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Fluorescent Silica Aerogels for Advanced and Forensic Applications

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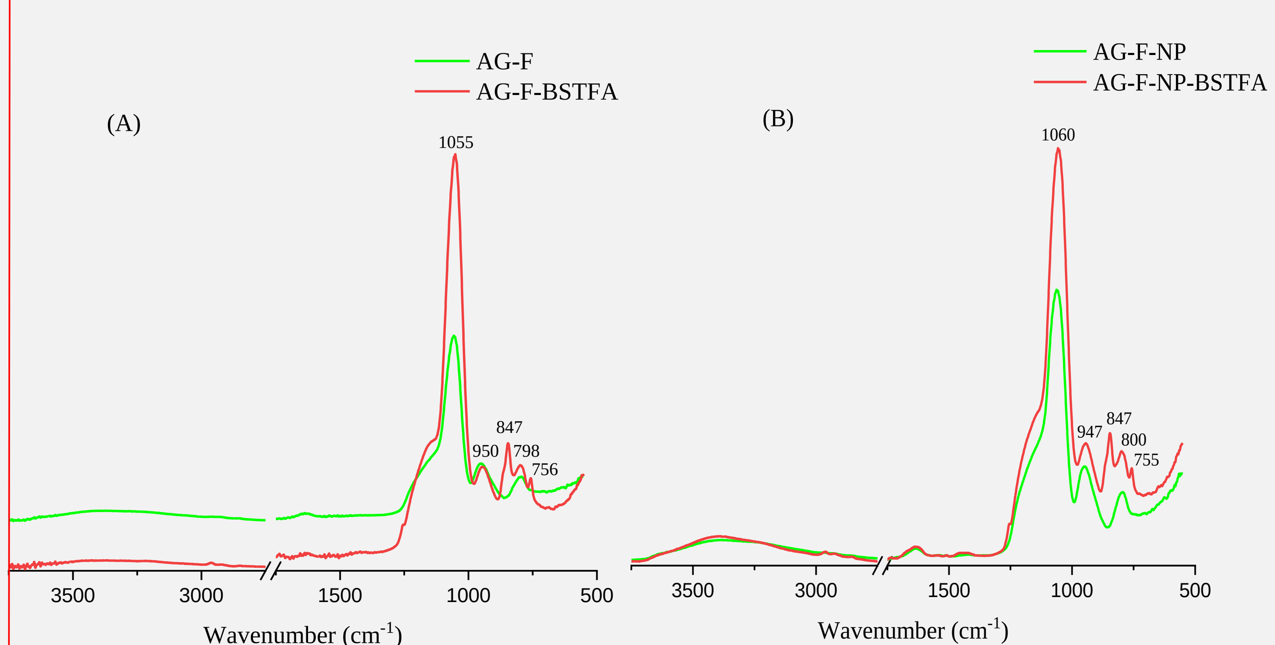
Abstract

This study reports on the design and characterization of fluorescent silica aerogels as hybrid materials with potential in additive manufacturing for multifunctional applications. We establish a synthesis pathway for producing nanocomposite aerogels that incorporate fluorescein, BSTFA for surface functionalization, and Fe_3O_4 nanoparticles. Comprehensive characterization (XRD, BET, TGA, SEM-EDS, FTIR, and fluorescence spectroscopy) demonstrates how nanoscale engineering strategies translate into macroscopic optical, structural, and functional properties. The resulting aerogels combine high porosity, tunable luminescence, and magnetic responsiveness, making them strong candidates for advanced integration into additively manufactured systems. Photophysical studies reveal stable, excitation-dependent fluorescence with high emission intensity, while structural analyses confirm the preservation of the aerogel framework after modification. Surface functionalization enhances hydrophobicity without impairing optical performance. Beyond applications in energy systems, biomedical platforms, and aeronautical technologies, these engineered aerogels also show great promise in forensic science, where their fluorescent response enables sensitive and reliable fingerprint development. Overall, this work highlights fluorescent silica aerogels as versatile hybrid materials and provides a framework for their tailored design in additive manufacturing across both technological and forensic domains.

Methods and Results

IR Spectroscopy

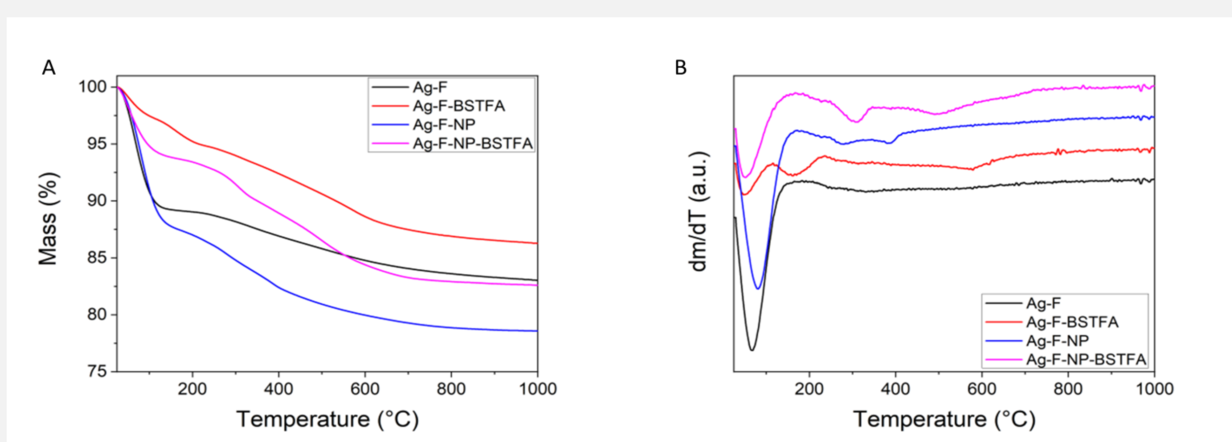


*Comparative analysis of the IR spectra between the non-functionalized fluorescein-doped silica aerogel **(AG-F)** and its BSTFA-functionalized counterpart **(AG-F-BSTFA)** (Figure A) revealed two characteristic infrared bands: the asymmetric stretching vibrations of Si-O-Si (ν_{as}Si-O-Si) at **1055 cm^{-1}**, confirming the silica network structure, and the in-plane stretching vibrations of surface silanol groups (ν_{ip}Si-OH) at **950 cm^{-1}**.*

*The investigation was extended to fluorescent aerogels **incorporating Fe_3O_4 magnetic nanoparticles**, which underwent identical **BSTFA functionalization**.*

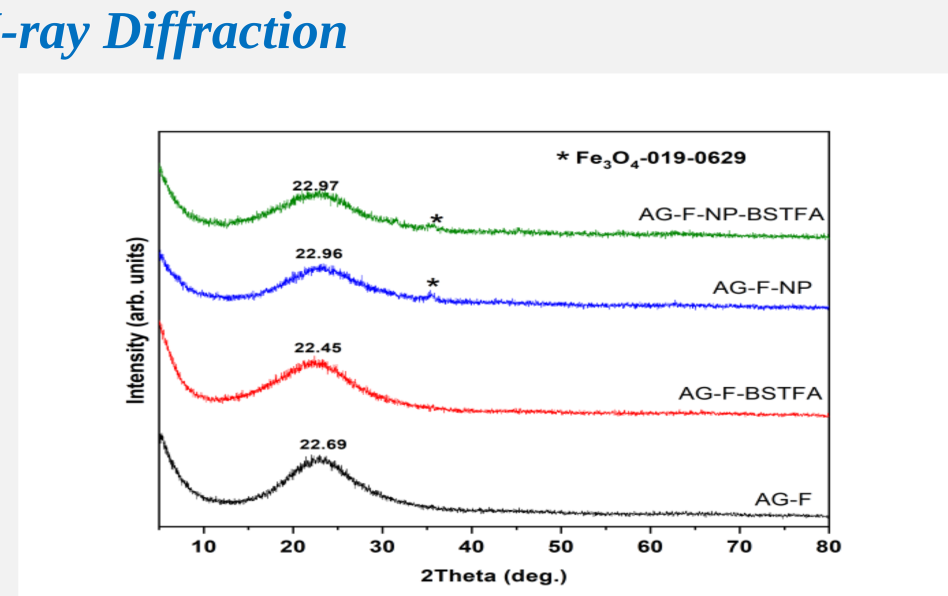
Successful functionalization was unequivocally demonstrated by the emergence of diagnostic trimethylsilyl group vibrations at 847 cm^{-1} and 755 cm^{-1}, mirroring the spectral modifications observed in the non-magnetic system.

Thermogravimetric Analysis (TGA)



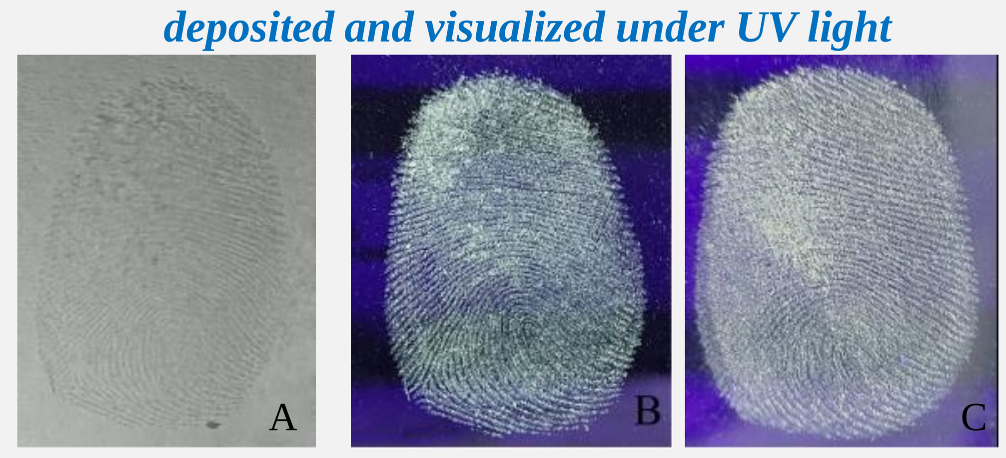
*Thermogravimetric analyses (TGA) were carried out in order to assess the thermal stability and the composition of the aerogel samples (Figure A). Three distinct mass loss events can be noticed for all samples: (i) an initial **1.5-2.5 %** wt. mass loss between **25-140°C** corresponds to the dehydration of physisorbed water, (ii) a gradual **4-7%** wt. mass loss in the **140-1000°C** temperature range, associated with the dehydration of the silanol groups and (iii) the combustion of functionalized organic groups between **140 and 330 °C**. The three mass loss events can also be noticed in the differential thermogravimetric analysis data (Figure B).*

X-ray Diffraction



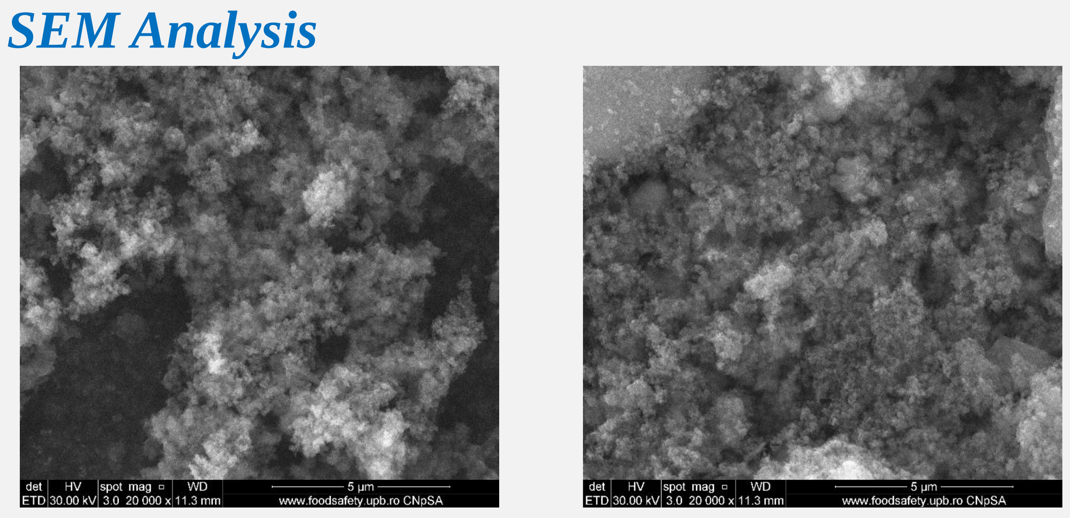
*X-ray diffraction analysis confirmed the structural characteristics of the silica-based aerogels, revealing their amorphous nature through a broad diffraction band centered at 2θ = 22°, consistent with typical amorphous silica materials. For aerogel samples incorporating magnetic nanoparticles (**AG-F-NP** and **AG-F-NP-BSTFA**), distinct diffraction peaks corresponding to magnetite **(Fe_3O_4)** crystalline phases were observed, confirming the successful integration of nanoparticles within the amorphous silica matrix.*

Imprint (A), and material AG-F (B) and AG-F-NP (C) deposited and visualized under UV light



The applied materials facilitate the visualization of fingerprint ridge patterns and enhance the clarity of all critical fine details.

SEM Analysis

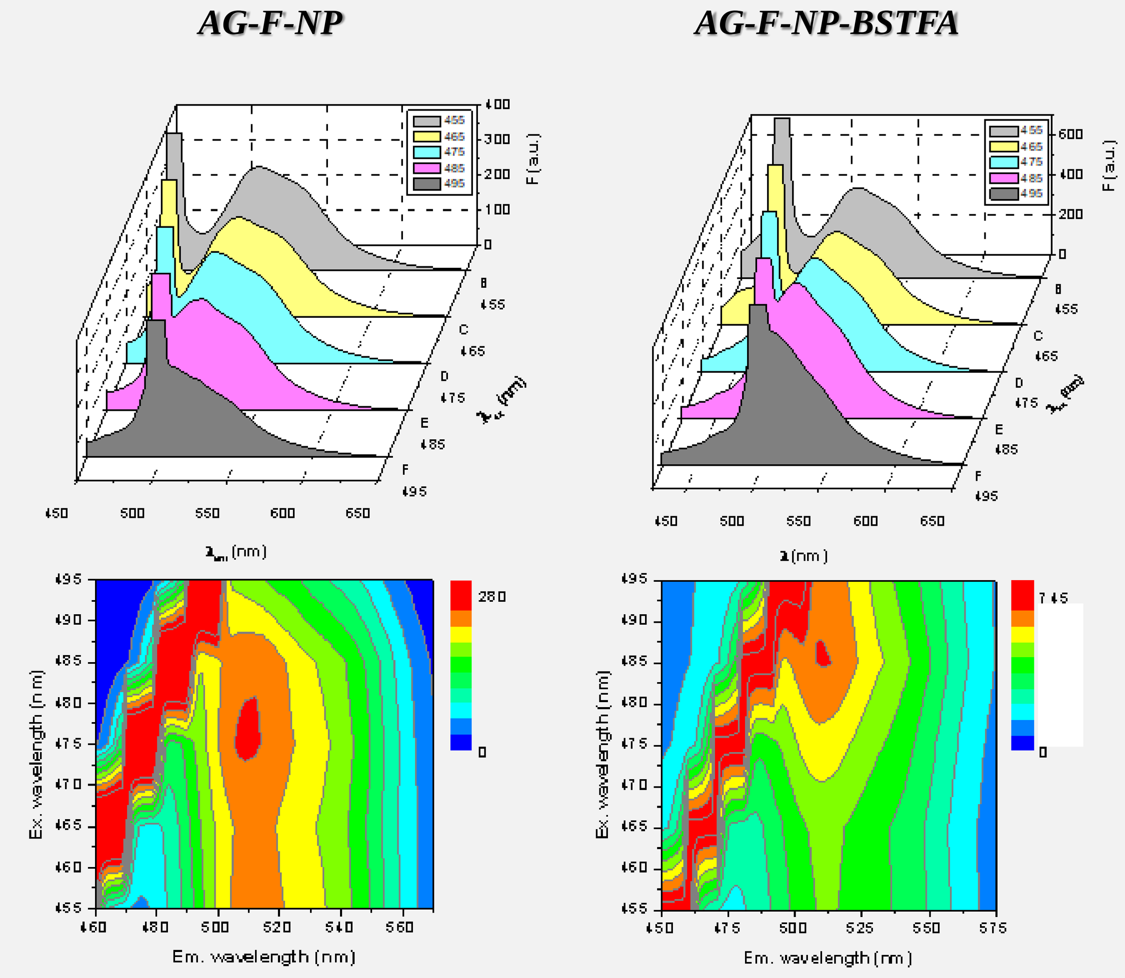


AG-F ***AG-F-BSTFA***

*High-resolution SEM images at **5 μm magnification** revealed the characteristic macroporous architecture with irregular, interconnected voids.*

Fluorescence Spectroscopy

AG-F-NP ***AG-F-NP-BSTFA***



*The EEM matrices were obtained by recording the emission spectrum of each sample for five consecutive excitation wavelengths. These contour plots represent a 'fingerprint' of the emissive behaviour of the material. They allow us to immediately extract information on the **optimum $\lambda_{ex}/\lambda_{em}$** pair leading to the maximum fluorescence emission. As can be seen from Figure, the characteristic excitation/emission wavelength pairs for the **AG-F** and **AG-F-NP** nanomaterials are **485/511 nm** and **477/510 nm**, respectively. After functionalization with BSTFA, the $\lambda_{ex}/\lambda_{em}$ pairs are **487/515 nm** for **AG-F-BSTFA** and **486/511 nm** for **AG-F-NP-BSTFA**.*

BET Analysis

	AG-F	AG-F-BSTFA	AG-F-NP	AG-F-NP-BSTFA
Specific surface area (m^2/g)	**487.088**	**200.826**	**364.824**	**208.904**
Total pore volume (cm^3/g)	**0.5123**	**0.3086**	**0.3724**	**0.2591**
Pore diameter (nm)	**4.2068**	**6.1464**	**4.0835**	**4.9606**

*Comparative analysis between **AG-F** and **AG-F-BSTFA** demonstrated a systematic reduction in specific surface area and total pore volume accompanied by increased average pore diameter, directly attributable to pore occupation by trimethylsilyl groups during functionalization.*

Conclusions

This study establishes fluorescent silica aerogels as effective materials for latent fingerprint visualization, making use of their exceptional optical properties to reveal ridge details with superior contrast under UV illumination. The forensic application of these aerogels represents a methodological advancement, enabling rapid, high-precision fingerprint detection. Crucially, the materials maintain their emissive characteristics post-functionalization, with magnetic nanoparticle incorporation (Fe_3O_4) demonstrating compatibility across both aqueous suspensions and solid-state applications.

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