ATATÜRK ÜNİVERSİTESİ YAYINLARI
ATATURK UNIVERSITY PUBLICATIONS

NanoEra

Research Article

DOI: 10.5152/NanoEra.2023.23015

Nonporous Carbon-Supported Platinum Catalyst for Polymer Electrolyte Membrane Fuel Cell

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ABSTRACT

In this study, a commercial, nonporous carbon black was used as catalyst support for the dispersion of platinum (Pt) nanoparticles (NPs) in a polymer electrolyte membrane (PEM) fuel cell. The microstructure of nonporous carbon black was determined by Brunauer–Emmett–Teller analysis and crystal structure by x-ray diffraction (XRD) analysis. The surface area of carbon black is 72.6 m^2/g, and the micropore volume has low fraction in the total volume. The fact that the $d_{(002)}$ value determined according to XRD analysis is 0.377 nm indicates the amorphous structure of nonporous carbon. Inductively coupled plasma mass spectrometry (ICP-MS) analysis determined the Pt loading on nonporous carbon as 15 wt.%. Catalyst support was also investigated electrochemically by cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS). In CV analysis, as the scan rate increases, capacitive property increases. Furthermore, the low current density of the quinone-hydroquinone (Q-HQ) redox peak suggests nonporous carbon black's corrosion resistance. Nonporous carbon black, whose charge transfer resistance is 454.5 Ω based on EIS analysis, facilitates the mass transfer of species due to its low porosity. Nonporous carbon is preferred to alleviate the water flooding that occurs at the cathode electrode of PEM fuel cells. Platinum NPs supported with nonporous carbon provided 15 and 40 mW/cm^2 maximum power densities in PEM fuel cell performance tests at 60°C and 70°C, respectively. As the sustainable energy conversion technology of the future, PEM fuel cells can produce enough power to operate everything from mW-scale portable applications to kW-MW-scale transportation and residential uses. In this study, the performance of the nonporous carbon-supported Pt catalyst can be suitable for mW scale applications.

Keywords: Nonporous carbon black, Pt catalyst, support material, ORR, PEM fuel cell

INTRODUCTION

Solar, wind, marine, nuclear, hydro, biofuels, and geothermal fuels are renewable energy sources that can be alternatives to traditional fossil fuels to meet the increasing energy demand of the world population. Another alternative, which has gained importance in recent years due to its enormous energy content, is hydrogen. Chemical energy is directly and cleanly converted to electricity in fuel cells by using hydrogen as fuel. Efforts continue to meet the energy needs of the transportation sector, which constitutes 60% of total energy consumption, with hydrogen-based energy systems.[1] A polymer electrolyte membrane (PEM) fuel cell is a kind of fuel cell in which a thin, solid membrane that is permeable to hydrogen ions but not electrons is used as an electrolyte.[2]

The kinetics of the oxygen reduction reaction (ORR) taking place at the cathode electrode of a PEM fuel cell are quite slow. Thus, highly active and stable platinum (Pt) catalysts are often used to catalyze this reaction.[3] Expensive and rare Pt metals are dispersed on conductive carbon materials to increase catalyst utilization. The preference for carbon-based materials in PEM fuel cell catalysts is due to their nano-sized morphology, pore structure, high surface area, good electrical conductivity, and corrosion resistance. The electrical conductivity, active surface area, and stability of the support material are effective in determining the performance of the carbon-supported Pt catalyst in the PEM fuel cell. Excluding the most widely used carbon black,[4] carbon nanotubes (CNTs) and graphene are also frequently used carbon-based support materials.[5]

Microstructure in carbon black refers to three types of pore structures. These are micro-, meso-, and macropores, respectively. The micropores represent the pores within the primary carbon particles, while the meso- and macropores represent the pores within the aggregates formed by these primary carbon particles.[6] Generally, as a result of the exposure of carbon structures to various activation processes, the micropore (<2 nm) fraction increases, and the Brunauer–Emmett–Teller (BET) surface area

Received: 05.12.2023
Accepted: 06.12.2023
Publication Date: 31.12.2023

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Cite this article as: Öztürk Aydin A, Bayrakçeken Yurtcan A. Nonporous Carbon-Supported Platinum Catalyst for Polymer Electrolyte Membrane Fuel Cell. *NanoEra* 2023;3(2):53-60.

varies between 800-1200 m^2/g according to the degree of activation. Activated carbon materials can be preferred as catalyst support materials in different fuel cell types due to their large surface areas.[7] However, the abundance of meso- and macropores in the total area instead of micropores provides a more effective distribution of metal catalyst nanoparticles (NPs) on the support.[8] Although the use of carbon black as a support material in fuel cells is common, the intense microporosity of some types reduces the activity of the catalyst because it traps metal NPs.[9] Microporosity directly affects the catalyst and ionomer interaction, so it is proper to have accessible pores in the support.[9,10]

In recent years, studies on the utilization of nonporous carbons in electrochemical applications have appeared in the literature. Han et al[11] obtained nonporous graphite from low-cost coal for use as material in the anode electrodes of lithium-ion batteries. They intended to eliminate the side reactions with the electrolyte in large surface areas and porous carbon materials by using a nonporous and less defective carbon structure. The authors attained a high reversible capacity value of 347 mAh/g for the storage of lithium ions with this new carbon structure. Additionally, nonporous carbon provided better electrical conductivity and facile ion transfer. Mizutani et al[12] developed a nonporous carbon as an alternative to the conventional mesoporous carbon as the catalyst support material for the PtCo NPs in PEM fuel cells. While the catalyst utilization rate (%) in the mesoporous carbon-supported PtCo catalyst was poor below 60% relative humidity (RH), the catalyst utilization rate (%) in the nonporous carbon-supported PtCo catalyst was around 80% under all RH conditions. The authors observed that the majority of PtCo NPs in the mesoporous carbon structure remained in the pores of the carbon, while the PtCo NPs in the nonporous carbon were located on the outer surface of the carbon by using the 3D TEM imaging technique. The PEM fuel cell performance of the PtCo catalyst under low humidity and high current density conditions was improved via facilitated mass transfer by the nonporous carbon. In another study,[13] three carbon blacks with different textural structures (Ketjen black (KB), Acetylene black (AB), and Vulcan (V)) with a micropore density order of KB>AB>V exhibited the opposite ranking in terms of PEM fuel cell performance. The poorest performance of KB is attributable to those Pt catalysts trapped within the micropores that are no longer accessible.

In this study, inspired by the examples of nonporous carbon utilization in the literature, commercial nonporous carbon black was tried as a support material for Pt catalyst in the cathode electrode of a PEM fuel cell. Besides several physical analyses of nonporous carbon black, it was also electrochemically analyzed in a standard three-electrode cell system. Nonporous carbon black-supported Pt catalyst exhibited fuel cell performance in a PEM fuel cell test station.

MATERIAL AND METHODS

Materials

Conductive nonporous carbon black (purity: 99.9%, size: 24 nm, Nanografi) was used as a catalyst support for Pt NPs. Chloroplatinic acid hydrate ($H_2PtCl_6 \cdot 6H_2O$, Sigma Aldrich) was used as a precursor for the Pt NPs along with the reducing agent of ethylene glycol (Sigma Aldrich). Nafion 212 polymer membrane was used as an electrolyte in the PEM fuel cell. The anode and cathode electrodes were constructed on the commercial gas diffusion layer (GDL, Sigracet 34 BC). Tanaka catalyst (67.7 wt.% Pt, Pt/C) was used at the anode electrode, while the nonporous carbon black-supported Pt catalyst was used at the cathode electrode. Nafion solution (15 wt.%, Ion Power) and isopropanol (Sigma Aldrich) were the ingredients of both catalyst inks at the anode and cathode electrodes. 1,2-Propanediol (Sigma Aldrich) was the solvent for nonporous carbon black and Nafion solution in the standard three-electrode cell system's working electrode (WE) ink.

Catalyst Preparation

Pt catalyst on nonporous carbon black was prepared by using microwave-assisted polyol method. The certain amount of nonporous carbon was added to the beaker with 50 mL of ethylene glycol. About 2.6 mL of Pt catalyst precursor solution was added to the mixture. The ultimate solution was mixed for 30 minutes. Therefore, the solution was held on the domestic type microwave oven for 1 minute at 800 W. Pt NPs were loaded on the nonporous carbon in metallic form. At the end of the time, the solution was quickly cooled down to the room temperature. The solid catalyst sample was collected subsequent to the multiple stages of centrifugation and drying processes.[14] Figure 1 shows a schematic representation of the preparation of the Pt catalyst over nonporous carbon black. The microwave technique is an energy- and time-saving technique in the synthesis of heterogeneous catalysts.[15] Especially homogeneously distributed and ultrafine NPs are obtained by the microwave-assisted polyol method, in which ethylene glycol with a high dielectric constant is used as a dispersing and reducing agent.[16] Platinum NPs obtained with this method are generally in the range of 3-5 nm.[17-20]

Membrane Electrode Assembly (MEA) Preparation

A commercial Tanaka catalyst was used in the anode electrode part of the prepared MEA. Tanaka catalyst and Nafion solution were combined in a specific ratio (70:30) and dissolved in 2-propanol and distilled water. After mixing for a while, the catalyst ink was homogenized. Spraying the produced catalyst ink onto the GDL provided 0.4 mg Pt/cm^2 loading. To construct the cathode electrode, a Pt catalyst supported by nonporous carbon was dissolved in 2-propanol and water solvents with Nafion solution, homogenized, and sprayed on a separate GDL with a loading of 0.4 mg Pt/cm^2. Following the construction of the anode and cathode electrodes, a 5 × 5 cm Nafion-212 membrane was placed between the electrodes in contact with the catalyst layers. The triple structure was compressed in a hot press device at 130°C and 400 psi pressure for a certain period. The assembled structure was used as an MEA in the PEM fuel cell test station. Figure 2 shows the preparation steps for MEA.

Physical Characterizations

The physical characterizations of the nonporous carbon black were performed with BET (Micromeritics 3Flex) and X-Ray Diffraction (XRD) (PANalytical Empyrean, Cu Kα radiation, operated at 45 kV). The amount of Pt amount on the nonporous carbon black support was detected by an inductively coupled plasma mass spectrometer (ICP-MS, Agilent 7800).

Electrochemical Characterization

Electrochemical characterization of the nonporous carbon black was conducted with the VersaSTAT 3 potentiostat-galvanostat electrochemical analysis instrument. Ag/AgCl, platinum wire, and glassy carbon (GC) electrodes (5 mm diameter, 0.1963 cm^2) were employed as the reference electrode, counter electrode, and working electrode in a standard three-electrode cell system, respectively. The WE ink was composed of a carbon sample (70 wt.%), Nafion solution (30 wt.%), 1,2-propanediol, and distilled water. The material loading amount was set to the 28 µg catalyst

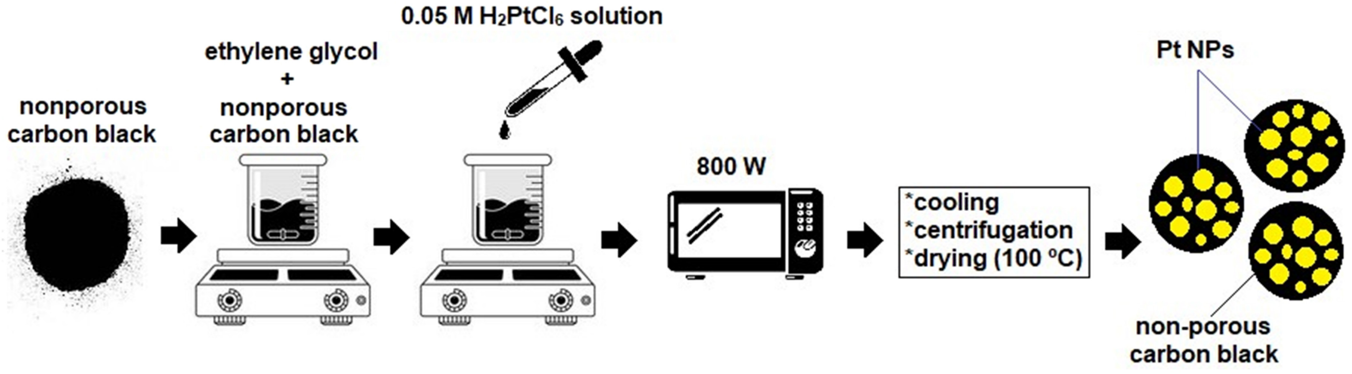

Figure 1. Preparation of a nonporous carbon-supported Pt catalyst.

sample/GC electrode area. About 5 μL of the ultimate WE ink was dropped over the GC electrode and dried at room temperature. Firstly, the potential was linearly swept between the potential range of (−0.28) and (0.92) V at different scan rates (20, 50, and 100 mV/s) through 3 cycles in a N_2-saturated 0.5 M H_2SO_4 electrolyte solution in CV analysis. Then, CV analysis was continued at the same electrolyte conditions for 3 cycles at a constant scan rate of 50 mV/s but at different upper potential values (0.4, 0.6, 0.8, and 1.0 V). Electrochemical impedance spectroscopy tests (potentiostatic mode; 0.4, 0.65, and 0.9 V) were carried out in N_2-saturated 0.5 M H_2SO_4 over a frequency range of 1-10^5 Hz.

The PEM fuel cell performance of a nonporous carbon-supported Pt catalyst was measured using a test station. The prepared MEA was placed on the active region of the single-cell contacting the gas flow channels, and then the cell was closed by compressing the screws at appropriate torque pressures. The cell was swept with nitrogen gas for approximately 1 hour for cleaning and reaching the desired temperatures of the humidification tanks, gas flow lines, and fuel cell before the measurements. The humidification tank temperatures were adjusted to 60°C and 70°C, respectively, while the cell temperature was 70°C. After sweeping, hydrogen gas was fed to the anode side, and oxygen gas was fed to the cathode side. By turning on the load connected to the cell, corresponding current values were recorded starting from the open-circuit voltage and decreasing the voltage at 0.05 V intervals every 30 minutes. Finally, polarization curves were obtained with the recorded potential and current density data.[21]

RESULTS AND DISCUSSION

Brunauer–Emmett–Teller

Brunauer–Emmett–Teller analysis is an empirical technique to calculate surface area per weight or volume by performing gas adsorption experiments on porous materials. Brunauer–Emmett–Teller surface area depends strongly on pore size, structural homogeneity, and the adsorbate-adsorbent relationship.[22] Table 1 shows the BET analysis results for the nonporous carbon. The micropore volume of nonporous carbon black is insignificant compared to the cumulative adsorption and desorption volumes, and the surface area was as low as 72.6 m^2/g. There is hardly any difference between adsorption and desorption volumes in Figure 3(A). Nitrogen gas is reversibly adsorbed in the form of mono- or multi-layers in nonporous or macroporous solids according to the type-II isotherm,[23,24] The Barrett–Joyner–Halenda adsorption pore size distribution of nonporous carbon black is shown in Figure 3(B). The average adsorption pore size was in the range of 30-40 nm.

Figure 4 shows the XRD pattern of the nonporous carbon black. Two distinct peaks at around 24° and 43° represent the (002) and (100) planes of graphite, respectively.[24,25] Additionally, the peak around 80° belongs to the (110) plane of graphite.[20] Actually, (002) reflection is positioned at 26°, but the peak appears at smaller angles compared to the crystalline graphite in this case due to its amorphous nature. Because the shift of the (002) plane to lower angle values means there will be a larger d-spacing between the

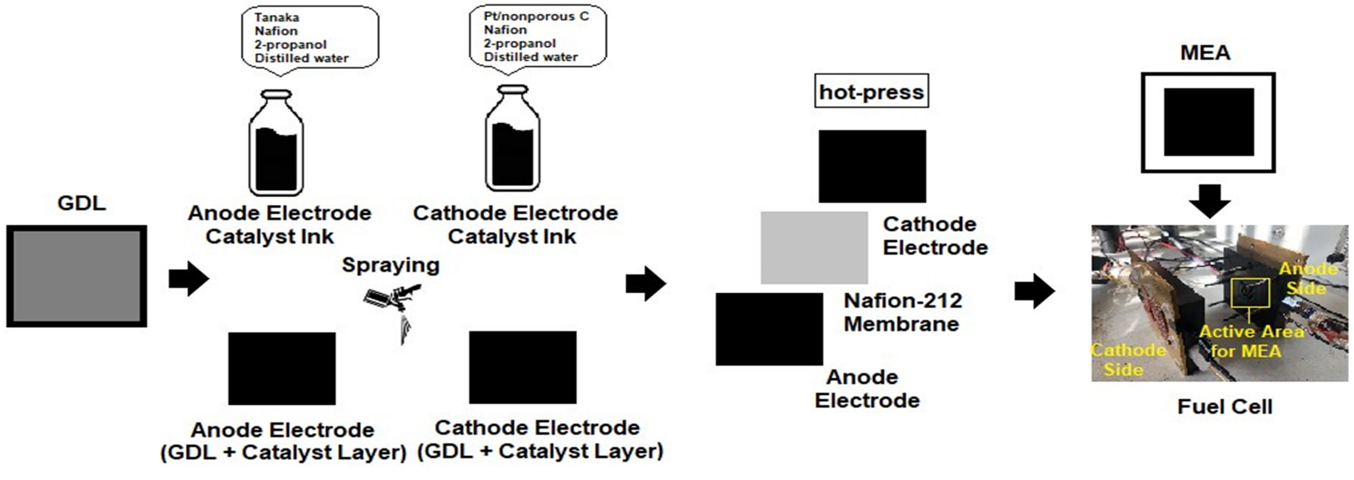

Figure 2. Preparation steps for MEA.

Table 1. Structural Properties of the Nonporous Carbon

Sample	BET Surface Area (m²/g)	Dubinin–Astakhov Micropore Volume (cm³/g)	BJH Adsorption Cumulative Volume of Pores (cm³/g)	BJH Desorption Cumulative Volume of Pores (cm³/g)	BJH Adsorption Average Pore Width (nm)	BJH Desorption Average Pore Width (nm)
Nonporous carbon	72.6	0.024	0.729	0.728	37.6	31.4

BET, Brunauer–Emmett–Teller; BJH, Barrett–Joyner–Halenda.

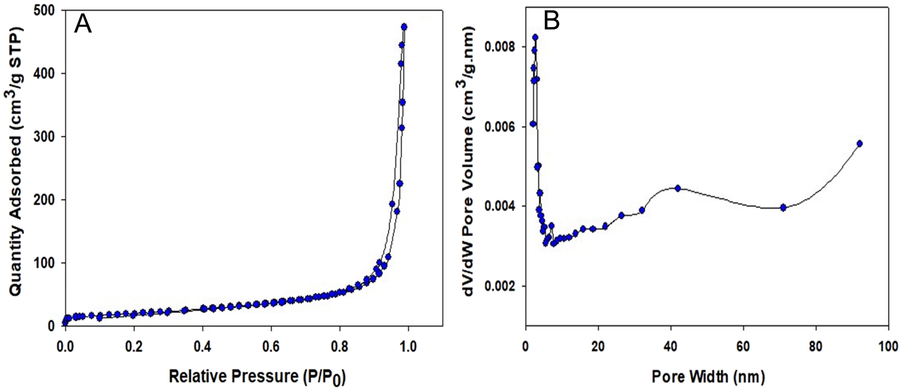

Figure 3. BET analysis of nonporous carbon: (A) adsorption-desorption isotherms; (B) BJH adsorption pore size distribution.

layers, which causes a deviation from the d-spacing (0.335 nm) of crystalline graphite.[26,27] In reality, when the $d_{(002)}$ value of nonporous carbon black was computed using Bragg's Law,[28] it was found to be 0.377 nm, confirming the previous interpretation. Although the structure of carbon black is similar to that of graphite, the difference that distinguishes it from graphite is that it consists of a heterogeneous mixture of turbostratic regions rather than entirely of fine graphite crystals.[29] ICP-MS analysis was used to measure the amount of Pt metal loaded on nonporous carbon. As a result of the analysis, the amount of Pt was detected at 15 wt.%. The amount of Pt NPs on the support material is a parameter that affects the porosity and thickness of the catalyst layer. In the literature, the generally accepted Pt loading amount for PEM fuel cell cathode electrodes is 0.4 mg_{Pt}/cm^2. A lesser amount of Pt/C catalyst with a higher mass Pt% value is adequate to obtain a loading of 0.4 mg_{Pt}/cm^2; however, more Pt/C catalyst with a lower mass Pt% value is required to accomplish the same loading. This case leads to an increase in the fraction of carbon and ionomer, thus increasing the thickness and reducing the porosity of the catalyst layer.[30] The thickness of the catalyst layer makes it difficult to transfer the species required for electrochemical reactions to active sites by longer pathways, which causes lower PEM fuel cell performance.[31]

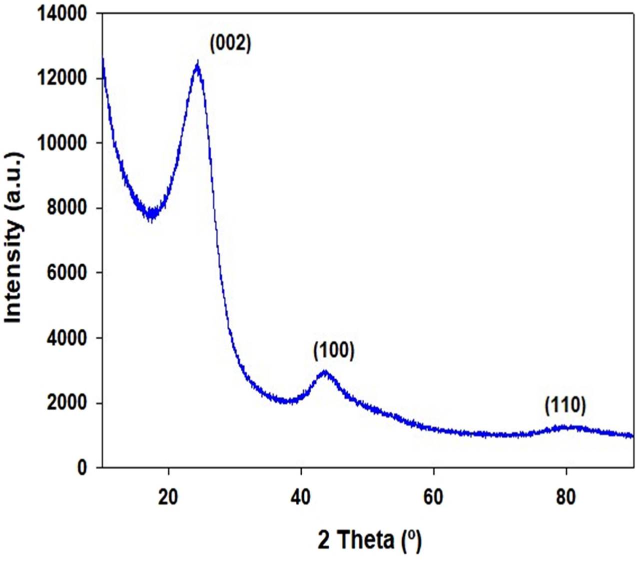

Figure 4. XRD analysis of nonporous carbon.

Figures 5(A) and (B) show CV diagrams of nonporous carbon black at different scan rates and upper potential limits, respectively. The capacitive storage feature increases in the CV curves of Figure 5(A) as the scan rate increases.[32] In Figure 5(B), the capacitive field becomes more pronounced with the increase in the upper potential limit.[33] The quinone-hydroquinone (Q-HQ) redox peaks appeared at around 0.5-0.7 V in the positive sweep and 0.4-0.6 V in the negative sweep due to the change of the carbon surface with the potential cycling,[34,35] Carbon support materials undergo electrochemical oxidation and deteriorate due to the production of surface oxides and CO_2/CO in aqueous acidic electrolyte conditions, including the PEM fuel cell. The production of oxygen-containing groups on the carbon surface is triggered, especially at potential values greater than 1 V. Since corrosion promotes carbon loss, the interaction of the support with Pt NPs weakens, and the sintering of Pt NPs accelerates. Furthermore, the decrease in electrode thickness owing to material loss increases resistance and decreases conductivity. All of these unfavorable aspects contribute to poor PEM fuel cell performance. As a result, the corrosion resistance of carbon is critical.[36] At scan rates of 20, 50, and 100 mV/s, the current density values obtained by the peak of the Q-HQ redox couple on nonporous carbon black were roughly 0.14, 0.31, and 0.57 mA/cm². According to the CV diagrams acquired at a scan rate of 10 mV/s for holding under 1.2 V (0 h) in Wang et al's work,[37] the current density values reached by the peak of the Q-HQ redox couple on Vulcan XC-72 and Black Pearls (BP) 2000 carbon blacks are approximately 1 and 1.5 mA/cm². BP-2000 carbon black is more susceptible to oxidation due to its higher micropore density. Based on the lower current density values obtained for the Q-HQ redox couple in this study, nonporous carbon black will be more resistant to oxidation in the fuel cell environment.

EIS analysis is a method that provides useful information in a short time to better understand the ORR mechanism in fuel

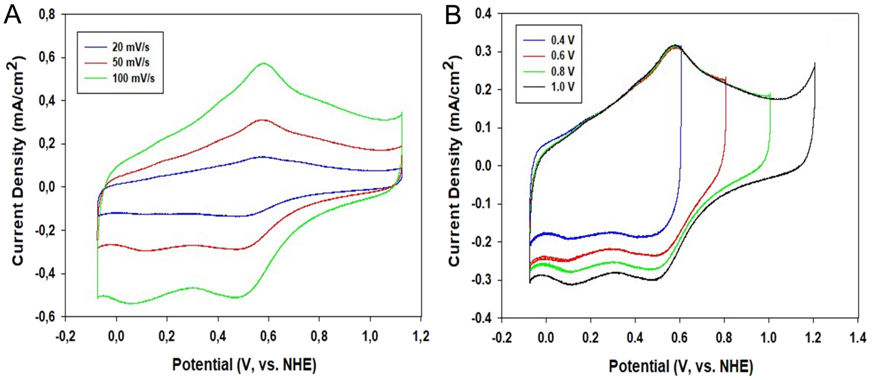

Figure 5. CV measurements of nonporous carbon: (A) different scan rates (20, 50, and 100 mV/s; potential range: −0.28 to 0.92 V); (B) different upper potentials (0.4, 0.6, 0.8, and 1.0 V; scan rate: 50 mV/s).

cells, determine electrode properties, and evaluate diffusion-induced transfer losses.[38] Figure 6 shows the Nyquist plots of the nonporous carbon at different voltages. The Nyquist plot fits the fundamental Randles equivalent electrical circuit with membrane and electrolyte resistances (R_S) and charge transfer resistance (R_{CT}) at 0.9 V.[39] Table 2 gives the R_S and R_{CT} values as 34.3 Ω and 454.5 Ω, respectively. Liu et al[40] performed an EIS study on Pt catalysts produced on highly graphitic carbon black (GCB) and Vulcan XC-72 in the frequency range of 0.01 Hz-100 kHz at 0.54 V in a 0.5 M H_2SO_4 environment. The R_{CT} values of the Pt/GCB and Pt/Vulcan XC-72 catalysts were 331.5 Ω.cm^2 and 443.9 Ω.cm^2, respectively. When we multiply the R_{CT} value we obtained for nonporous carbon black in this study by the electrode area (0.1963 cm^2), we get a value of 89.2 Ω.cm^2. In another study, Yan et al[41] prepared nitrogen (N)/phosphorus (P) co-doped nonporous carbon nanofibers (N/P-NPCNFs) for supercapacitors by the electrospinning method. The EIS analysis (at 1 M H_2SO_4 electrolyte) of the N/P-NPCNFs-5 (63.62 m^2/g), N/P-NPCNFs-10 (33.94 m^2/g), N/P-NPCNFs-20 (12.15 m^2/g), and N/P-NPCNFs-30 (10.34 m^2/g) samples created by varying the polyacrylonitrile/phosphoric acid ratio yielded low R_{CT} values for all of them. It is clear from these examples that nonporous carbon structures can achieve lower R_{CT} values. The lower R_{CT} at the electrode/electrolyte interface means higher ORR activity in the PEM fuel cell.[42] In the Nyquist plot given in the inset figure of Figure 6, slope angles higher than 45° were obtained in the high-frequency region in the impedance spectroscopy taken at lower potentials. This case represents the pore structure with a wide mouth and narrowing down shape.[43]

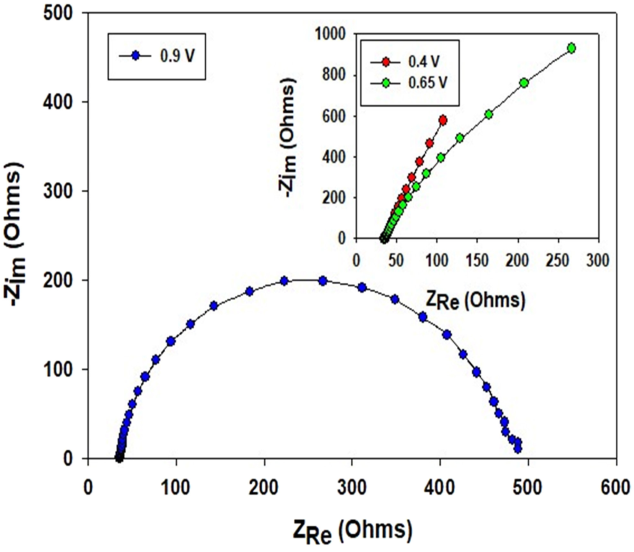

Figure 6. EIS measurements of nonporous carbon.

Figure 7 demonstrates the performances of MEAs prepared with Pt catalysts supported with nonporous carbon at 2 different humidification temperatures. The maximum current density at 60°C was recorded as 86 mA/cm^2 and 193 mA/cm^2 at 70°C. There is a 2.25-fold increase in maximum current density at 70°C despite excess water at the cathode electrode at a higher humidification temperature. The Pt catalyst achieved a maximum power density of 15 mW/cm^2 at 60°C and 40 mW/cm^2 at 70°C. The performance values of the nonporous carbon-supported Pt catalyst in this study were better than the results obtained with the Pt catalyst in MEA, which was prepared by Rohendi et al[44] by the casting method with 1.5 mg/cm^2 Vulcan carbon black loading in its microporous layer. In addition, the mentioned MEA failed in water management, and a rapid decrease in current density was experienced. The nonporous carbon structure can facilitate the removal of excess water released at the cathode electrode by not trapping water in the pores. Since the mass transfer resistance is less in nonporous carbons than in porous carbons, it is easier for water to drain from the catalyst layer, thus preventing the catalyst from overflowing. In this sense, it is thought that it may be advantageous to use nonporous carbon catalyst support at the cathode electrode of a PEM fuel cell. Lefèvre et al[45] prepared iron (Fe) catalysts on different carbon blacks and used them in the PEM fuel cell. The BET surface areas and micropore areas of SR0, SR1, Vulcan XC-72R, and BP 2000 carbon blacks are (71;29), (441;272), (213;114), and (1379;934) m^2/g, respectively. Fe/SR0 carbon black gives the best results in PEM fuel cell performances; however, Fe/BP 2000, which has the highest micropore area, deteriorates faster than the others in the high current density region. The authors stated that nonporous SR0 carbon black is better than its porous counterparts.

Nonporous carbon structures improve catalyst utilization by ensuring that catalysts are put onto the support material and are in easily accessible locations. Takeshita et al[46] investigated the Nafion ionomer coating on the cathode electrodes of MEAs made with Pt catalysts placed on commercial nonporous carbon black

Table 2. Resistance values of nonporous carbon (@0.9 V)

Sample	R_S (Ω)	R_{CT} (Ω)
Nonporous carbon	34.3	454.5

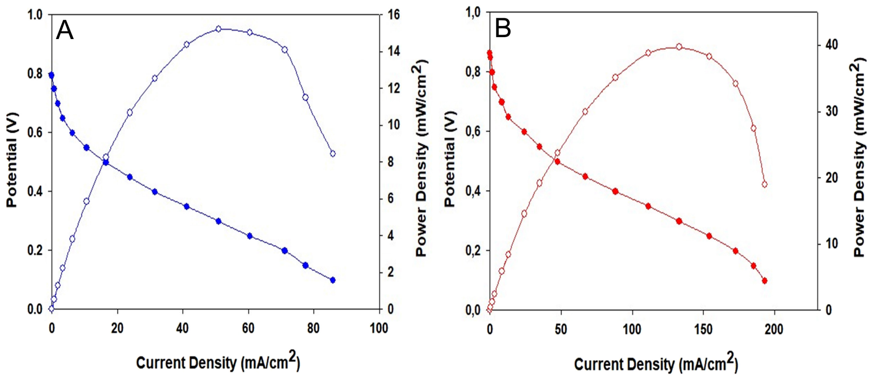

Figure 7. PEM fuel cell performance of the Pt catalyst supported with nonporous carbon at different humidification temperatures (A) 60°C and (B) 70°C.

(Vulcan, MEA-1) and porous carbon blacks (Ketjen Black, MEA-2; Cnovel, MEA-3). The researchers determined that almost all of the Pt NPs on nonporous Vulcan were coated with Nafion ionomer and positioned on the outer surface of carbon. However, they did state that a significant proportion of Pt NPs were found at the inner surface of porous Ketjen Black and Cnovel carbons, and they could not be covered with Nafion ionomer. The authors reported the estimated Nafion coverage percentages as 90 ± 2% for MEA-1, 60 ± 7% for MEA-2, and 57.4 ± 0.3% for MEA-3, respectively. Nonporous carbons also contribute to the fuel cell's durability. Some studies indicate that nonporous carbons give more stability than porous carbons within the catalytic framework. O'Brien et al[47] used 5 carbon materials (AB (524 m^2/g), EA (109 m^2/g), E (527 m^2/g), VA (70 m^2/g), and V (160 m^2/g)) with different structures as the support for the PtCo catalyst and tested their durability in PEM fuel cells. In their EIS analysis for carbon materials (at 1.0 A/cm^2, 80°C, 100% RH), before applying accelerated stress testing (AST), the authors stated that samples with lower surface areas such as VA, EA, and V had lower mass transfer resistance, and this was also associated with the low total micropore volume. In the EIS analyses performed under the same conditions after the AST test, the mass transfer resistance of AB and E carbons with high surface areas increased significantly, while the mass transfer resistance of carbons such as VA, EA, and V did not change noticeably. Additionally, the authors stated that porous carbons such as AB and E were more prone to Co leaching. Tian et al[48] synthesized Fe/N/C catalysts using extremely microporous BP 2000 (1379 m^2/g) and Ketjenblack EC-600JD (1417 m^2/g) carbon blacks as well as nonporous N330 carbon black (74 m^2/g) and CNT (257 m^2/g). According to the normalized mass activities based on polarization curves after holding the catalysts at 0.5 V for different periods, the Fe/N/C catalysts with N330 carbon black and CNT were substantially more stable than those of BP 2000 and Ketjenblack.

Figure 8 depicts the main topics on the advantages of nonporous carbons in PEM fuel cells based on studies in the literature. In these carbons, nonporosity provides better usage of metal catalysts, facile mass transfer of the species, better water management, and long durability.

This study, unlike the examples in the literature, aimed at using a nonporous commercial carbon black as a support material for the PEM fuel cell catalyst. The nonporous structure ensures better metal loading and utilization by preventing the metal NPs from being trapped in the pores of the support material. Platinum metal was used as the catalyst. As a result of the reduction of Pt salt in the microwave, Pt metal was obtained in metallic form on nonporous carbon. The structural properties of nonporous carbon were evaluated by BET analysis, and its surface area was found to be quite low, 72.6 m^2/g. The nonporous carbon BET isotherm exhibited no hysteresis and conformed to the type-II isotherm. Through XRD analysis, it has been understood that nonporous carbon has an amorphous structure.

The nonporous carbon structure was further studied using CV and EIS analyses in a 3-electrode setup. In the CV analysis, it was observed that the capacitive property increased considerably with the increase in the scan rate. In the EIS analysis, it was found that under high potential, nonporous carbon responded appropriately to the Randles cell, and R_s (34.3 Ω) and R_{CT} (454.5 Ω) values were obtained depending on this cell type. Membrane electrode assemblies produced with a nonporous carbon-supported Pt catalyst provided maximum power densities of 15 mW/cm^2 and 40 mW/cm^2 at humidification temperatures of 60°C and 70°C, respectively. A balanced drop in fuel cell performance was observed when descending to low voltages with nonporous carbon. In addition, better performance at high humidification showed that water management is proper. Nonporous carbons as alternate catalyst support materials can be used to create

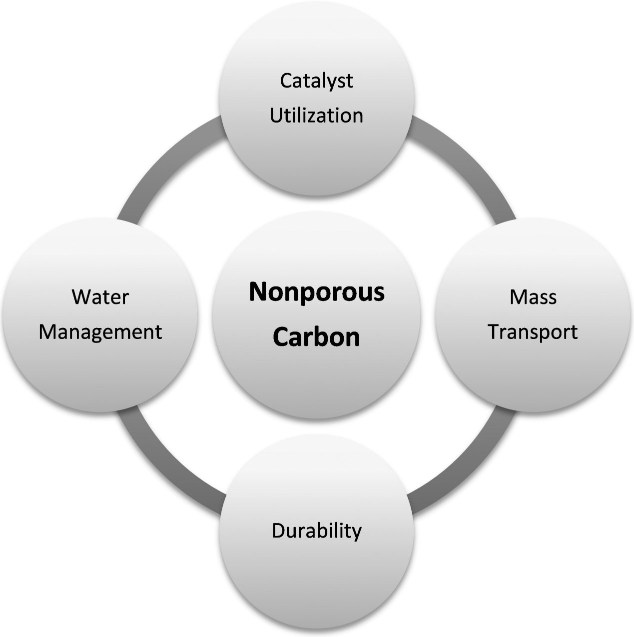

Figure 8. Advantages of nonporous carbons in PEM fuel cells.

high-performance fuel cells with facile water management and long-term durability for portable applications with mW scale.

Peer-review: Externally peer-reviewed.

Acknowledgements: The authors thank the Nanografi Nanotechnology Company for providing commercial nonporous carbon black. The authors also appreciate the East Anatolia High Technology Application and Research Center (DAYTAM) for BET, XRD, and ICP-MS analyses.

Author Contributions: Concept – A.Ö.A.; Supervision – A.B.Y.; Resources – A.B.Y.; Materials – A.Ö.A.; Data Collection and/or Processing – A.Ö.A.; Analysis and/or Interpretation – A.Ö.A.; Writing Manuscript – A.Ö.A., A.B.Y.; Critical Review – A.B.Y.

Declaration of Interests: The authors declare that they have no competing interests.

Funding: The authors declared that this study has received no financial support.

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