




Exploring the morphological surface resistance and optical absorption of thin black carbon nanotube films for electronic and optoelectronic devices

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Received: 28 December 2023

Accepted: 27 February 2024

Published online:
21 March 2024

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ABSTRACT

This study investigates the optical and electrical properties of thin black films of carbon nanotubes (CNTs) fabricated under various conditions to explore their potential integration as either a perfect broadband absorber or enhanced counter electrode. The study involves SEM measurements, surface resistance measurements, and UV–Vis. spectrometer analysis. The results show that the CNT thin films exhibit high electrical conductivity and strong light absorption across various wavelengths. Optically, we investigated the impact of varying the growth temperature and catalyst temperature on the absorption profile of the thin films. The fabricated and deposited CNTs showed broadband absorption spectra, reaching 92.8% of the commercial reference sample, covering both visible and near-infrared spectra. Alternatively, the morphological surface resistance for the CNT thin films recorded agonist commercial CNT samples and FTO-coated glass. An average surface resistance of 20.5 Ω /Sq.

1 Introduction

Carbon nanotubes (CNTs) have garnered significant attention in electronic and optoelectronic devices due to their exceptional electrical, optical, and mechanical properties [1, 2]. Thin black films of CNTs have emerged as promising materials for various applications, including perfect broadband absorbers and counter electrodes [3, 4].

CNTs have garnered significant interest for their potential utilization as black absorbers in optoelectronic devices [1, 5–7]. The unique structural and electronic properties of CNTs enable them to efficiently absorb light across a broad spectrum, ranging from ultraviolet to infrared wavelengths [7]. This exceptional light absorption capability, coupled with their high electrical conductivity, makes CNTs promising candidates for enhancing the performance of optoelectronic devices such as photodetectors [6], solar cells

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[5], and light-emitting diodes [4, 8]. Using CNTs as black absorbers holds great promise for improving the efficiency and functionality of optoelectronic devices, paving the way for advanced applications in energy harvesting, sensing, and photonics.

Alternatively, CNTs have emerged as auspicious materials for utilization as electrodes in electronic devices due to their exceptional electrical, mechanical, and thermal properties [1, 9–12]. The high electrical conductivity of CNTs, along with their large surface area and mechanical flexibility, makes them well-suited for various electrode applications [13]. CNT electrodes have been explored in a wide range of electronic devices, including supercapacitors [4, 11, 12], batteries [14], sensors [15], and transistors [16]. Their high aspect ratio and unique one-dimensional structure enable efficient charge transport and provide a large active surface area for electrochemical reactions [15]. Additionally, CNT electrodes' mechanical robustness and chemical stability contribute to their long-term reliability and performance in electronic devices [17]. Furthermore, the tunable electronic properties of CNTs, achieved through doping or functionalization, offer opportunities for tailoring the electrode characteristics to meet specific device requirements [18].

The innovation in this study lies in the comprehensive investigation of the optical and electrical properties of thin black films of carbon nanotubes under various growth conditions, focusing on their potential integration as either a perfect broadband absorber or enhanced counter electrode in electronic and optoelectronic devices. The combination of SEM measurements, surface resistance measurements, and UV-Vis spectrometer analysis provides a holistic understanding of the CNT thin films. The research delves into the impact of growth and catalyst temperatures on the absorption profile of the thin films, revealing their strong light absorption across a wide range of wavelengths with broadband absorption spectra. Furthermore, the exploration of morphological surface resistance, which recorded competitive values against commercial CNT samples and FTO-coated glass, highlights the potential of the CNT thin films for high-performance electronic and optoelectronic applications. This comprehensive approach to characterizing and understanding the properties of CNT thin films under varying growth conditions contributes to advancing knowledge in the field. It offers valuable insights for

the development of next-generation electronic and optoelectronic devices.

2 Experimental work

Carbon nanotubes (CNTs) have been widely studied due to their unique mechanical, electrical, and thermal properties. Various techniques are employed in the growth of carbon nanotubes, including chemical vapor deposition (CVD) [19], arc discharge [20], laser ablation [21], and others [22]. The choice of technique significantly impacts the quality, structure, and properties of the nanotubes produced [22]. Temperature plays a crucial role in the growth process [22–24], influencing the growth rate, diameter, chirality, and alignment of the nanotubes. Higher temperatures typically lead to faster growth rates but can also affect the structural quality and purity of the nanotubes [24]. Optimal temperature control is essential to achieve the desired properties and characteristics of carbon nanotubes during their synthesis [22–24]. Herein, we investigate different conditions for the growth of CNTs. The growth of CNTs typically involves using a catalyst, such as iron, nickel, or cobalt, which is deposited on a substrate and then heated to a high temperature in the presence of a carbon source, such as acetylene or ethylene [25]. The growth conditions, mainly the temperature of the catalyst (T_c) and the growth temperature (T_g), significantly affect the morphology and properties of the resulting CNTs [25]. Other factors, including the use of preheating and different catalyst holders, also impact the growth of CNTs. The current study is interested in exploring the electrical and optical variations observed by varying all these growth conditions, as illustrated in the next section.

Various methods can be used to deposit thin black films of CNTs on microscopic glass substrates, including but not limited to spin-coating, dip-coating, or spray-coating. This study uses a spin-coater, WS-650-23 Spin Coater while considering p-doped Si-wafer as the substrate. A suspension containing CNTs is deposited onto the substrate and then spun at high speeds to distribute the CNTs evenly; see the recipe in [26]. After deposition, the CNT thin film is annealed at high temperatures to improve its properties and adhesion to the substrate. The output thin black film is demonstrated in Fig. 1a, with a zoomed demonstration in Fig. 1b.

Fig. 1 **a** A series of fabricated thin black films of CNT on a p-doped silicon substrate, and **b** thin black film in a magnified image

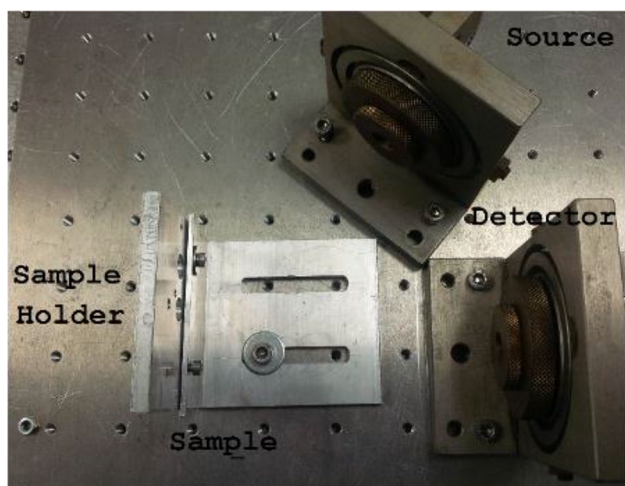
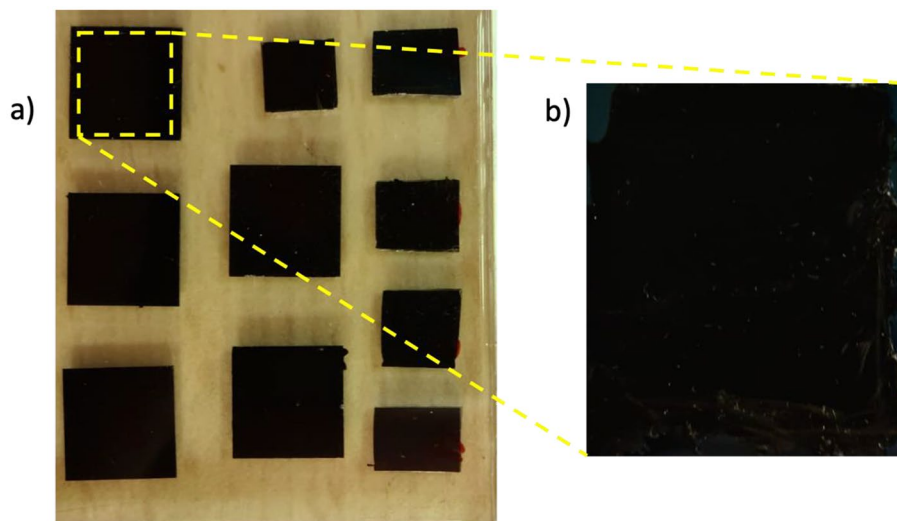


Fig. 2 The optical arrangement of the source, sample holder, and detector to detect the reflected beam at an angle of 25°

The SEM (Quattro et al.) was utilized to analyze the thin film structure of the prepared samples. To measure the reflectance and absorption spectra of the samples, a UV-Vis-NIR Ocean optics spectrometer was employed with a wavelength range of 200 to 1100 nm, see Fig. 2. The setup was designed to measure the reflectance beam intensity (R) at various angles of the incident, where angles are adjusted based on the position of the source and detector on the optical bench, see Fig. 2, and the absorption (A) was determined using the equation presented in [27], which is given as [27]:

$$A = -10\log(R) \quad (1)$$

Herein, we consider the optical extinction behavior is mainly due to absorption, as the scattering mechanisms either due to surface or even the volume porosity can be neglected.

To investigate the morphological surface resistance of the fabricated sample, a hardware prototype of a customized scanning four-probe station was used. Gold-plated needles with ultra-low resistivity were created to establish a connection between the sample under test and a Keithley 2410 source meter. The four needles were fixed on a movable head with an x - y - z controller, which scan the sample in a two-dimensional scale up to 0.1 mm per step. The surface resistance per unit area was estimated using a Keithley 2401 source/meter.

3 Results and discussion

As stated earlier, this manuscript focuses on the impact of varying the CNT growth parameters on the optical and electrical performance of the thin film as a postnatal layer in various electronic and optoelectronic devices. In Table 1, five different growth conditions are illustrated. Herein, we evaluate the thin black film of CNTs against our commercially utilized FTO-coated glass, purchased from Sigma-Adrtich 735,167, with a surface resistance of 7 Ω /Sq. Previous attempts promote the fabrication of symmetric optoelectronic devices, where FTO-coated glass is used in both front and counter electrodes [27–35]. Additionally, we treat the thin black film of commercially purchased CNTs

Table 1 Extracted experimental parameters for five different CNT growth samples

Exp #	The temperature of the catalyst (T_c)	The growth temperature (T_g),	Preheated	Acetylene	Density (mg/mm^3)	Height (nm)	Absorption band (nm)	Average surface resistance (Ω/Sq)
1	500 °C	600 °C	Yes	No	0.0118	0.737	362	25.5
2	700 °C	700 °C	No	Yes	0.0097	0.509	362	24.9
3	700 °C	680 °C	Yes	No	0.0265	0.961	394	23.8
4	700 °C	680 °C	Yes	No	0.0174	1.414	453	23.1
5	830 °C	700 °C	Yes	No	0.0396	0.447	545	20.5
Commercial CNTs	Not given	Not given	Not given	Not given	0.017	Not given	587	15.7
FTO [36]	NA	NA	NA	NA	NA	NA	NA	7
[37]	NA	700 to 1200 °C	NA	NA	NA	NA	230	10–100
[38]	NA	500 to 900 °C	NA	NA	NA	NA	430	200
[38]	500 to 900 °C	Up to 980 °C	NA	NA	NA	NA	UV-Vis	100–350

as a bare sample. The commercial CNTs are purchased from Sigma-Adrtech, 724,777 Carbon nanotube, single-walled $\geq 90\%$ carbon basis ($\geq 80\%$ as carbon nanotubes), 1–2 nm diameter. For further inspection, we compare our parameters with the previous investigations in [36–38].

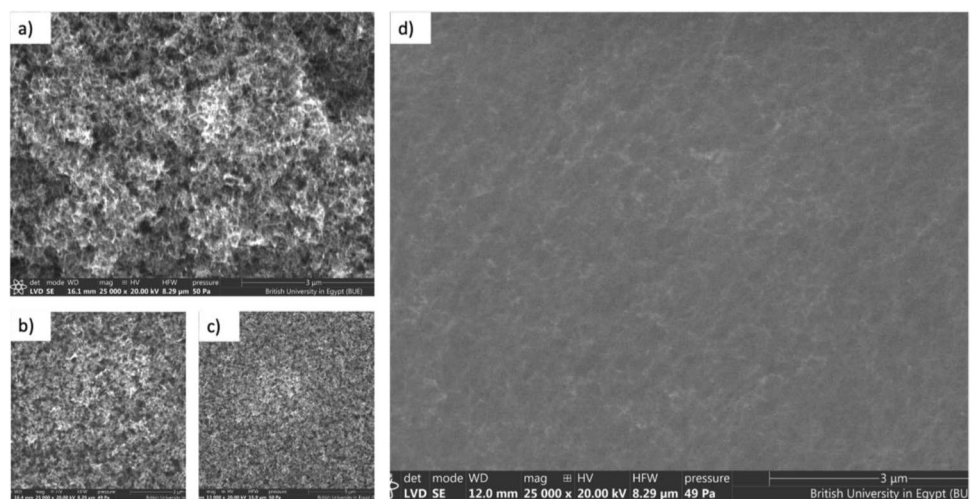
SEM measurements were conducted to analyze the thin black film of carbon nanotubes under different growth conditions, mainly varying the catalyst temperature and growth temperature, see Fig. 3. The results demonstrated a significant impact of these temperature variations on the thin film's consistency, porosity, and uniformity. Higher catalyst temperatures promoted denser and uniform CNT growth, producing a more consistent, less porous, thin film, cf—figure 3d. Conversely, lower growth temperatures

were associated with increased porosity and non-uniformity in the thin film, as in Fig. 3a.

The thin film output showed relatively low porosity with acceptable uniformity while observing the SEM results in Fig. 3 and applying our post-processing algorithm in [39]. This validates the minimal impact of the scattering, leaving the thin black film absorption as the main dominating extinction behavior.

Thin black films are prepared for the sake of neatly perfect absorption. In this regard, the reflectance is measured for the five prepared samples as well as the commercial CNT sample using the setup in Fig. 2; see the reflectance in Fig. 4. Consequently, the absorption is calculated as given in Eq. (1). The capability of broad absorption is determined through the absorption band coefficient, demonstrated in Fig. 5 for the commercial

Fig. 3 SEM measurements for a thin black film of CNTs under the growth conditions given in **a** Exp. #1, **b** Exp. #2, **c** Exp #4, and **d** Exp. #5



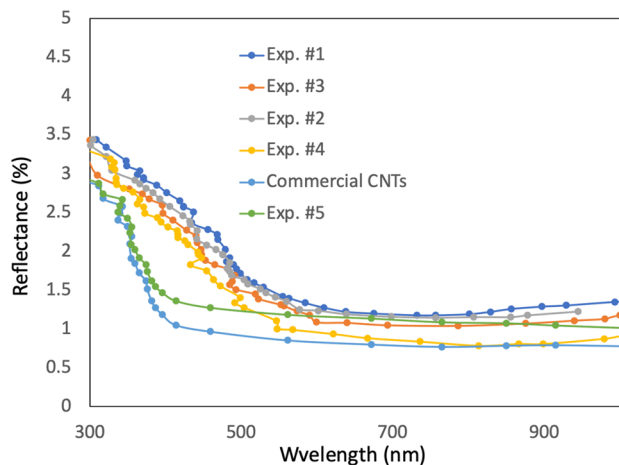


Fig. 4 Reflectance measurements for a thin black film of CNTs under the growth conditions given in Table 1 against the commercial CNT sample as a reference sample

CNT sample. The results in Fig. 5 record a 587 nm absorption band starting with a visible wavelength of 413 nm up to the maximum measurement limit in the near infra-red region at 1000 nm. Alternatively, the absorption spectra for the five prepared samples are presented in Fig. 6. The variation in the growth conditions impacted the absorption capabilities of the samples, cf.: Fig. 6; Table 1. A minimum of 362 nm absorption, 61.6% of the commercial sample, is observed for Exp—#1. The absorption band enhanced performance, reaching 545 nm at Exp—#5.

The increase in growth and catalyst temperature in CNT synthesis led to increased absorption of the thin black layer of CNTs for several reasons. Firstly, higher temperatures promote the dissociation of the

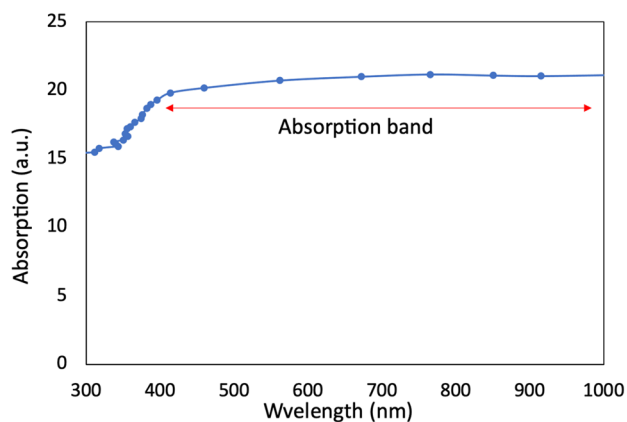


Fig. 5 The absorption spectrum for a thin black film of commercial CNTs

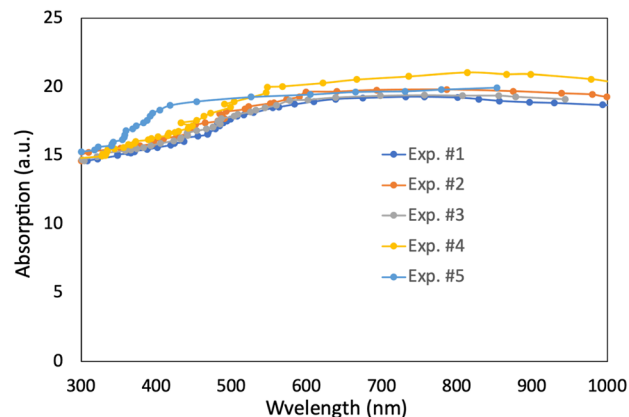


Fig. 6 Absorption spectra for a thin black film of CNTs under the growth conditions in Table 1, using the reflectance in Fig. 4 and Eq. (1)

carbon-containing gas molecules used in the CNT synthesis process, leading to a higher concentration of carbon atoms available for CNT growth. This, in turn, can increase the rate of CNT growth and the overall yield of CNTs.

Secondly, higher temperatures can lead to increased diffusion rates of the carbon atoms on the catalyst surface, which can promote the formation of more CNTs. The increased diffusion rate can also lead to a more uniform distribution of CNTs on the catalyst surface, resulting in a denser and more uniform CNT film. Lastly, higher temperatures promote the formation of a more stable catalyst surface, reducing the likelihood of catalyst deactivation and improving the overall quality of the CNTs produced.

Another critical parameter associated with the enrollment of thin black film of CNT in electronic and optoelectronic devices is the surface resistance, especially while considering such thin film as a potential electrode. Using our scanning four-probe station, the surface resistance for the two extreme experiments, 1 and 5, are measured and demonstrated in Fig. 7. This comparison involves the sample prepared with commercial CNTs and the Florine-doped tin oxide (FTO) coated on a glass substrate.

The growth and catalyst temperature play crucial roles in the synthesis of thin films of carbon nanotubes, see Fig. 7b and c. Higher growth temperatures can promote the kinetics of CNT growth, leading to faster and more efficient formation of nanotubes. This results in higher yields and denser CNT networks in the thin film. Increased growth temperature influences

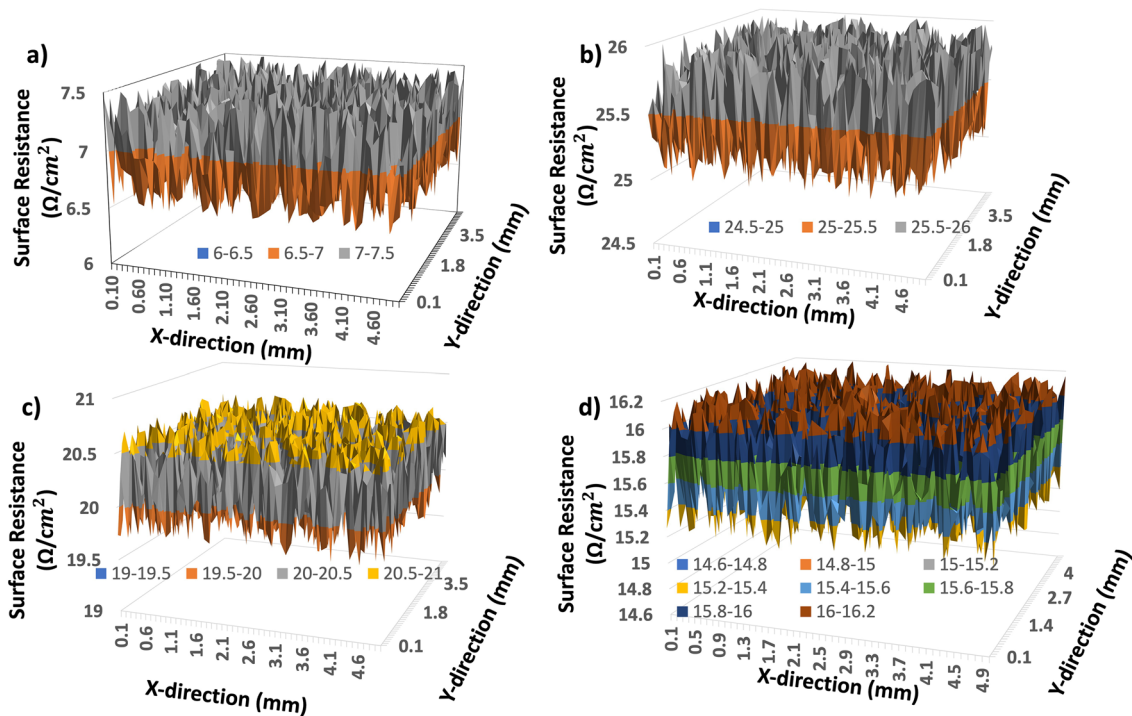


Fig. 7 Morphological surface resistance for **a** FTO-coated glass, **b** thin black film of CNTs under the growth conditions given in **b** Exp. #1, **c** Exp. #5, and **d** commercial CNTs

the crystal structure, alignment, and diameter distribution of the CNTs, impacting the resulting thin film's electrical, mechanical, and thermal properties. It also affects the purity and defect density of the CNTs, which in turn influences the thin film's overall electrical and mechanical performance.

Additionally, the catalyst temperature influences the nucleation and growth of CNTs. Higher catalyst temperatures enhance carbon-containing precursors' decomposition and active catalytic sites' formation, leading to increased CNT growth rates. Variation in catalyst temperature affects the size, distribution, and density of the catalyst particles, impacting the nucleation density and growth behavior of the CNTs. Moreover, catalyst temperature influences the selectivity of CNT growth, affecting the chirality and structural characteristics of the nanotubes.

Comparing the surface resistance of a thin black film of carbon nanotubes with FTO involves considering the electrical properties of both materials. FTO is a transparent conductive oxide commonly used in solar cells, touchscreens, and display applications. It typically exhibits sheet resistances of 7 ohms/square, making it a highly conductive transparent material. When comparing the surface resistance of thin black

films of carbon nanotubes with FTO, it is essential to consider the application's specific requirements. While FTO offers excellent transparency and conductivity, carbon nanotube films have higher surface resistances, see Fig. 7b–d, but can provide other advantages such as flexibility, mechanical robustness, and potential for tunable electrical properties.

Upon further analysis, an additional comparison can be drawn by examining the surface resistance values presented in both Table 1; Fig. 7, in conjunction with the data from previous studies referenced in [36–38], and listed in Table 1. The comparative evaluation reveals that our synthesized samples exhibit notably reduced surface resistance levels, signifying enhanced performance potential as electrodes in electronic and optoelectronic devices. This significant improvement underscores the promising prospects of our materials for applications requiring superior conductivity and efficiency in various technological advancements.

4 Conclusion

In conclusion, this study provides a comprehensive analysis of the optical and electrical properties of thin black films of carbon nanotubes, with a focus on their potential integration in electronic and optoelectronic devices. Through a combination of experimental measurements and computational analysis, the research has demonstrated the strong light absorption capabilities of the CNT thin films across a broad spectrum, highlighting their potential as efficient broadband absorbers. The investigation of morphological surface resistance further underscores the high electrical conductivity of the CNT thin films, positioning them as promising candidates for applications requiring enhanced electrical performance.

The exploration of varying growth and catalyst temperatures has shed light on the tunability of the absorption profile of the thin films, offering valuable insights for the optimization of CNT-based devices. Overall, the findings of this study contribute to the advancement of knowledge in the field of CNT. Thin films provide a foundation for developing high-performance electronic and optoelectronic devices.

Author's contributions

Conceptualization, S.A.; methodology, Z.K. and S.A.; software, Z.K.; validation, Z.K. and S.A.; formal analysis, Z.K. and S.A.; investigation, Z.K. and S.A.; resources, Z.K. and S.A.; data curation, Z.K., and S.A.; writing—original draft preparation, Z.K., and S.A.; writing—review and editing, S.A.; visualization Z.K., and SA.; supervision, S.A.; project administration, S.A. All authors have read and agreed to the published version of the manuscript.x.

Funding

Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB). Not Applicable.

Data availability

The datasets generated during and analyzed during the current study are available from the corresponding author upon reasonable request.

Code availability

Not applicable for that section.

Declarations

Competing interests The authors declare that they have no competing interests.

Ethical approval Not applicable.

Consent to participate All authors confirm their participation in this paper.

Consent for publication All authors accept the publication rules applied by the journal.

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