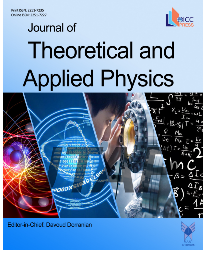

Volume 18, Issue 6, 182482 (1-8)

Journal of Theoretical and Applied Physics (JTAP)

https://dx.doi.org/10.57647/j.jtap.2024.1806.82

Identify the color of pollution with fabrication of nanofibers for smart masks containing antibacterial nanoparticles and photoluminescence

Amir Hoshang Ramezani[1,*], Zhaleh Ebrahiminejad[1], Somayeh Asgary[1], Laya Dejam[1], Kasra Behzad[2]

[1] *Physics Department, West Tehran Branch, Islamic Azad University, Tehran, Iran.*
[2] *Department Of Physics, Saxion University, Enschede, Overijssel, Netherlands.*

*Corresponding author: ah.ramezani@wtiau.ac.ir

Original Research

Received:
9 October 2024
Revised:
5 November 2024
Accepted:
20 November 2024
Published online:
30 December 2024

Abstract:
This work presents a comprehensive investigation into the fabrication and characterization of nanofibers comprising silver nanoparticles and carbon nanoparticles. The nanofibers were synthesized through the electrospinning method, employing a range of voltages (5 to 20 kV) to explore their structural and functional variations. Analytical techniques, including XRD, SEM, UV-VIS, and (PL), were employed to scrutinize the nanofiber structure and properties.
The XRD analysis exposed distinct crystal planes in silver nanoparticles. Antibacterial tests revealed the remarkable antibacterial properties of these nanofibers, showcasing their efficacy in inhibiting the growth of coliform and pseudomonas bacteria. Furthermore, the PL spectroscopy of nanofibers containing silver nanoparticles and carbon nanoparticles were critically evaluated, considering the impact of pollution and bacteria on the nanofiber's photoluminescence. The findings open new avenues for controlling and preventing the spread of diseases, offering innovative solutions for respiratory protection in the face of environmental challenges.

Keywords: Nanofibers; Luminous carbon; Antibacterial silver; Smart mask; Photoluminescence; Electrospinning

1. Introduction

Nanofibers have garnered significant attention owing to their exceptional characteristics. In contrast to traditional fibrous structures, nanofibers exhibit lightweight properties possess small diameters, controllable pore structures, and a high surface-to-volume ratio. These attributes make nanofibers well-suited for diverse applications, including but not limited to filtration, sensors, protective clothing, tissue engineering, functional materials, and energy storage [1–5]. The exploration of novel composite nanofibers presents even greater potential, and there is a growing interest in investigating new polymer composite nanofibers to expand their multifunctional capabilities and improve both their physical and chemical properties. Polymer composite nanofibers typically encompass two or more composites, encompassing polymer/polymer composite nanofibers, polymer/nanoparticle composite nanofibers, and polymer/inorganic salts composite nanofibers, among other variations [6].

Face masks, like surgical masks, consist of multiple layers based on polymer. The outer layers are made of non-woven fabric between 20 and 50 grams per square meter, to create a barrier against moisture. In addition, a higher density layer of about 250 g/m is used to provide more rigidity and thickness to the face mask. Compared to surgical masks, face masks are tighter and stick to the face more to prevent inhalation of droplets and smaller particles [7–11].

Nanotechnology of masks allows eliminating the disadvantages of traditional surgical masks such as microbial growth and low filtration efficiency [12]. The use of a functionally intelligent hierarchical nanostructured material provides amazing new features for the face mask, including: light activation, on-demand pathogen removal, effective filtration, moisture control and the possibility of digital personalization of the final respirator [13]. A research study has shown that electrospinning is the most efficient method to obtain fibers based on synthetic or natural polymers with a nanoscale size that provide significant performance in terms of particle filtering and breathability [14].

The researches show that the Poly (L-lactic acid) (PLLA) piezoelectric nanofibers are used to make reusable, moisture-resistant and highly effective face mask filters with long-term biodegradability. PLLA filter can provide an environmentally friendly solution to prevent the transmission of highly infectious viruses and solve the environmental crisis caused by the widespread use of current plastic face mask permanent filters [15]. Mass production of polymer-based respirators during the Covid-19 pandemic has rekindled the issue of environmental pollution from non-recyclable plastic waste. To reduce this problem, conventional filters should be redesigned with improved filtration performance during their operational lifetime, while at the end they degrade naturally [16]. Other results have shown that the multi-functional mask can also monitor breathing status wirelessly and in real-time and collect breathing data for epidemiological analysis [17]. In another research, an easy and simple method for creating biodegradable and self-disinfecting masks based on collagen fiber networks has been presented. These masks not only provide excellent protection against a wide range of hazardous substances in polluted air, but also address environmental concerns associated with waste disposal [18].

Flexible piezoelectric and electrostatic (including triboelectric and electret) nanogenerators offer general and useful routes to transfer mechanical energy from body actions (including walking, arm movement, finger movement, and breathing) to electricity to build self-powered systems. Typically, flexible electrical nanogenerators, with the basic working mechanism of electrostatic induction due to excess charges retained in the electret material, have significant advantages in output performance, low cost to manufacture, and a wide range of applications, etc. In a specific research, a self-powered smart face mask introduced consisting of an electrical nanogenerator with a sandwich structure with electrospun polyetherimide (PEI) as the electret material. Due to the additional charges in the PEI non-woven fabric, the smart face mask has two functions of effectively removing suspended particles during the inhalation process and harvesting the energy generated from exhalation [19].

New results have shown that using a “smart mask” to monitor human physiological signals is very useful for personal and public health [20] and [21]. A smart mask can be a truly advanced device that expands knowledge on health monitoring to reach the next level of wearables. A smart mask can also measure air pollution and several other environmental variables such as air quality, temperature and humidity [22] and [23]. In the present work, the goal is to make nanofibers for smart masks with antibacterial and photoluminescence properties. The results and analyzes of the tests conducted using various techniques and antibacterial tests with coliform and pseudomonas bacteria will be carefully have been reviewed. The crystalline structures of deposited thin films are studied by using STOE SIADI MP X-ray diffractometer for 2θ values up to 80° with Cu Kα radiation (1.5405 Å) as the source of X-ray radiation. The optical behavior of the produced was immediately characterized using a ultraviolet–visible (UV–Vis) spectrophotometer (CARY 500, Varian) in the range of 200 – 1100 nm. All spectra were measured at room temperature in a quartz cell with 10 mm optical path. SEM images were taken on KYKY-EM 3200 microscope operating at 25 kV accelerating voltage. The EDX spectrum along with the eZAF Smart quantitative results was recorded by using the TEAM EDX system attached to the SEM.

The surface of the prepared MoS2 NPs was considered by a FT-IR spectrophotometer Nexus 870 (Thermo Nicolet USA) in themid-IR region (4000–400 1/cm).

2. Materials and method

The manufacturing method of nanofibers used in smart masks containing antibacterial nanoparticles and photoluminescence in order to identify the color of pollution is as follows (Fig. 1):

1. Synthesis of carbon nanoparticles (luminescent carbon dots):

- Citric acid is available from lemons. Mix this citric acid with ethylene diamine in 500 mL of deionized water at a molar ratio of one to one.
- Place the mixture in an autoclave reactor and pressurize it for 72 hours at 250 °C.
- The result of the synthesis will be carbon nanoparticles (light-emitting carbon dots) which are used as light-emitting material in smart masks.

2.1 Synthesis of silver nanoparticles (antibacterial silver dots)

Silver nanoparticles were synthesized via an ultrasonic method, involving the combination of silver with a solu-

Figure 1. Citric acid solution obtained from lemons, which is placed in an autoclave.

tion followed by ultrasound application to form nanoparticles. To enhance their properties, purification was achieved through washing with different solvents and utilizing a Buchner funnel. The synthesis process involved the preparation of a silver nitrate solution using lactose as a masking agent. Deposition of silver nanoparticles was facilitated by 5 M ammonia as a precipitation agent, applying 200 W ultrasonic waves at 80 °C for one hour. Optimal power ensured the formation of silver oxide layers on silver. Washing with water, ethanol and then drying at 50 °C removed impurities and residual solvents. A power of 200 watts was deemed suitable to prevent impurity and oxidation during silver nanoparticle synthesis. In contrast, a power of 1000 W was utilized for carbon nanoparticle preparation due to the absence of similar concerns. The finalized silver nanoparticles are now ready for integration into nanofiber manufacturing.

2.2 Preparation of nanofibers

The preparation of nanofibers incorporating carbon and silver nanoparticles involves the electrospinning method. In this process, a solution containing a mixture of carbon and silver nanoparticles is jetted through a spinning element, applying voltage on polymer salts to form fibers. The resulting nanofibers exhibit uniform distribution of carbon and silver nanoparticles within their structure. These nanofibers, characterized by antibacterial properties, serve a dual purpose by easily identifying pollution color through photoluminescence. Upon contact with a pollutant, the nanofibers absorb light corresponding to the pollutant's color, emitting photoluminescence that enables precise pollutant color detection. To ensure the nanoquantization of carbon plates post-reactor and washing, ultrasonic waves with a power of 1000 watts are applied for 60 minutes. This ultrasonic treatment serves as a method to confirm and validate the nanoquantity of the samples. The carbon dots within the carbon sheets composed of single-layer graphene sheets, exhibit nanoscale dimensions in three directions. These particles possess extreme quantum dot characteristics, showcasing unique luminescence colors due to quantization and discretization of electron levels. The quantum electronic and optical properties of these carbon sheets, including luminescence colors, make them valuable for diverse applications in nanoelectronics, nanophotonics, and other fields of nanotechnology.

2.3 Preparation of nanofibers based on polyvinyl acetate for use in smart masks

In this method, polyvinyl acetate-based nanofibers are prepared for smart mask applications. Initially, a polyvinyl acetate solvent is created by dissolving three grams of polyvinyl acetate in 30 mL of acetone. Subsequently, carbon and silver nanoparticles are added in appropriate amounts to the solvent based on required weight percentages. The solution undergoes treatment in a Peruvian ultrasonic bath, applying weak waves to both the polyvinyl acetate solvent and the sample containing carbon and silver dots. Following this, the composite solution is introduced into electrolysis, applying voltages ranging from 5 to 20 kV with a nozzle-to-collector distance of 20 cm. The resulting nanofibers, exhibiting yellow and gray colors due to silver, are collected on aluminum foil, forming a thin layer resembling paper towels after excess material is removed. This nanofiber layer is ready for use in the fabrication of smart masks with antibacterial and photoluminescent properties, showcasing the transformation of the initially white polymer to an orange hue upon the addition of nanoparticles. The process is illustrated in Fig. 2.

3. Analysis and results

In this section, we will meticulously examine the results and analyses derived from experiments conducted using diverse techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM), ultraviolet-visible (UV-VIS) spectroscopic analysis, photoluminescence (PL) spectroscopy, and antibacterial tests involving two bacteria strains, coliform and Pseudomonas. These findings bear a significant relevance to the primary aim of the research, which revolves around the fabrication of nanofibers designed for smart masks endowed with antibacterial and photo luminescent properties.

3.1 X-ray diffraction pattern

In this section, we delve into the investigation of the crystal structure of nanomaterials utilizing the X-ray diffraction (XRD) technique. The outcomes of this analysis play a pivotal role in enhancing our comprehension of the crystalline properties and atomic structure of nanoparticles utilized in mask production. Figure 3 depicts the X-ray diffraction pattern of silver nanoparticles. The prepared sample exhibits four distinct peaks in the X-ray diffraction pattern, corresponding to the crystal planes (111), (200), (220), and (311) of the face-centered cubic (FCC) structure. The FCC structure, a subtype of cubic crystal structures, is commonly observed in metallic and semi-metallic materials, where

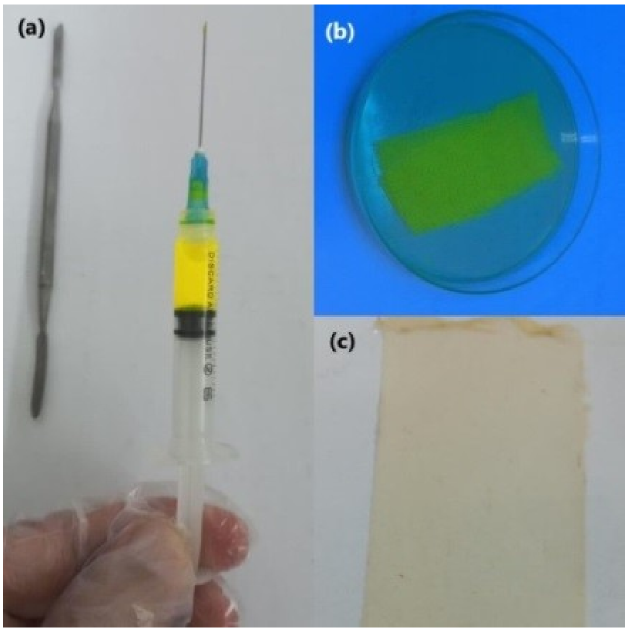

Figure 2. (a) The composite solution is placed in the syringe. (b) Polyvinyl acetate nanofiber containing yellow and silver gray nanoparticles (c) Nanocomposite spun polymer.

2251-7227[https://dx.doi.org/10.57647/j.jtap.2024.1806.82]

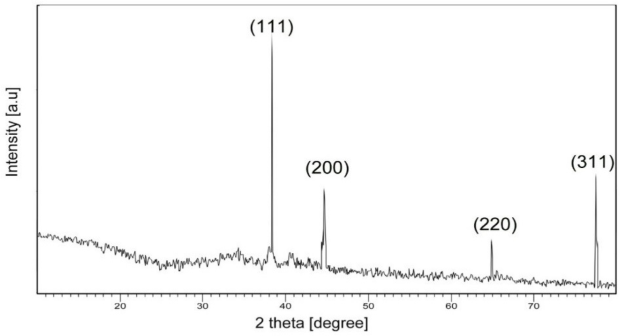

Figure 3. X-ray diffraction pattern of silver nanoparticles.

atoms are precisely concentrated at specific points in space. In Figure 4, X-ray diffraction pattern of the carbon dot sample, a broad peak is evident at an angle of 23 degrees, corresponding to the (002) plane. Essentially, the XRD results reveal an incomplete crystal structure and the presence of crystal defects in the carbon dot sample, attributed to the observed peak width and increased layer-to-layer distance. These findings align with the selected-area electron diffraction (SAED) pattern and collectively indicate the lower quality of carbon dot crystals.

3.2 Optical microscope images

Analyzing optical microscope images of nanofibers under varying voltages (10, 5, and 18 kV) reveals crucial insights into their characteristics. The increase in voltage is anticipated to enhance the microscopic display of nanofiber details, as evidenced by Figure 5 (a, b, c), showcasing clearer details with higher voltage. This voltage modulation also influences the structure and properties of nanofibers, potentially altering their shapes and indices, as observed in the three provided images. Moreover, fluctuations in voltage impact sediments and suspended particles within the nanofiber environment, distinctly visible in the images. In conclusion, a comparative analysis indicates that the 18 kV image surpasses the 5 kV image in precisely depicting nanofiber details, suggesting an enhancement in image accuracy with increased voltage.

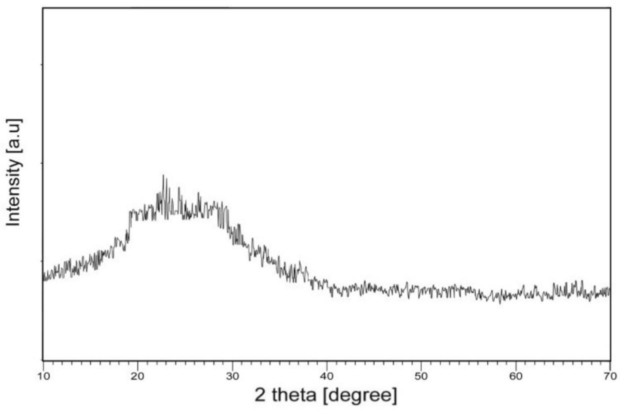

Figure 4. X-ray diffraction pattern of carbon dot.

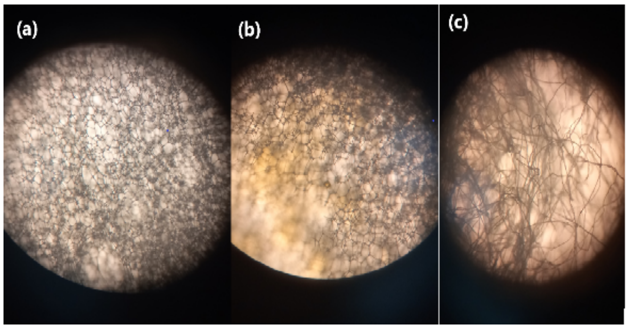

Figure 5. Optical microscope image of nanofibers with applied voltage: (a) 5, (b) 10, and (c) 18 kV.

3.3 Scanning electron microscope images

Scanning Electron Microscope (SEM) images serve as a valuable tool to elucidate the surface structure and morphology of nanofibers, offering detailed insights into their shape, size, and surface compositions (Figs. 6,7,8). In Figure 6 a, the SEM image showcases silver nanoparticles, meticulously prepared at a 500 nm scale, exhibiting a regular and closely aligned arrangement. The average crystal size of these nanoparticles is measured to be approximately 50 nm. Figure 6 b, further presents an SEM image depicting carbon quantum dot particles with an average size of 60 nm and dimensions of 500 nm. Notably, this image reveals a homogeneous distribution of particles, underscoring their uniform appearance within the specified dimensions.
In the fabrication of nanofibers for this study, the electrospinning method was employed, incorporating carbon and silver nanoparticles. This intricate process involved applying voltages of 5, 10, and 18 kV to polymer salts, facilitating the uniform integration of carbon and silver nanoparticles within the formed fibers. The synthesis of silver nanoparticles encompassed the preparation of a silver nitrate solution, followed by precipitation through ammonia, and subsequent washing and drying stages. Notably, different voltage levels were crucial in applying waves to polymer salts for effective fiber formation. Furthermore, a power of 200 watts was applied during the ultrasonic wave synthesis of nanofibers. The experimental results suggest that the application of higher voltage leads to the production of nanofibers with

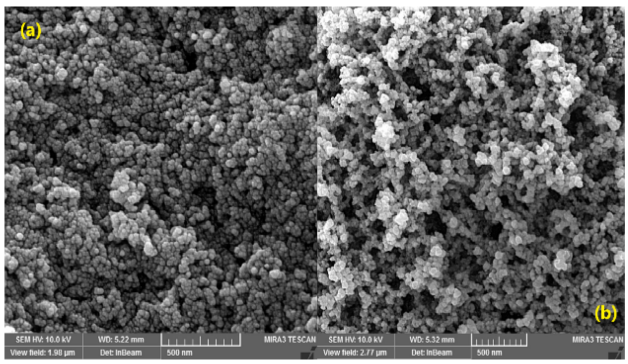

Figure 6. (a) Scanning electron microscope image of silver nanoparticles. (b) Carbon quantum dot scanning electron microscope image.

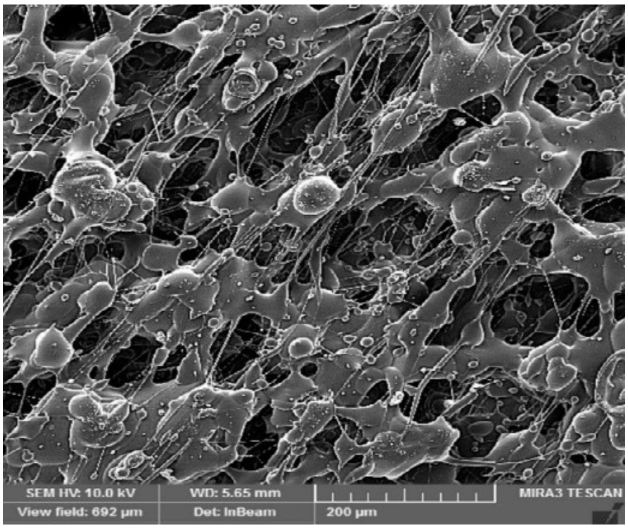

Figure 7. Scanning electron microscope image of nanofibers with 5 kV applied voltage.

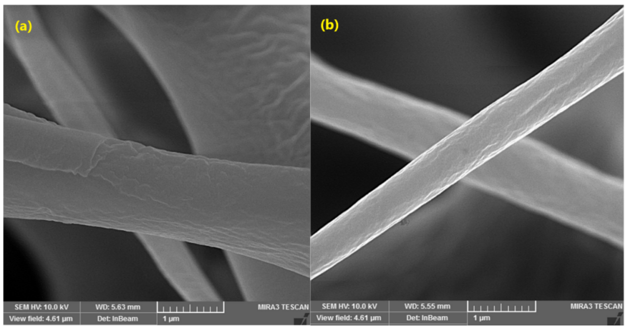

Figure 8. The image of the scanning electron microscope of nanofibers with voltage (a) of 10 and (b) of 18 kV.

reduced thickness, highlighting the intricate relationship between voltage levels and nanofiber dimensions.

3.4 Ultraviolet Visible Spectroscopic analysis (UV-Vis)

The optical characteristics of the nanoparticles were scrutinized through UV-VIS spectroscopy as is presented in Fig. 9. The depicted peak in the spectrum, observed at a wavelength of 530 nm, signifies a green hue. Quantum dot carbon exhibits fluorescence properties, absorbing light energy at specific wavelengths and reflecting light at longer wavelengths. Typically, these carbon dots display light absorption in the UV region, extending into the visible range with a characteristic tail. This distinctive behavior underlines the capacity of quantum dot carbon to interact with light in a unique manner, demonstrating potential applications in various optical and photonic contexts.

3.5 Photoluminescence spectroscopy (PL)

The utilization of the photoluminescence technique provides valuable insights into the light-induced emission of nanomaterials, facilitating an in-depth exploration of their optical and electronic properties. In Figure 10, the photoluminescence spectroscopy of nanofibers, comprising silver and carbon nanoparticles, is presented, offering a unique perspective on the impact of pollution and bacteria on the

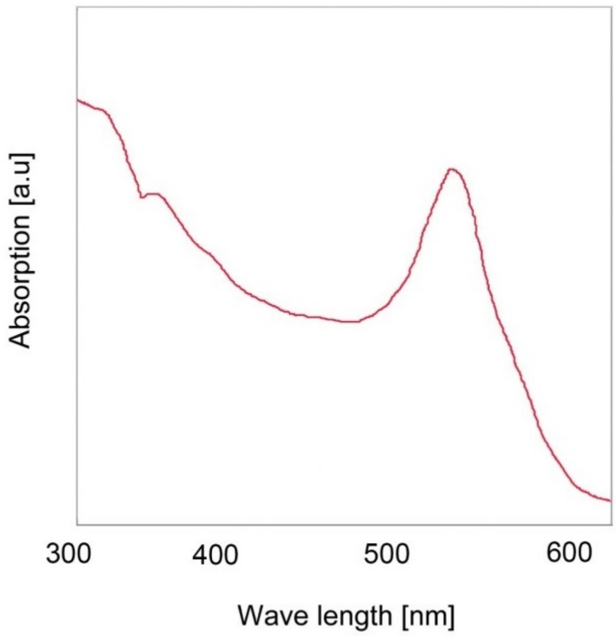

Figure 9. visible-ultraviolet spectroscopy of nanofibers composed of silver nanoparticles and carbon nanoparticles.

luminescence of smart masks. This serves as a crucial indicator in understanding the response of nanofibers to external disturbances, such as bacteria or metal and heavy ion infiltration, which excite electrons and induce light absorption. The main red diagram in the figure encapsulates the photoluminescence spectroscopy of nanofibers, providing insights into their optical and electronic characteristics. Additionally, the two accompanying green and blue graphs, exhibiting lower energy levels, likely signify distinct effects

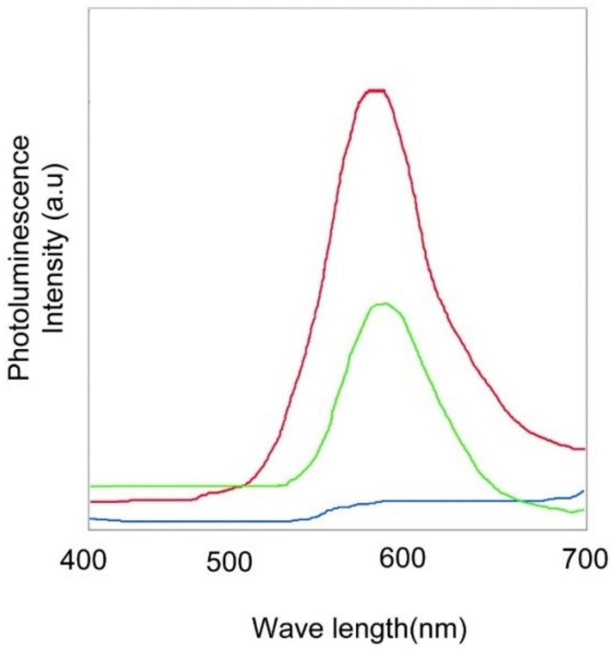

Figure 10. Photoluminescence measurement of nanofibers consisting of silver nanoparticles and carbon nanoparticles.

of pollution and bacteria on luminescence, further enhancing our comprehension of the material's behavior in varied environmental conditions.

3.6 Explanations about testing with bacteria

Red sample: pure sample without contamination or bacteria, whose luminescence is preserved.
Green sample: a small amount of bacteria has been added to the sample, which reduces the luminescence.
Off sample (blue): A large amount of coliform bacteria has been added to the sample, and its luminosity has decreased and turned off. In general, it can be concluded that during the experiments by adding bacteria to the samples, changes in luminescence were observed and these nanofibers may have been used as an indicator to detect contamination or the presence of bacteria in the environment.

3.6.1 Antibacterial test process

The antibacterial testing process involved the selection of two model bacteria, coliform, and pseudomonas, to assess the efficacy of nanofibers. Nanofibers, incorporating silver and carbon nanoparticles, were applied to discs, which were subsequently placed on a culture medium (Figs 11a and b). The formation of halos around these discs was indicative of the antibacterial effect, with the observed halos signifying inhibited bacterial growth in the vicinity of the nanofiber-impregnated discs. This antibacterial property holds significant promise for diverse applications, notably in the production of smart masks with enhanced antibacterial features. Notably, the comparison of halos between Pseudomonas and coliform bacteria revealed variations in sensitivity, offering valuable insights into the nanofibers' differential effectiveness against distinct bacteria types. This information is instrumental in guiding material selection for the production of antibacterial products tailored to combat a range of bacterial strains.

4. Conclusion

In conclusion, this study focused on the fabrication and characterization of nanofibers incorporating silver and carbon nanoparticles for potential applications in smart masks with antibacterial and photoluminescent properties. Various analytical techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM), UV-VIS spectroscopy, and photoluminescence (PL) spectroscopy, were employed to assess the crystal structure, morphology, and optical features of the nanomaterials. The XRD analysis revealed distinct crystal planes in silver nanoparticles, while SEM images illustrated the surface structure and particle distribution in both silver and carbon nanoparticles. UV-VIS spectroscopy highlighted the unique optical properties of the nanoparticles, emphasizing their potential in fluorescence applications. Photoluminescence spectroscopy further explored the impact of pollution and bacteria on the luminescence of the nanofibers, providing insights into their response to external stimuli. Antibacterial tests demonstrated the efficacy of nanofibers in inhibiting bacterial growth, particularly noteworthy for smart mask applications. The observed variations in sensitivity between different bacterial strains underscored the potential for tailored antibacterial solutions. Overall, this comprehensive exploration of nanofiber properties opens avenues for the development of advanced materials with diverse applications in nanotechnology and healthcare.

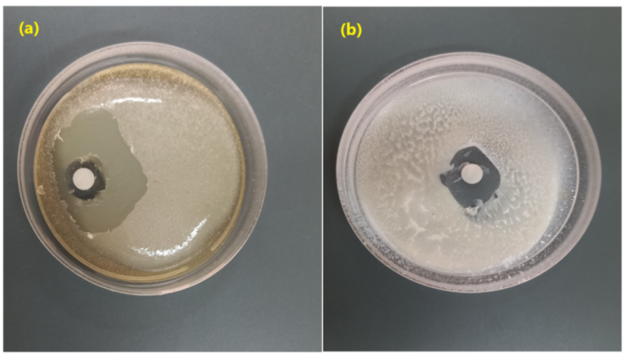

Figure 11. Bacteria (a) pseudomonas, (b) coliform.

Authors contributions
All authors conceived of the study, participated in its design and coordination, drafted the manuscript, participated in the sequence alignment, and read and approved the final manuscript.

Availability of data and materials
The data that support the findings of this study are available on request from the corresponding author.

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

References

[1] Z. M. Huang, Y. Z. Zhangb, M. Kotakic, and S. Ramakrishna. "A review on polymer nanofi bers by

electrospinning and their applications in nanocomposites.". *Composites Science and Technology*, **63**: 2223–53, 2003. DOI: https://doi.org/10.1016/S0266-3538(03)00178-7.

[2] M. Bognitzki, W. Czado, T. Frese, A. Schaper, M. Hellwig, M. Steinhart, et al. "Nanostructured fibers via electrospinning. ". *Advanced Materials*, **13**:70–72, 2013. DOI: https://doi.org/10.1002/1521-4095(200101)13:1<70::AID-ADMA70>3.0.CO;2-H.

[3] S. W. Choi, S. M. Jo, W. S. Lee, and Y.-R. Kim. "An electrospun poly(vinylidene fl uoride) nanofi brous membrane and its battery applications. ". *Advanced Materials*, **15**:2027–32, 2003. DOI: https://doi.org/10.1002/adma.200304617.

[4] G. M. Kim, G. H. Michler, F. Ania, and F. J. B. Calleja. "Temperature dependence of polymorphism in electrospun nanofi bres of PA6 and PA6/clay nanocomposite. ". *Polymer*, **48**:4814–23, 2007. DOI: https://doi.org/10.1016/j.polymer.2007.05.082.

[5] L. Huang, R. A. McMillan, R. P. Apkarian, B. Pourdeyhimi, V. P. Conticello, and E. L. Chaikof. "Generation of synthetic elastin-mimetic small diameter fibers and fiber networks. ". *Macromolecules*, **33**:2989–97, 2000. DOI: https://doi.org/10.1021/ma991858f.

[6] V. S. Naragund and P. K. Panda. "Electrospun nanofiber-based respiratory face masks-A review.". *Emergent Materials*, **5**:261–278, 2022. DOI: https://doi.org/10.1007/s42247-022-00350-6.

[7] W. Essa, S. Yasin, I. Saeed, and G. Ali. "Nanofiber-based face masks and respirators as COVID-19 protection: a review. ". *Membranes*, **11**:250, 2021. DOI: https://doi.org/10.3390/membranes11040250.

[8] Z. Zhang, D. Ji, H. He, and S. Ramakrishna. "Electrospun ultrafine fibers for advanced face masks.". *Mater. Sci. Eng. R Rep.*, **143**:100594, 2021. DOI: https://doi.org/10.1016/j.mser.2020.100594.

[9] I. Armentano, M. Barbanera, E. Carota, S. Crognale, M. Marconi, S. Rossi, G. Rubino, M. Scungio, J. Taborri, and G. Calabro. "Polymer materials for respiratory protection: processing, end use, and testing methods. ". *ACS Appl. Polym. Mater.*, **3**:531–548, 2021. DOI: https://doi.org/10.1021/acsapm.0c01151.

[10] S. Das, S. Sarkar, A. Das, S. Das, P. Chakraborty, and J. Sarkar. "A comprehensive review of various categories of face masks resistant to Covid-19. ". *Clinical Epidemiology and Global Health*, **12**:100835, 2021. DOI: https://doi.org/10.1016/j.cegh.2021.100835.

[11] S. Rossettie, C. Perry, M. Pourghaed, and M. Zumwalt. "Effectiveness of manufactured surgical masks, respirators, and home-made masks in prevention of respiratory infection due to airborne microorganisms. ". *Chronicles*, **8**:11–26, 2020. DOI: https://doi.org/10.12746/swrccc.v8i34.675.

[12] A. Maher, M. S. Abdo, and H. S. Abdo. "Nanotechnology-enhanced face masks: future scopes and perspectives. ". *Advances in Materials Science and Engineering*, , 2022. DOI: https://doi.org/10.1155/2022/1497910.

[13] L. De Sio, B. Ding, M. Focsan, K. Kogermann, P. Pascoal-Faria, F. Petronela, and F. Pierini. "Personalized reusable face masks with smart nano-assisted destruction of pathogens for COVID-19: A Visionary Road. ". *Chemistry–A European Journal*, **27**:6112–6130, 2021. DOI: https://doi.org/10.1002/chem.202004875.

[14] A. Cimini, E. Imperi, A. Picano, and M. Rossi. "Electrospun nanofibers for medical face mask with protection capabilities against viruses: State of the art and perspective for industrial scale-up. ". *Applied Materials Today*, **32**:101833, 2023. DOI: https://doi.org/10.1016/j.apmt.2023.101833.

[15] T. T. Le, E. J. Curry, T. Vinikoor, R. Das, Y. Liu, D. Sheets, K. T. M. Tran, C. J. Hawxhurst, J. F. Stevens, et al. "Piezoelectric nanofiber membrane for reusable, stable, and highly functional face mask filter with long-term biodegradability.". *Advanced Functional Materials*, **32**:2113040, 2022. DOI: https://doi.org/10.1002/adfm.202113040.

[16] Y. Cho, Y. Son, J. Ahn, H. Lim, S. Ahn, J. Lee, et al. "Multifunctional filter membranes based on self-assembled core–shell biodegradable nanofibers for persistent electrostatic filtration through the triboelectric effect. ". *ACS nano*, **16**:19451–19463, 2022. DOI: https://doi.org/10.1021/acsnano.2c09165.

[17] F. Zhang, J. Lin, M. Yang, Y. Wang, Z. Ye, J. He, et al. "High-breathable, antimicrobial and water-repellent face mask for breath monitoring.". *Chemical Engineering Journal*, **466**:143150, 2023. DOI: https://doi.org/10.1016/j.cej.2023.143150.

[18] A. H. Ramezani, S. Hoseinzadeh, and Zh. Ebrahiminejad. "Statistical and fractal analysis of nitrogen ion implanted tantalum thin films.". *Applied Physics A*, **126**:481, 2020. DOI: https://doi.org/10.1007/s00339-020-03671-7.

[19] Y. Cheng, C. Wang, J. Zhong, S. Lin, Y. Xiao, Q. Zhong, et al. "Electrospun polyetherimide electret nonwoven for bi-functional smart face mask.". *Nano Energy*, **34**:562–569, 2017. DOI: https://doi.org/10.1016/j.nanoen.2017.03.011.

[20] A. H. Ramezani, M. R. Hantehzadeh, M. Ghoranneviss, and E. Darabi. "Structural modification of tantalum crystal induced by nitrogen ion implantation. ". *Bulletin of Materials Science*, **39**:633–640, 2016. DOI: https://doi.org/10.1007/s12034-016-1212-0.

[21] P. Zhao, R. Wang, J. Xiang, J. Zhang, X. Wu, C. Chen, and G. Liu. "Antibacterial, antiviral, and biodegradable collagen network mask for effective particulate removal and wireless breath monitoring. ". *Journal of Hazardous Materials*, **456**:131654, 2023. DOI: https://doi.org/10.1016/j.jhazmat.2023.131654.

[22] J. Suo, Y. Liu, C. Wu, M. Chen, Q. Huang, Y. Liu, et al. "Wide-bandwidth nanocomposite-sensor integrated smart mask for tracking multiphase respiratory activities. ". *Advanced Science*, **9**:2203565, 2022. DOI: https://doi.org/10.1002/advs.202203565.

[23] P. Lee, H. Kim, Y. Kim, W. Choi, M. S. Zitouni, A. Khandoker, et al. "Beyond pathogen filtration: Possibility of smart masks as wearable devices for personal and group health and safety management. ". *JMIR mHealth and uHealth*, **10**:38614, 2022. DOI: https://doi.org/10.2196/38614.