1 M KOH. Scan rate: 50 mV/s.

hybrid **4C** exhibited the better activity compared to the **4A** and **4B**. The specific activity at the total current (Hydrazine) was calculated as 3.66 $mA.cm^{-2}$ (17.24 $mA.mg^{-1}$ catalyst). Fig. 3**c** showed a comparison of hybrid **4C** not only 1 M KOH, but also KOH (1 M) + hydrazine (1/2 M) solutions. The 3.66 $mA.cm^{-2}$ specific activity is the catalytic activity obtained from hydrazine sources. Our electrochemical results improved that thymol natural product and derivatives may be alternative anode catalyst for the hydrazine fuel cells.

Hybrids 4(A-C) catalysts were tested for the investigation of hydrazine electrooxidation performances via cyclic voltammetry analysis. Cyclic voltammetry measurements are given in Fig. 3 in the presence of

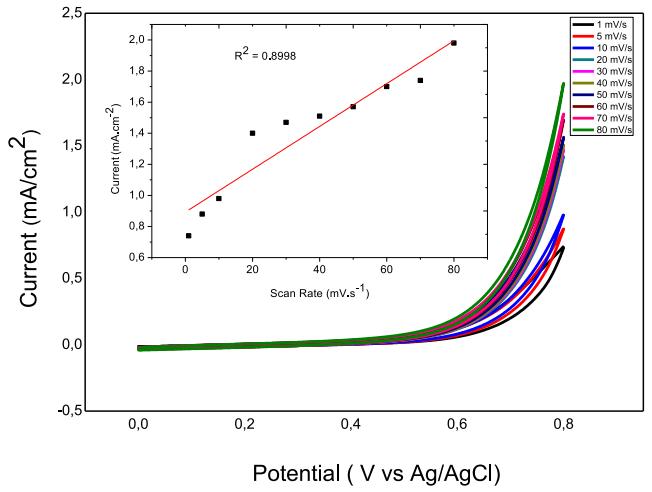

Fig. 5. CV analysis of hybrid **4C** catalyst at different scan rates (1–80 $mV.s^{-1}$). Inset of graph: plots of current against scan rate.

KOH (1 M) solution and KOH (1 M) + M N_2H_4 (0.5) solution.

The effect of KOH (a) and hydrazine (b) concentration change of hybrid **4C** organic-based catalyst on hydrazine electrooxidation was researched and the results were given in Fig. 4 **(a, b).** The catalytic activity of hybrid **4C** for hydrazine electrooxidation was examined by keeping the hydrazine concentration constant at 0.5 M and modifying the KOH concentrations between 0.025 and 2 M (Fig. 4**a**). As seen in Fig. 4**a**, the catalytic activity increased as the KOH concentration increased. The effect of hydrazine concentration for hydrazine electrooxidation was found by using the 1 M KOH and different concentrations of hydrazine mixtures (0.025 M to 2 M) **(**Fig. 4**b).** Interestingly, the catalytic activity increased when hydrazine concentration increased in KOH solution. The analysis of the hybrid **4C** organic-based catalyst taken at different scan rates is shown in Fig. 5 **(a, b).** The scan rate effect was also investigated. The range changed between 1 and 80 $mV.s^{-1}$ on the hybrid **4C** organic-based catalyst in 1 M KOH + 0.5 M hydrazine. As shown in Fig. 5**a**, when scan rates (1–80 $mV.s^{-1}$) increased, the catalytic activity increased. If current ($mA.cm^{-2}$) values were plotted against the square root of the scan rate (mVs^{-1}) (inset of the graph), the current value increase and varied linearly with scan rate. It means that diffusion controlled kinetics for hydrazine electrooxidation was observed.

Chronoamperometry (CA) measuruments helped to appraise the stability, and displayed poison resistance of thymol hybrid molecules. Fig. 6**(a)** demonstrates the CA curves of hybrid **4C** organic catalyst at different potentials. Chronoamperometry analysis gave the best resistance and good stability at 0.0 V potential. Hybrid **4C** organic catalyst has better activity and high stability (0.28 $mA.cm^{-2}$ specific activity) after 1000 s **(**Fig. 6**b).** CV results displayed that hybrid **4C** organic-based catalyst gave the best activity. Moreover, hybrid **4C** found as most stable organic catalyst when compared to other thymol based catalysts.

Fig. 7**(a, b)** shows the Nyquist plots obtained from the EIS was used for the investigation of the electrocatalytic resistance of the thymol hybrid catalysts (**4A-C**). EIS measurements usually give the semicircles to calculate the electrocatalytic resistance. When resistance increases, the diameter of the circle decrease [47,48]. Fig. 7a indicates the Nyquist plots of the hybrid **4C** organic-based catalyst taken at different potentials (0.2, 0.4, 0.6, and 0.8 V). As seen in Fig. 7**a**, if the Nyquist plot taken at the 0.8 V, the high electrochemical resistance was obtained. Fig. 7**b** demonstrates the Nyquist plots of **4A**, **4B**, and **4C** thymol organic-based catalysts at 0.8 V potential. Hybrid **4C** organic-based catalyst gives smaller Rct value than **4A** and **4B**. EIS results also improved that the thymol hybrid molecule **4C** has the best catalytic activity, high stability, and lower resistance in direct hydrazine fuel cell applications.

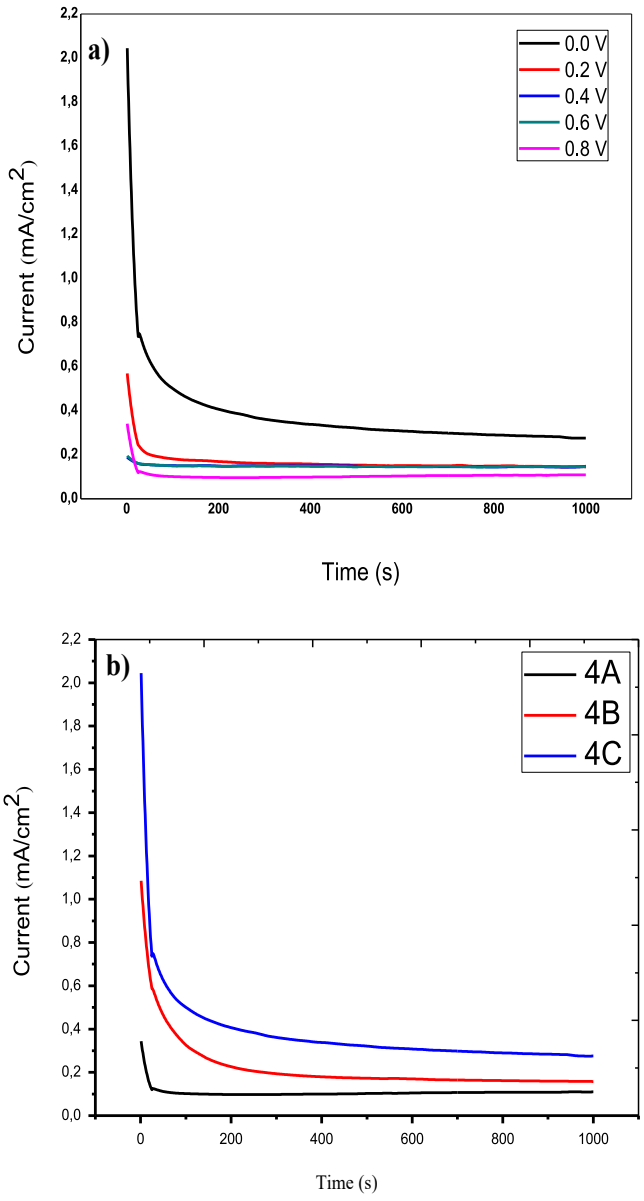

Fig. 6. CA analysis of (a) hybrid **4C**, (b) hybrid **4A**, hybrid **4B** and hybrid **4C**.

3. Conclusions

Herein, novel thymol based hybrid compouds (**4A-C**) are synthesized via Steglich Esterification and Sonogashira coupling reactions. Initially, 4-(5-iodothiophen-2-yl)-4-oxobutanoic acid were prepared by starting from 2 to iodothiophene. Then, Steglich esterification reaction was chosen for the formation of 1-(5-iodothiophen-2-yl)-4-(2-isopropyl-5-methylphenyl)butane-1,4-dione. For the formation of desired products (**4A-C**), Pd-catalyts Sonagashira coupling reaction was used. Secondly, the electrochemical anode catalyst performance of thymol hybrids **4A-C** were investigated by using CV, CA, and EIS in hydrazine solution. The best performance was obtained from the hybrid **4C** catalysts as 3.66 $mAcm^{-2}$ (17.24 $mAmg^{-1}$ **4C**). This study also improve that natural products may be alternative and environmentally friendly catalyst for the producing clean energy due to their electronic properties. As a result, thymol based new hybrids may be new anode catalyst for direct hydrazine fuel cell applications.

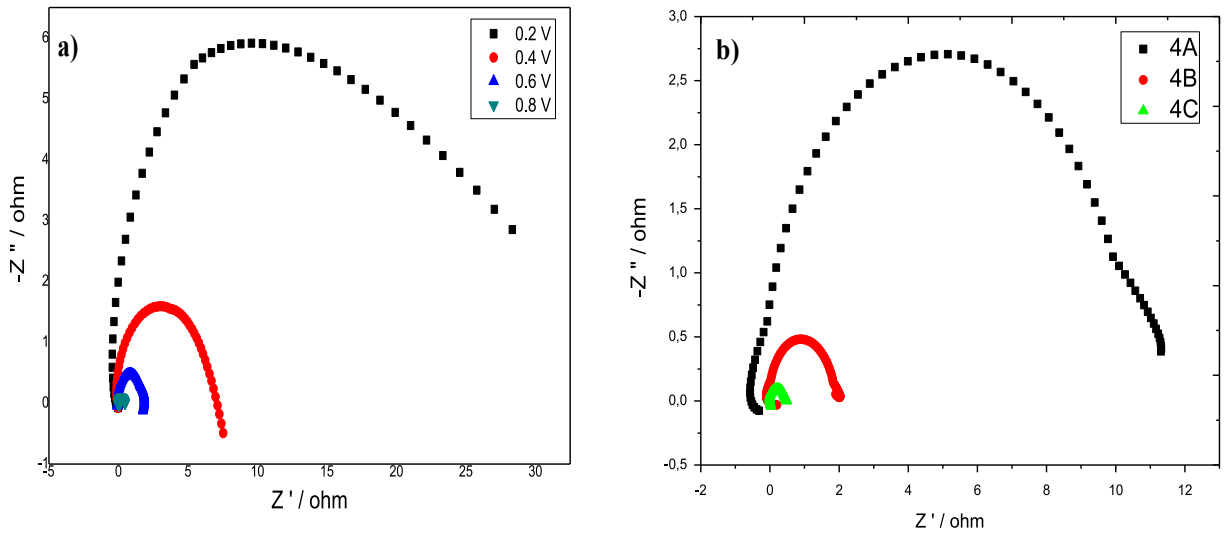

Fig. 7. EIS measurements of (a) hybrid **4C**, (b) hybrid **4A**, hybrid **4B** and hybrid **4C**.

CRediT authorship contribution statement

Kawa Hama Sharif: . **Hilal Kivrak:** Supervision, Validation. **Omruye Ozok-Arici:** . **Aykut Caglar:** . **Arif Kivrak:** Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2022.125597.

References

[1] Liu J, Chen C, Liu Z, Jermsittiparsert K, Ghadimi N. An IGDT-based risk-involved optimal bidding strategy for hydrogen storage-based intelligent parking lot of electric vehicles. J Storage Mater 2020;27:101057.
[2] Gopi CVVM, Reddy AE, Kim H-J. Wearable superhigh energy density supercapacitors using a hierarchical ternary metal selenide composite of CoNiSe2 microspheres decorated with CoFe2Se4 nanorods. J Mater Chem A 2018;6:7439–48.
[3] Rani BJ, Ravi G, Yuvakkumar R, Ravichandran S, Ameen F, Al-Sabri A. Efficient, highly stable Zn-doped NiO nanocluster electrocatalysts for electrochemical water splitting applications. J Sol-Gel Sci Technol 2019;89:500–10.
[4] Wang J-Y, Ouyang T, Li N, Ma T, Liu Z-Q, N S. co-doped carbon nanotube-encapsulated core-shelled CoS2@Co nanoparticles: efficient and stable bifunctional catalysts for overall water splitting. Sci Bull 2018;63:1130–40.
[5] Dar AA, Hameed J, Huo C, Sarfraz M, Albasher G, Wang C, et al. Recent optimization and panelizing measures for green energy projects; insights into CO_2 emission influencing to circular economy. Fuel 2022;314:123094.
[6] Noh JH, Im SH, Heo JH, Mandal TN, Seok SI. Chemical Management for Colorful, Efficient, and Stable Inorganic-Organic Hybrid Nanostructured Solar Cells. Nano Lett 2013;13(4):1764–9.
[7] Kivrak A, Er OF, Kivrak H, Topal Y, Kus M, Camlisoy Y. Synthesis and solar-cell applications of novel furanyl-substituted anthracene derivatives. Opt Mater 2017;73:206–12.
[8] Mujtaba MA, Kalam MA, Masjuki HH, Gul M, Soudagar MEM, Ong HC, et al. Comparative study of nanoparticles and alcoholic fuel additives-biodiesel-diesel blend for performance and emission improvements. Fuel 2020;279:118434.
[9] Caglar A, Cogenli MS, Yurtcan AB, Alal O, Kivrak H. Remarkable activity of a ZnPdPt anode catalyst: Synthesis, characterization, and formic acid fuel cell performance. J Phys Chem Solids 2021;156.
[10] Abdolmaleki M, Ahadzadeh I, Goudarziafshar H. Direct hydrazine-hydrogen peroxide fuel cell using carbon supported Co@Au core-shell nanocatalyst. Int J Hydrogen Energy 2017;42:15623–31.
[11] Park M, Lee T, Kim BS. Covalent functionalization based heteroatom doped graphene nanosheet as a metal-free electrocatalyst for oxygen reduction reaction. Nanoscale 2013;5:12255–60.
[12] Özarslan S, Atelge MR, Kaya M, Ünalan S. Production of dualfunctional carbon material from biomass treated with NaOH for supercapacitor and catalyst. Energy Storage 2021:e257.
[13] Luo S, Zeng Z, Wang H, Xiong W, Song B, Zhou C, et al. Recent progress in conjugated microporous polymers for clean energy: Synthesis, modification, computer simulations, and applications. Prog Polym Sci 2021;115:101374.
[14] Caglar A, Ulas B, Sahin O, Kıvrak H. Synthesis of in situ N-, S-, and B-doped few-layer graphene by chemical vapor deposition technique and their superior glucose electrooxidation activity. Int J Energy Res 2019;43:8204–16.
[15] Asset T, Roy A, Sakamoto T, Padilla M, Matanovic I, Artyushkova K, et al. Highly active and selective nickel molybdenum catalysts for direct hydrazine fuel cell. Electrochim Acta 2016;215:420–6.
[16] Ma S, Hu X, Zhao Y, Wang X, Dong C. Design and Evaluation of a Metal-Supported Solid Oxide Fuel Cell Vehicle Power System with Bioethanol Onboard Reforming. ACS Omega 2021;6(43):29201–14.
[17] Subramani V, Gangwal SK. A review of recent literature to search for an efficient catalytic process for the conversion of syngas to ethanol. Energy Fuels 2008;22(2):814–39.
[18] Yang Y, Liew RK, Tamothran AM, Foong SY, Yek PNY, Chia PW. Gasification of refuse-derived fuel from municipal solid waste for energy production: a review. Environ Chem Lett 2021;19(3):2127–40.
[19] Rokni M. Thermodynamic and thermoeconomic analysis of a system with biomass gasification, solid oxide fuel cell (SOFC) and Stirling engine. Energy 2014;76:19–31.
[20] Feng G, Kuang Y, Li P, Han N, Sun M, Zhang G, et al. Single Crystalline Ultrathin Nickel-Cobalt Alloy Nanosheets Array for Direct Hydrazine Fuel Cells. Adv Sci 2017;4(3):1600179.
[21] Er OF, Caglar A, Kivrak H. Enhanced electrochemical glucose oxidation in alkaline solution over indium decorated carbon supported palladium nanoparticles. Mater Chem Phys 2020;254:123318.
[22] Rice C, Ha RI, Masel RI, Waszczuk P, Wieckowski A, Barnard T. Direct formic acid fuel cells. J Power Sources 2002;111:83–9.
[23] Kamarudin MZF, Kamarudin SK, Masdar MS, Daud WRW. Review: Direct ethanol fuel cells. Int J Hydrogen Energy 2013;38:9438–53.
[24] A. Demirbas, Direct use of methanol in fuel cells, Energy Sources Part a-Recovery Utilization and Environmental Effects, 30 (2008) 529-535.
[25] Paik Y, Kim SS, Han OH. Fuel cells - Methanol behavior in direct methanol fuel cells. Angewan Chemie-Int Edi 2008;47:94–6.
[26] Benvidi A, Kakoolaki P, Zare HR, Vafazadeh R. Electrocatalytic oxidation of hydrazine at a Co(II) complex multi-wall carbon nanotube modified carbon paste electrode. Electrochim Acta 2011;56:2045–50.

[27] Wang YC, Wang Q, Wan LY, Han Y, Hong YH, Huang L, et al. KOH-doped polybenzimidazole membrane for direct hydrazine fuel cell. J Colloid Interface Sci 2020;563:27–32.
[28] Wang Y, Wan Y, Zhang D. Reduced graphene sheets modified glassy carbon electrode for electrocatalytic oxidation of hydrazine in alkaline media. Electrochem Commun 2010;12:187–90.
[29] Deng J, Li X, Imhanria S, Chen K, Deng X, Wang W. Molybdenum carbide-nitrogen doped carbon composites as effective non-precious electrocatalyst for direct hydrazine fuel cell. Electrochim Acta 2021;384:138417.
[30] Lovic J.D., Electrodeposited palladium as efficient electrocatalyst for hydrazine and methanol electrooxidation and detection. J Electrochem Sci Eng.
[31] Faruk Er O, Ulas B, Ozok O, Kivrak A, Kivrak H. Design of 2-(4-(2-pentyllbenzo b thiophen-3-yl)benzylidene)malononitrile based remarkable organic catalyst towards hydrazine electrooxidation. J Electroanal Chem 2021;888:115218.
[32] Lou WH, Ali A, Shen PK. Recent development of Au arched Pt nanomaterials as promising electrocatalysts for methanol oxidation reaction. Nano Res 2022;15:18–37.
[33] Caglar A, Cogenli MS, Yurtcan AB, Kivrak H. Effective carbon nanotube supported metal (M=Au, Ag Co, Mn, Ni, V, Zn) core Pd shell bimetallic anode catalysts for formic acid fuel cells. Renewable Energy 2020;150:78–90.
[34] Meng YY, Zou XX, Huang XX, Goswami A, Liu ZW, Asefa T. Polypyrrole-Derived Nitrogen and Oxygen Co-Doped Mesoporous Carbons as Efficient Metal-Free Electrocatalyst for Hydrazine Oxidation. Adv Mater 2014;26:6510–6.
[35] Burshtein TY, Farber EM, Ojha K, Eisenberg D. Revealing structure-activity links in hydrazine oxidation: doping and nanostructure in carbide-carbon electrocatalysts. J Mater Chem A 2019;7:23854–61.
[36] Askari MB, Salarizadeh P, Beitollahi H, Tajik S, Eshghi A, Azizi S. Electro-oxidation of hydrazine on $NiFe_2O4$-rGO as a high-performance nano-electrocatalyst in alkaline media. Mater Chem Phys 2022;275:125313.
[37] Rostami H, Omrani A, Rostami AA, Emamgholizadeh A. Electrooxidation of hydrazine in alkaline medium at carbon paste electrode decorated with poly(P-phenylendiamine/ZnO) nanocomposite. Ionics 2015;21:1073–80.
[38] Hama AK, Algso MAS, Kavak E, Kivrak A. Synthesis of Novel Benzothiophene Derivatives via Cyclization Reactions. Russ J Org Chem 2020;56:1272–8.
[39] Carbas BB, Kivrak A, Teke E, Zora M, Onal AM. Electrochemical polymerization of a new low-voltage oxidized thienylenepyrrole-derivative and its electrochromic device application. J Electroanal Chem 2014;729:15–20.
[40] Kivrak A, Carbas BB, Zora M, Onal AM. Synthesis and electropolymerization of an ion sensing and fluorescent fluorene derivative bearing a quinoxaline moiety and its analogues with different donor units. React Funct Polym 2012;72:613–20.
[41] E. Kavak, D. Mutlu, O. Ozok, S. Arslan, A. Kivrak, Design, synthesis and pharmacological evaluation of novel Artemisinin-Thymol, Natural Product Research.
[42] Pilati F, Degli Esposti M, Bondi M, Iseppi R, Toselli M. Designing of antibacterial plastics: thymol release from photocured thymol-doped acrylic resins. J Mater Sci 2013;48:4378–86.
[43] Buyukleyla M, Rencuzogullari E. The effects of thymol on sister chromatid exchange, chromosome aberration and micronucleus in human lymphocytes. Ecotoxicol Environ Saf 2009;72:943–7.
[44] Freyssin A, Page G, Fauconneau B, Bilan AR. Natural stilbenes effects in animal models of Alzheimer's disease. Neural Regener Res 2020;15:843–9.
[45] Najafloo R, Behyari M, Imani R, Nour S. A mini-review of Thymol incorporated materials: Applications in antibacterial wound dressing. J Drug Delivery Sci Technol 2020;60.
[46] Rajkumar P, Selvaraj S, Suganya R, Velmurugan D, Gunasekaran S, Kumaresan S. Vibrational and electronic spectral analysis of thymol an isomer of carvacrol isolated from Trachyspermum ammi seed: A combined experimental and theoretical study. Chem Data Collect 2018;15–16:10–31.
[47] Hansu TA, Caglar A, Sahin O, Kivrak H. Hydrolysis and electrooxidation of sodium borohydride on novel CNT supported CoBi fuel cell catalyst. Mater Chem Phys 2020;239:122031.
[48] Ulas B, Caglar A, Sahin O, Kivrak H. Composition dependent activity of PdAgNi alloy catalysts for formic acid electrooxidation. J Colloid Interface Sci 2018;532:47–57.