

**IMPROVING SOME STRUCTURAL PROPERTIES OF NON-WOVEN NETWORKS
COMPOSED OF CARBON NANOFIBERS RECYCLED FROM ACRYLIC YARNS****Ismail Aodah^{1*}, Ghazal Tohmaz², Majdeddin Ali³**¹PhD Student, Department of Textile Engineering and Spinning, Faculty of Chemical and Petroleum Engineering - Homs University, Syria.²Professor Department of Textile Engineering and Spinning, Faculty of Chemical and Petroleum Engineering -Homs University Syria.³Assistant Professor Department of Electronics and Communications Engineering, Faculty of Mechanical and Electrical Engineering -Homs University, Syria.

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ABSTRACT

In this research, non-woven carbon nanofiber networks were fabricated starting from acrylic yarn polymer. The yarns were recycled by dissolving them in N,N-Dimethylformamide (DMF) solvent to form a polymer solution. The optimal conditions for the electrospinning process were determined, and the electrospinning process was conducted to obtain a non-woven nanofiber network. Subsequently, heat treatment processes were performed on the prepared networks through thermal stabilization by placing the sample in an oven up to a temperature of 230°C for two hours to ensure structural stability. Then, the carbonization process was carried out under different operating conditions (gas used and temperature) with a heating rate of one degree per minute, aimed at removing non-carbon elements. The samples were analyzed using a scanning electron microscope (SEM) to determine the morphological structure of the prepared samples. EDX analysis was also performed to determine the carbon percentage in the sample and to ensure the formation of a non-woven carbon nanofiber network. The results obtained by exposing the sample to heat and Argon gas up to 750°C were compared with a carbon nanofiber sample prepared at 650°C in the presence of Nitrogen. Finally, The electrical conductivity of the prepared carbon nanofiber network was measured using a four-probe device, it was (84.11 S/cm).

KEYWORDS: Acrylic yarns, Carbon Nanofibers (CNF), Thermal stabilization, Electrospinning, Carbonization, Non-woven network.**1- INTRODUCTION**

Carbon nanofibers have received great attention due to their superiority in chemical, electrical, and mechanical properties, combined with their unique nanostructure and characteristics. Carbon nanofibers are defined as materials consisting of very fine fibers with diameters in the nanometer range, composed mostly of carbon atoms bonded together in microscopic crystals oriented parallel or otherwise to the fiber axis. This orientation makes the fibers very strong compared to their size.

With the emergence of the electrospinning technique and its development and entry into the practical field in the period between 2000-2010, eyes turned towards forming electrospun carbon nanofibers. In 2009, researchers were able to produce a carbon nanofiber network prepared from electrospun fibers, and since then, this topic has become the focus of many researchers.^{[1], [2]}

2- Research Objective

The objective of this research is to form non-woven networks of nanofibers using the electrospinning method

under specific and ideal conditions starting from recycled acrylic yarns, thermally stabilizing them, and then performing the carbonization process in an inert atmosphere and at high temperatures to obtain carbon nanofibers. This is done while varying some operating conditions and selecting the best conditions to improve some structural properties and reach the highest possible carbon percentage in the resulting samples as a result of modifying some operating conditions.

3- MATERIALS AND RESEARCH METHODS

3-1- Materials used in the research

- Acrylic yarns.
- N,N-Dimethylformamide (DMF) solvent (99.7%). Chemical Formula: $(CH_3)_2NC(OH)$

3-2- Devices and tools used in the research

- Electrospinning device located in the Nanofibers Lab, Department of Textile Engineering and Spinning, Faculty of Chemical and Petroleum Engineering -Homs University.
- G18 size needle.
- Heater with magnetic stirrer (Nanofibers Lab).
- Thermal stabilization oven (Textile Chemistry Lab).
- Muffle furnace (Textile Chemistry Lab).
- Nitrogen gas cylinder (Textile Chemistry Lab).
- Argon gas cylinder (99% purity) (Textile Chemistry Lab).

3-3- Method of Work

The experiments were completed according to the following sequence.

- Preparation of the acrylic solution and determining the appropriate conditions for the electrospinning process and producing samples of nanofiber networks using the electrospinning technique.
- Performing a thermal stabilization process for the resulting nanofiber network in hot air for two hours at a temperature of 230°C.^[3]

c- Performing the carbonization process for the thermally stabilized nanofiber network.

1_ Exposing the sample to heat within a Nitrogen atmosphere.

2_ Performing the carbonization process for the thermally stabilized nanofiber network with direct exposure to Argon gas.^{[3], [4]}

d- Conducting tests to determine the effect of changing some operating conditions on the resulting nanofiber network:

1- Examining the samples using the Scanning Electron Microscope (SEM) and determining the change in the diameter of the nanofibers resulting from thermal treatments and changes in some operating conditions.

2- Determining the carbon percentage in the samples using the EDX test, and determining the change in carbon percentage resulting from thermal treatments and changes in some operating conditions.

A) Production of a nanofiber network using the electrospinning technique

Preparation of the polymeric acrylic solution

Acrylic yarns are weighed and placed in a glass beaker, then dimethyl formamide is added (density 0.99). Heating is carried out with stirring using a magnetic stirrer up to (100°C), and heating is continued for three hours until complete dissolution of the yarns is observed.^{[5],[6]}

Electrospinning process: The optimum conditions are determined (electrospinning process variables), under which the electrospinning process can be carried out and polyacrylic nanofibers obtained. These parameters were determined after conducting many experiments until reaching the appropriate concentration and suitable values, as follows.

Table 1: Optimum conditions for the electrospinning process obtained experimentally.

Acrylic yarn concentration (g/100 ml)	Applied voltage (kV)	Distance between collector and needle (cm)	Flow rate (ml/hr)
18	20	10	2

After determining the optimal parameter values for the electrospinning process, we perform the electrospinning process (Figure (1)) using the electrospinning device located at Homs University -Faculty of Chemical and Petroleum Engineering - Department of Textile and Spinning Engineering (Figure (2)).

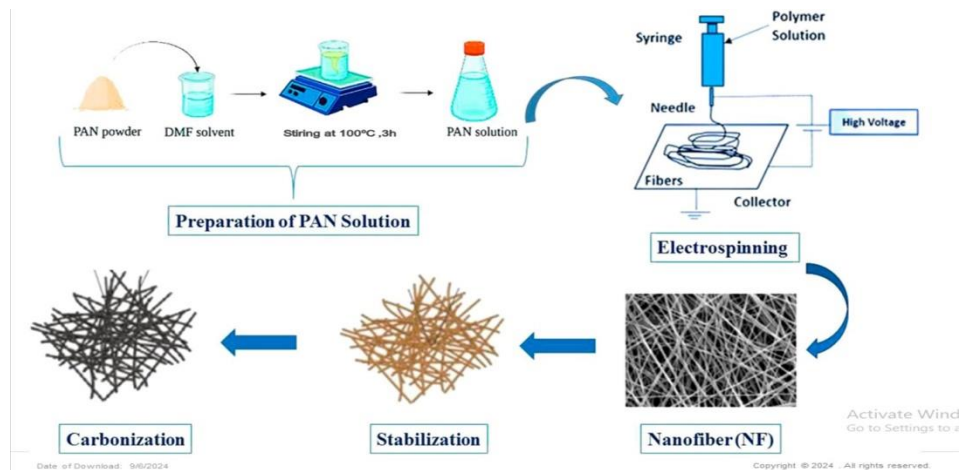


Figure (1): Schematic diagram for the preparation of the polymer solution, the electrospinning process, and subsequent heat treatments.^[7]

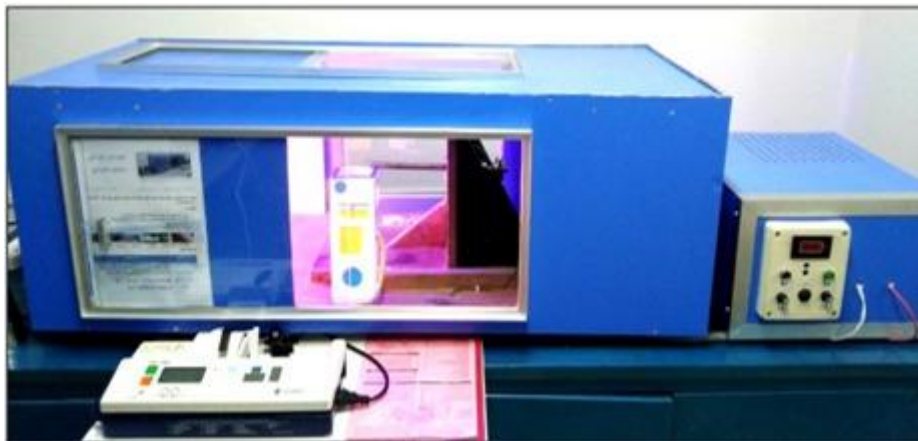


Figure (2): Electrospinning Device.

After the completion of spinning the sample, the product is carefully removed from the collector (Figure(3)).



Figure (3): Samples resulting from the electrospinning process of the acrylic solution.

B) Performing a Thermal Stabilization Process for the Resulting Fiber Network

Thermal stabilization leads to the formation of a cyclic structure or what is known as the ladder structure. This occurs through creating cross-links between the molecular chains of Polyacrylonitrile (PAN) fibers. This step is necessary to maintain the chemical structural stability of the PAN fibers during the carbonization process. In this step, the sample is fixed with special clamps and placed in a muffle furnace in a hot air atmosphere. The maximum temperature is set at 230°C

and the time required to reach this temperature is determined (120 minutes) (Figure (4)).^{[8], [9]}



Figure (4): Sample resulting from the thermal stabilization process of the prepared fiber network.

C) Performing the Carbonization Process for the Thermally Stabilized Nanofiber Network

The carbonization or charring process aims to convert the thermally stabilized nanofiber networks into carbon fibers by heating to high temperatures in an atmosphere free of air. During this stage, the carbon content increases while maintaining the morphological structure of the fibers and the partial crystalline structure, noting that most non-carbon elements are removed during the carbonization process.^[10] In this process, the thermally stabilized sample was fixed with special clamps and placed inside the muffle furnace in an inert atmosphere. The temperature was raised slowly to the required value

(at a rate of one degree per minute) according to the following.

1- By exposing the sample to thermal treatment with a temperature elevation rate of 1°C per minute, accompanied by the injection of nitrogen gas into the carbonization chamber. It was observed that the sample maintained its structural integrity up to 650°C, whereas fragmentation and shattering of the sample occurred beyond this temperature. Consequently, the carbonization process was optimized and concluded at 650 °C. Figure (5).

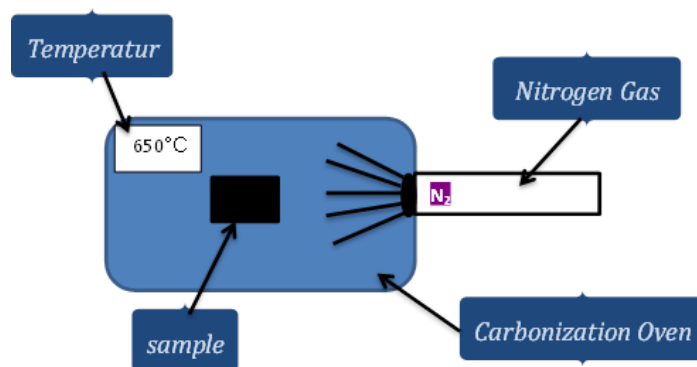


Figure (5): Schematic Diagram of the Carbonization Chamber.

2- The carbonization process for the thermally stabilized nanofiber network was performed with direct exposure to pure Argon gas up to 750°C, Figure (6).^[11]

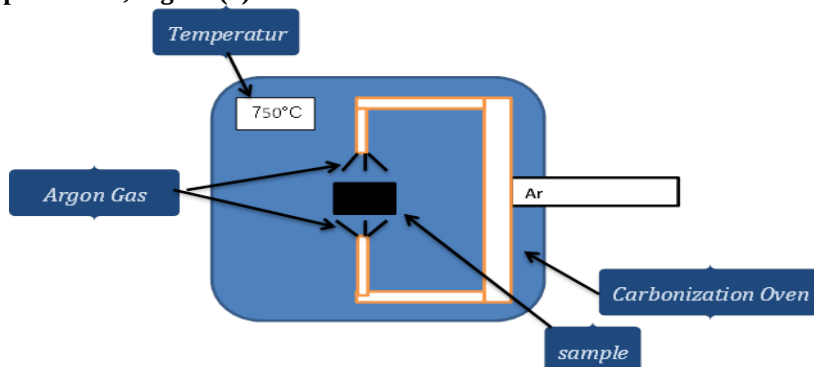


Figure (6): Schematic Diagram of the Carbonization Chamber.

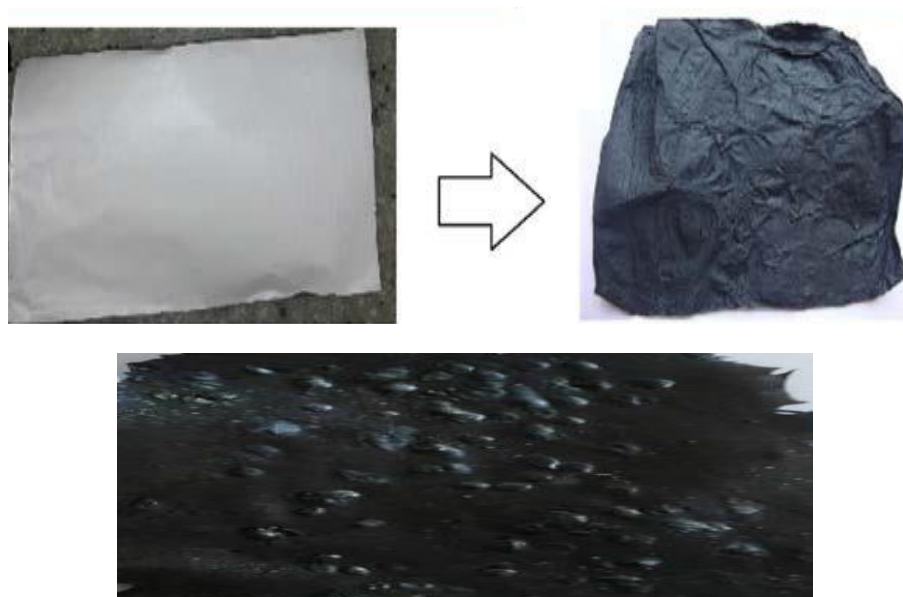


Figure (7): The sample resulting from the carbonization process of the thermally stabilized nanofiber network.

D-Conducting tests to determine the effect of varying certain operating conditions on the resulting nanofiber network.

1- Morphological Analysis using Scanning Electron Microscopy(SEM)

The samples were scanned using Scanning Electron Microscopy (SEM) to determine the changes in the morphological structure (shape changes) resulting from the thermal stabilization and carbonization processes under different operating conditions. Changes in the diameters of the nanofibers were also determined following the applied thermal treatments using ImageJ software. A decrease in the average diameter of the resulting nanofibers was observed as a result of the applied thermal treatments, where the average diameter was. 116 nm for the electrospun acrylic sample.

102 nm for the thermally stabilized acrylic sample.

75 nm for the carbonized nanofiber sample prepared in the presence of Nitrogen at 650°C.

68 nm for the carbonized nanofiber sample prepared in the presence of pure Argon at 750°C.

A decrease in the average diameter of the nanofibers is observed as a result of increasing the applied heat temperature. This is due to the disposal of moisture present in the sample, sample shrinkage, removal of non-carbon elements, and the transformation of the linear atomic structure of the acrylic nanofibers into a cyclic structure in the carbon nanofibers.^{[11], [12]}

Below are the scanning electron microscope (SEM) images of the samples along with diameter measurements using (image j) software.

1- acrylic nanofiber network sample

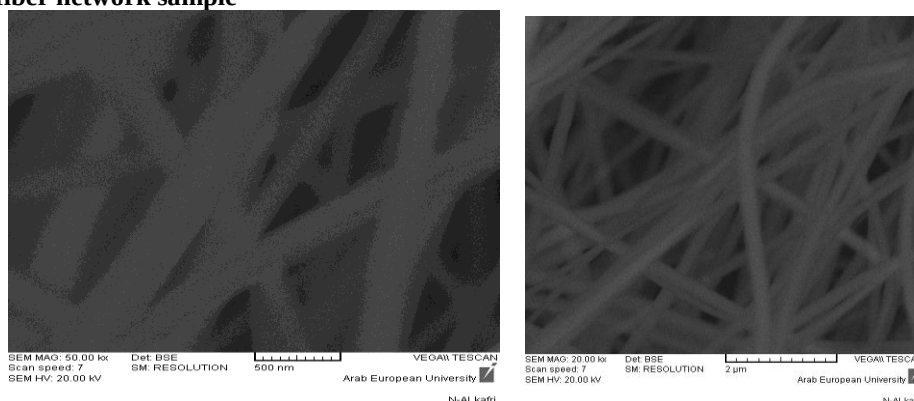


Figure (8): SEM image of the prepared acrylic nanofiber network sample; average diameter recorded was 116 nm using ImageJ.

2- the thermally stabilized acrylic nanofiber network sample

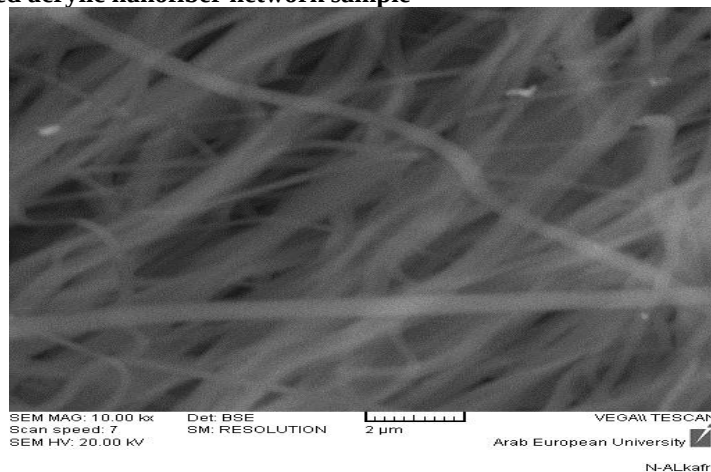


Figure (9): SEM image of the thermally stabilized acrylic nanofiber network sample; average diameter recorded was 102 nm using ImageJ.

3-carbonized polyacrylonitrile nanofiber network sample

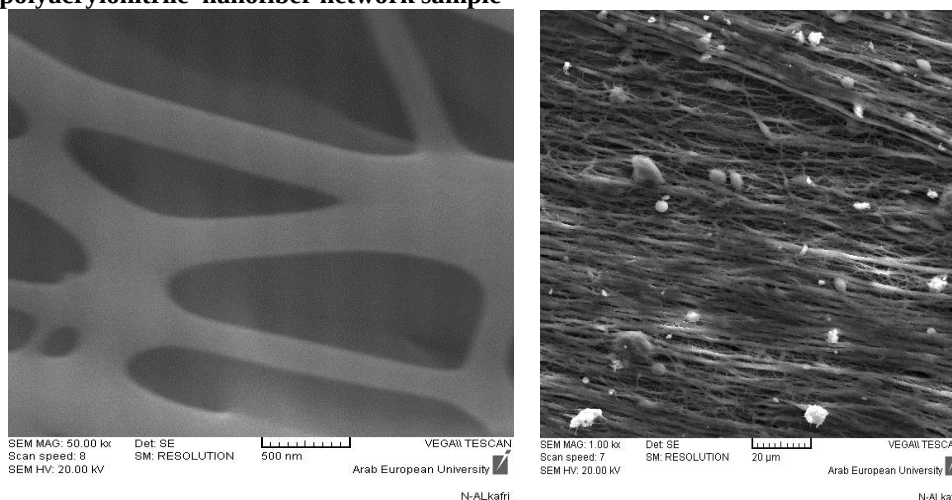


Figure (10): SEM images of carbonized acrylic nanofiber network samples: a) in Nitrogen up to 650°C, b) with direct exposure to Argon gas up to 750°C.

The diameters were measured using image j software, recording an average diameter of 75 nm in the presence of nitrogen up to 650 °C, and an average diameter of 68 nm under direct exposure to pure argon gas up to 750°C

2- Determination of Carbon Percentage in Samples using

The percentage of the carbon element in the prepared samples was determined using the EDX test. The results showed that the carbon percentage in the acrylic nanofiber network sample was 59%, while the percentage in the thermally stabilized sample was 65.23%. As for the carbonized acrylic nanofiber network at 650°C in the presence of Nitrogen, it was 84.63%, whereas the carbon percentage in the carbonized acrylic nanofiber network at 750°C with direct exposure to pure Argon gas was 89.67%.

This means a non-woven network of carbon nanofibers was obtained. The difference in carbon percentage is

attributed to the fact that most non-carbon elements are removed as a result of the applied thermal treatments. Changing some carbonization process conditions through direct exposure of the sample to pure Argon gas allowed us to raise the carbonization temperature up to 750°C while maintaining the sample's cohesion. This led to the removal of more non-carbon elements and consequently an increase in the sample's carbon content. This is because higher carbonization temperatures provide more of the energy required to expel non-carbon elements.

Furthermore, the type of inert gas used and its purity play a significant role in the final carbon percentage in the sample. Some studies have shown that the use of Nitrogen gas may lead to the appearance of nitrogen element in the sample, while treatment in a pure Argon atmosphere ensures a clean environment free of Oxygen, which improves the efficiency of the carbonization process.^{[11], [12], [13]}

1- acrylic nanofiber network sample

eZAF Smart Quant Results										
Creation D #####										
Project	3	Area 1	Full Area 1							
Specimen										
Area										
Sampling Region										
kV	20									
Live Time	35.922									
Amp Time	7.68									
Takeoff An	39.24									
Resolution	126.6711									
Element	Weight %	Atomic %	Error %	Net Int.	K Ratio	Z	R	A	F	
C K	59.42	64.5	3.16	10595.75	0.4956	1.0106	0.9955	0.7893		1
N K	10.85	12.93	6.35	591.28	0.0261	0.9863	1.0051	0.0902		1
O K	8.51	5.57	5.04	388.17	0.0076	0.9652	1.0137	0.0963		1
S K	5.47	4.12	1.05							
Cl K	5.15	4.17	2.4							
Si K	4.81	3.44	2.8							
Na K	3.06	2.84	3.05							
Al K	2.73	2.43	1.15							

Figure (11): Elements composing the acrylic nanofiber sample with the mass percentages of the elements.



Figure (12): Elements composing the acrylic nanofiber sample.

2- the thermally stabilized acrylic nanofiber network sample.

eZAF Smart Quant Results										
Creation D #####										
Project D Area 1 Full Area 1										
Specimen										
Area										
Sampling Region										
KV 20										
Live Time 35.701										
Amp Time 7.68										
Takeoff An 39.18										
Resolution 126.6711										
Element	Weight %	Atomic %	Error %	Net Int.	K Ratio	Z	R	A	F	
C K	65.23	69.55	3.27	9443.27	0.5139	1.0107	0.9954	0.7794		1
N K	23.35	21.35	11.07	385.95	0.0198	0.9863	1.005	0.0861		1
O K	11.25	9	10.87	488.4	0.0111	0.9853	1.0137	0.1021		1
Na K	0.17	0.09	16.32	41.22	0.0006	0.8751	1.0356	0.4342	1.0018	

Figure (13): Elements composing the thermally stabilized acrylic nanofiber sample with the mass percentages of the elements.



Figure (14): Elements composing the thermally stabilized acrylic nanofiber sample.

3-carbonized polyacrylonitrile nanofiber network sample

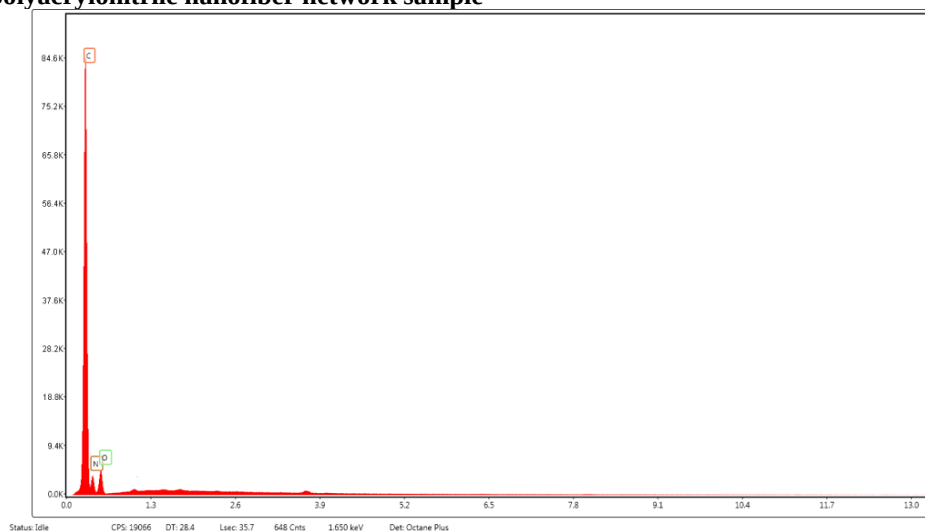


Figure (15): Elements composing the carbonized acrylic nanofiber network samples at 650°C.

eZAF Smart Quant Results										
Creation D #####										
Project D Area 1 Full Area 1										
Specimen										
Area										
Sampling Region										
kV 20										
Live Time 35.701										
Amp Time 7.68										
Takeoff An 39.18										
Resolution 126.6711										
Element	Weight %	Atomic %	Error %	Net Int.	K Ratio	Z	R	A	F	
C K	84.63	86.55	3.27	9443.27	0.5139	1.0107	0.9954	0.7794	1	
O K	7.81	8.05	11.07	385.95	0.0198	0.9863	1.005	0.0861	1	
N K	7.56	5.4	10.87	486.4	0.0111	0.9653	1.0137	0.1021	1	

Figure (16): Elements composing the carbonized acrylic nanofiber network samples at 650°C with the mass percentages of the elements.

eZAF Smart Quant Results										
Creation D #####										
Project 2 Area 1 Full Area 1										
Specimen										
Area										
Sampling Region										
kV 19										
Live Time 35.975										
Amp Time 7.68										
Takeoff An 39.64										
Resolution 126.6711										
Element	Weight %	Atomic %	Error %	Net Int.	K Ratio	Z	R	A	F	
C K	89.67	92.04	2.24	9858.07	0.7977	1.0046	0.998	0.8857	1	
O K	10.33	7.96	10.95	333.1	0.0117	0.9583	1.0159	0.1183	1	

Figure (17): Elements composing the carbonized acrylic nanofiber network samples at 750°C with the mass percentages of the elements.

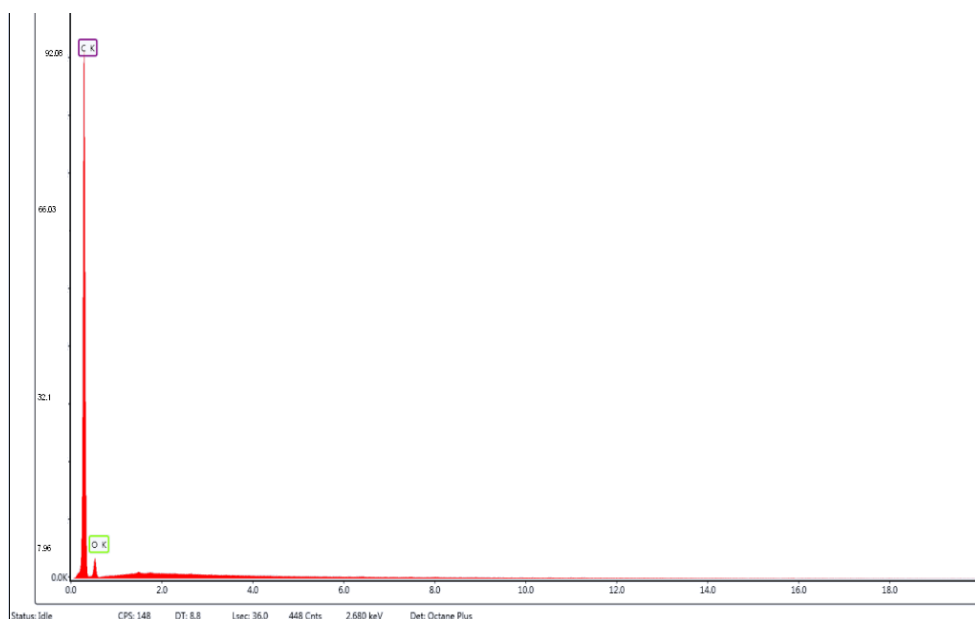


Figure (18): Elements composing the carbonized acrylic nanofiber network samples at 750°C.

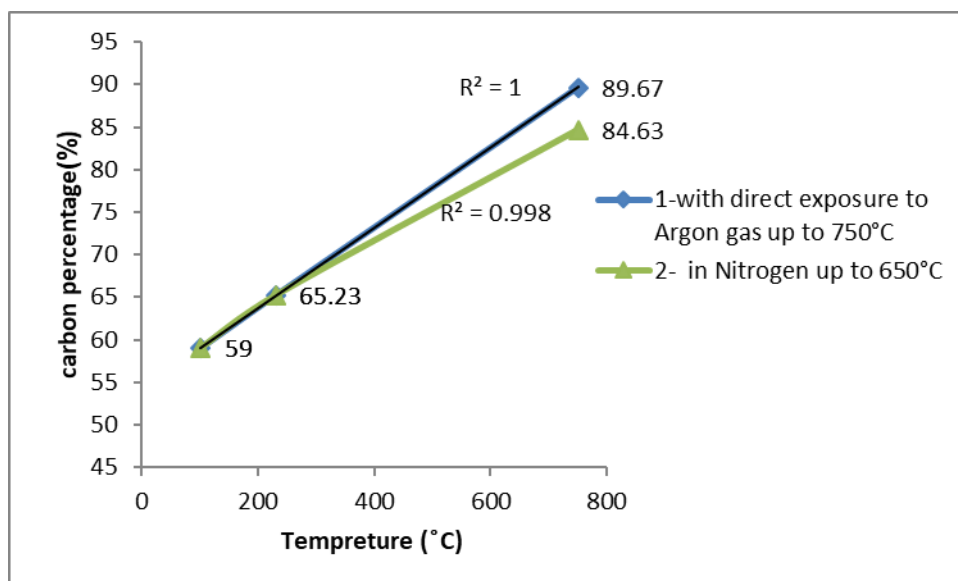


Figure (19): The relationship between the applied temperature and the carbon percentage in the sample: 1. Under direct exposure to argon gas 2. In a nitrogen atmosphere.

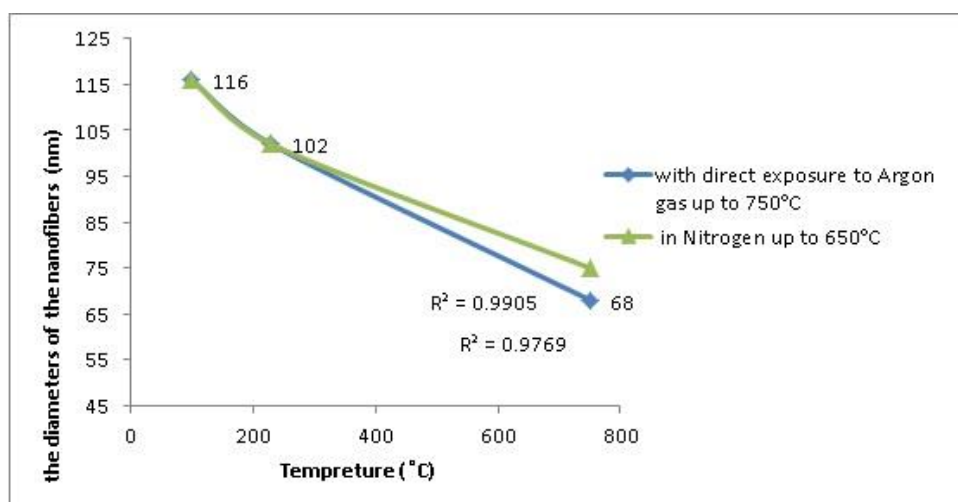


Figure (20): The relationship between the applied temperature and the diameters of the nanofibers in the sample: 1. Under direct exposure to argon gas 2. In a nitrogen atmosphere.

3- Determination of Electrical Conductivity of Carbon Nanofiber Network

The electrical conductivity of the prepared samples was measured using the four-probe device at the Higher Institute for Applied Sciences and Technology in Damascus. This device calculates specific electrical resistance based on the relationship between applied currents and the resulting voltages. The results showed that the carbon nanofiber network exhibited high electrical conductivity (84.11 S/cm).

This high conductivity is explained by the fact that the carbon compounds have SP² hybridization, where each carbon atom possesses four bonds: three sigma (σ) bonds, which are very strong and require high energy to break (responsible for the stiffness of carbon compounds), and one pi (π) bond, which is crucial as it grants carbon compounds most of their kinetic, thermal, and electrical properties. Electrons in (π) bonds are

loosely bound to the atoms and require only a small amount of energy to be excited..

CONCLUSION

- Nanofiber networks were prepared from acrylic by dissolving it in DMF and performing the electrospinning process under optimal conditions, resulting in a network with an average diameter of 116nm.
- Carbon nanofiber networks were prepared through two successive thermal treatments: thermal stabilization (at 230°C in air) and carbonization.
- The thermal stabilization process was carried out in a furnace with a gradual and slow increase in temperature to ensure structural stability during carbonization.
- The carbonization process increased the carbon content and removed most non-carbon elements.

- Carbon nanofibers with an average diameter of 75nm and a carbon percentage of 84.63% were obtained when treated in Nitrogen up to 650°C.
- Carbon nanofibers with an average diameter of 68nm and a carbon percentage of 89.67% were obtained when treated with direct exposure to Argon gas up to 750°C.
- The change in some carbonization conditions, specifically the direct exposure of the sample to pure Argon gas, enabled us to raise the carbonization temperature up to 750°C while maintaining the sample's cohesion. This led to the removal of more non-carbon elements and consequently an increase

in the sample's carbon content. Additionally, the average diameter of the nanofibers decreased as a result of the applied thermal treatments, improving the structural properties of the carbon nanofiber network.

- The average diameter of the nanofibers shrinks due to the removal of moisture, sample contraction, removal of noncarbon elements, and the transformation of the linear atomic structure of acrylic nanofibers into a cyclic structure in the carbon nanofibers (Figure 19).

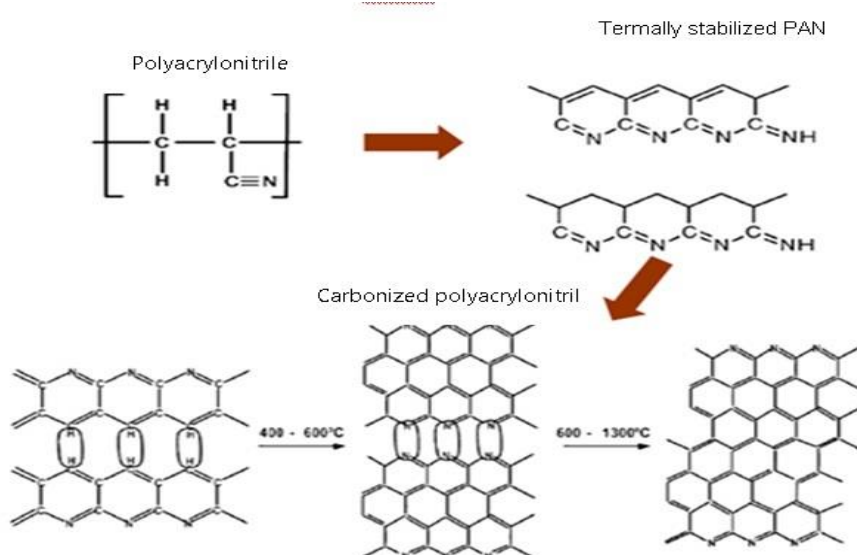


Figure (21): Change in the atomic structure of acrylic due to thermal treatments.^[16]

- The carbon nanofiber network exhibited high conductivity (84.11 S/cm). This is explained by the fact that the hybridization pattern of the bonds in carbon compounds is (sp^2), where each carbon atom in carbon compounds possesses four bonds:
 - three (σ) bonds, which are strong bonds requiring high energy to break and are responsible for the hardness of carbon compounds
 - One (π) bond, its importance lies in the fact that it imparts to carbon compounds most of their dynamic properties, such as thermal, electrical, and magnetic properties. The (π) electrons are considered weakly bound between the atoms, meaning they require a minimal amount of energy to be excited.

REFERENCES

1. Electrospun Carbon Nanofibers and Their Applications in Several Areas, Tongtong Wang, Zhe Chen, Weibo Gong, Fei Xu, Xin Song, Xin He, and Maohong Fan, ACS omega, 2023; 8: 22316–22330.
2. Recent advances in carbon nanofibers and their applications — A review, Daman Yadav, Fedi Amini, Andrea Ehrmann, European Polymer Journal, 5 September 2020; 138: 109963.
3. Stabilization and Carbonization of PAN Nanofiber Mats Electrospun on Metal Substrates, JL Storck, B Brockhagen, T Grothe, L Sabantina, B Kaltschmidt, K Tuvshinbayar, L Braun, 2021 — Journal of Carbon Research, 27 January 2021.
4. Comparative Study of Metal Substrates for Improved Carbonization of Electrospun PAN Nanofibers, Jan Lukas Storck, Martin Wortmann, Bennet Brockhagen, Natalie Frese, Elise Diestelhorst, Timo Grothe, Christian Hellert, Andrea Ehrmann. Polymers, 2022; 14(4): 721.
5. Polyacrylonitrile nanofiber optimization as precursor of carbon nanofibers for supercapacitors, Yasin Altin, Ayse Celik Bedeloglu, Department of Polymer Materials Engineering, Bursa Technical University, 16310 Bursa, TURKEY, J Inno Sci Eng, 2020, 4(2): 69–83.
6. Electrospun polyacrylonitrile (PAN) carbon nanofibers (CFNs) as electrode material for supercapacitors: A comprehensive review of synthesis, characterization, and electrochemical performance, Dadaso D. Mohite, Sachin S. Chavan, Sumit Dubal, P. B. Karandikar, AIP Advances, 2023; 13: 120703.

7. Strengthening polyacrylonitrile-based carbon nanofibers via a hydrolysis-induced low-energy-barrier cyclization reaction Gao, Xin, et al. "" Polymer, 2025; 317: 127930.
8. Effect of Thermal Stabilization on PAN-Derived Electrospun Carbon Nanofibers for CO₂ Capture, Elisa Maruccia, Stefania Ferrari, Mattia Bartoli, Lorenzo Lucherrini.
9. Optimizing the Stabilization Temperature of Electrospun PAN Fibers Used for Synthesis of Carbon Nanofibers, zahra yousefi, Nafiseh Koohestani, danesh amiri, Robabeh Abdinia, ata Kamyabi-Gol, Elham Kamali Heidari, Journal of Ultrafine Grained and Nanostructured Materials. 10.22059/JUFGNSM.2021.01.05.
10. Effects of carbonization temperature on pore development in polyacrylonitrile-based activated carbon nanofibers, Hye-Min Lee, Kay-Hyeok An and Byung-Joo Kim Institute of Carbon Convergence Technology, Jeonju 561-844, Korea 2014.
11. Effect of stabilization and carbonization treatment on the chemical and physical transformation of polyacrylonitrile (PAN) based electrospun carbon nanofibers, Krittiya Singcharoen, Ratthapol Rangkupan, Soontree Khuntong, Thanakorn Wasanapiarnpong4,5, 28 May 2024, Vietnam Academy of Science & Technology.
12. Polyacrylonitrile-based carbon nanofiber electrode fabricated via electrospun for supercapacitor application, Sumit Dubal, Sachin Chavan, Deepak Kumar, Sage Journals, February 25, 2024.
13. Carbonisation temperature dependence of electrochemical activity of nitrogen-doped carbon fibres from electrospinning as air-cathodes for aqueous-alkaline metal-air batteries, Markus Gehring, Hermann Tempel, Alexandre Merlen, Roland Schierholz, Rüdiger-A. Eichel, Hans Kungl, hal.science/hal-02314100, 15 Jul 2024.
14. Carbonization-Temperature-Dependent Electrical Properties of Carbon Nanofibers—From Nanoscale to Macroscale. J Borowec, V Selmert, A Kretzschmar, Advanced Materials, 27 April 2023.
15. Assessing the Effect of Stabilization and Carbonization Temperatures on Electrochemical Performance of Electrospun Carbon Nanofibers from Polyacrylonitrile, F Boll, M Crisci, L Merola, F Lamberti, Advanced Energy, 2023 – Wiley Library.
16. Chronological effects of oxygen on the structural transformations of polyacrylonitrile fibers during the rapid thermal stabilization process. Li, Shiyang, et al. "" RSC advances, 2024; 14.48: 35560-35567.