



Development and Characterisation of Fish-Scale-Derived Carbon Nanodot Coatings on Cotton Fabric for Enhanced UV Absorption

Manju Lekshmi N.*, Anish Kumar K. C., and P. Muhamed Ashraf

ICAR-Central Institute of Fisheries Technology, P. O. Matsyapuri, Willingdon Island, Cochin - 682029, India

Abstract

Ultraviolet (UV) radiation, particularly UVA (315–400 nm) and UVB (280–315 nm), poses significant health risks. The use of textiles with enhanced UV absorption properties can be an effective means of reducing exposure to these harmful rays. This study explores the development of textiles with UV-absorbing properties using carbon nanodots (CNDs) synthesised from fish scales, an eco-friendly material developed from biowaste. Silane was employed as a coupling agent to improve the adhesion of CNDs to cotton fabric. The UV-absorbing efficiency of fabrics treated with varying concentrations of CNDs (0.02–0.5%) was assessed using UV-Visible spectrophotometry. Durability tests, including domestic and seawater washing (up to 30 cycles), evaluated the coating stability. Results demonstrated significant UV absorption in CND-coated fabrics, with optimal protection observed at 0.5% CND concentration. Fourier Transform Infrared Spectroscopy (FTIR) confirmed chemical interactions between CNDs and silane, while Scanning Electron Microscopy (SEM) revealed a uniform coating distribution and stability after washing. The findings indicate that fish-scale-derived CNDs, in combination with silane, offer a promising eco-friendly approach for developing UV-protective textiles, particularly benefiting high-risk groups such as fishermen.

Keywords: Carbon nanodots, fish scales, silane, UV-protective textiles

Introduction

Solar radiation, encompassing wavelengths from 290 to 3000 nm, plays a vital role in sustaining life on Earth, but its ultraviolet (UV) component (290–400 nm) poses significant health risks. Prolonged exposure to UV radiation, particularly UVA and UVB, can lead to various skin issues, including premature aging and skin cancer (Diffey, 2002; Shen, Zhen, Huang, & Xue, 2014). Therefore, protecting the human body from harmful UV exposure is crucial (Wang & Hauser, 2010). Clothing designed to shield against UVA/UVB radiation offers a practical and effective approach to minimising UV-related health risks. However, traditional textiles lack the intrinsic ability to block UV radiation effectively.

The UV protection efficacy of textiles is influenced by factors such as fabric structure, fibre type, and chemical treatments. Wong, Yuen, Leung, Ku, and Lam (2006) reported that, to enhance UV protection, compounds, including inorganic photoactive agents and organic UV absorbers such as SiO₂, TiO₂, ZnO, CuO, and Ag, could be applied to fabrics using various physical and chemical methods. While organic absorbers are efficient, they often raise toxicity concerns, while inorganic materials, despite being safer, face challenges such as agglomeration at effective concentrations (Fouassier & Lalevée, 2012). These limitations emphasise the need for sustainable, non-toxic alternatives for UV protection in textiles.

Carbon nanodots (CNDs) have emerged as highly promising materials for textile applications due to their exceptional properties, such as fluorescence, photostability, low toxicity, etc. (Ashraf, Stephen, & Binsi, 2021). However, one significant challenge in using nanoparticles in textiles is their tendency to leach out from the fabric surface over time,

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*Email: manjuaem@gmail.com

diminishing the coating's performance. Developing techniques to anchor nanoparticles to the fabric firmly is essential for enhancing durability and maintaining functionality. Silanes are often used as coupling agents in natural materials/polymer composites to promote interfacial bonding and improve material properties (Xie, Hill, Xiao, Militz, & Mai, 2010; Shi, Xu, & Zhang, 2019). Agrawal et al. (2020) demonstrated that silane cross-linkers form additional chemical bonds between nanoparticles and fabrics, thereby enhancing adhesion and improving the stability of coatings under various environmental conditions.

The incorporation of biowaste as a raw material for producing CNDs aligns with circular economy principles, transforming waste into valuable resources. Fish scales, a by-product of the fish processing industry, can be converted into eco-friendly, fluorescent CNDs using hydrothermal methods (Ashraf et al., 2021). This sustainable approach not only addresses waste management challenges but also provides a green solution for developing functional materials for the textile industry.

Fishermen, particularly in Asian countries, are a vulnerable group due to prolonged exposure to intense sunlight during fishing and related activities at sea and onshore. Despite the well-documented risks of UV-induced health issues in this sector, there has been limited research on developing UV-absorbing textiles specifically for fishermen. This study seeks to bridge this gap by developing UV-protective textiles using silane and CNDs derived from fish scales.

The research focuses on determining the optimal concentration of fish-scale-derived CNDs for textile coatings, assessing the durability of these coatings after exposure to domestic washing and seawater, and evaluating their UV absorption efficiency. The addition of silane facilitates the formation of robust chemical bonds between the CNDs and the fabric, which can ensure long-lasting adhesion and enhanced durability. By addressing these aspects, this study seeks to develop UV-protective clothing for fishermen, thereby addressing to their occupational health and safety while promoting a sustainable approach to resource utilisation within the fishing industry.

Materials and Methods

Carbon nanodots (CNDs) were synthesised using a modified hydrothermal method as described by

Ashraf et al. (2021). Fish scales, a biowaste material, were thoroughly washed with distilled water to remove impurities and then dried at 60 °C in a hot-air oven. The dried scales were subjected to a hydrothermal process in a Teflon-lined hydrothermal reactor heated in a Nebertherm muffle furnace, with a temperature program from room temperature (RT) to 180 ± 5 °C over 1 hour, maintained for 7 hours, resulting in the formation of fluorescent carbon nanodots. The CNDs obtained were purified and the filtrate was dialysed to eliminate residual impurities (Ashraf, Sahla, Anjana, & Binsi, 2025).

Handwoven white cotton fabric was procured from a Khadi shop in Kochi, Kerala. Circular fabric samples (3 cm diameter) were first washed with distilled water to remove surface contaminants and dried at 60 °C in a hot-air oven for 60 minutes. To enhance surface functionality and maximise CND binding, the fabric samples were immersed in a 0.01 M aqueous solution of (3-glycidyloxypropyl) trimethoxysilane (silane) for 120 minutes. Following this treatment, the silane-coated fabrics were dried in a hot-air oven set at 60 °C for 60 minutes.

To determine the optimal concentration of CNDs for maximum UV absorption, CND solutions were prepared at varying concentrations of 0.02% (T1), 0.05% (T2), 0.1% (T3), 0.2% (T4), and 0.5% (T5) (w/v), with untreated fabric serving as the control (T0). Silane-treated fabric samples (six per treatment) were immersed in these CND solutions overnight. Following immersion, the coated fabrics were dried in a hot air oven at 60 °C for 60 minutes. The UV absorption efficiency of the coated fabrics was evaluated using a double-beam UV-Visible spectrophotometer (Shimadzu 2450). The UV-Visible spectra were recorded in the wavelength range of 200–800 nm, with special emphasis on the UV-A to UV-C region (200–400 nm) to evaluate UV protection efficiency.

The durability of the coated fabrics with UV-absorbing efficiency was assessed through domestic washing (30 cycles) using distilled water. The washing was performed by hand in a 1 L beaker. The cloth was soaked in distilled water without detergent, gently agitated, rinsed, removed, and air dried at room temperature. This process was repeated for 30 cycles. Based on the UV absorption results, the two optimal CND concentrations were selected for further evaluation. The thus selected fabrics were washed in seawater for 30 cycles. After

each washing cycle, the fabrics were air-dried, and their UV absorption properties were re-evaluated using spectrophotometry. Each washed sample was labelled: W01T0 represented the control fabric after the first wash cycle, whereas W20T1 represented the 20th wash cycle of the T1 treatment.

Fourier transform infrared (FTIR) spectra were obtained using a Thermo Nicolet iS10 equipped with a μ ATR accessory. The FTIR spectra were recorded over a wavenumber range of 4000–400 cm^{-1} with a scanning interval of 1.0 cm^{-1} , a scanning speed of 2 mm/s, and a spectral resolution of 4 cm^{-1} . The material was scanned 50 times, and the averaged spectrum was shown as the final plot. The data were processed using OmnicTM software provided with the instrument. The analysis was performed on CNDs, untreated cotton, silane-coated cotton, and silane-CND-coated cotton to identify functional groups, particularly C=C systems, and their interactions with silane and CNDs.

The surface morphology of the modified fabrics was examined using scanning electron microscopy (SEM), and micrographs were recorded after gold sputtering in a JEOL JSM-6390LV. The fabric pieces were mounted on stubs, sputter-coated with gold, and imaged at varied magnifications (up to 5000 $\times$) with an accelerating voltage of 15 kV. Micrographs were obtained for untreated cotton, silane-coated cotton, silane-CND-coated cotton, and silane-CND-coated cotton after 30 washing cycles. The SEM analysis provided evidence of successful silane and CND coatings on the cotton fabric, as well as the stability and integrity of these coatings after repeated washing cycles. Statistical analysis was carried out using Microsoft Excel software.

Results and Discussion

Cotton fabric surfaces were modified with silane to facilitate the adhesion of carbon nanodots as described above. The silane-treated cotton was immersed in CND solutions of varying concentrations, and the samples were subjected to different tests. Zuo, Liang, Xu, Chen, and Zhang (2019) characterised the structure and properties of boron- and nitrogen-co-doped carbon nanodots on cotton fabrics using Fourier transform infrared spectroscopy, scanning electron microscopy, and UV-Vis spectroscopy.

The cotton fabric, silane-treated and silane-CND-treated fabrics were analysed using UV-Visible

spectroscopy (Fig. 1). The absorbance of the CND-coated fabric increased with increasing concentrations of CND, confirming effective adsorption onto the cotton-silane matrix. The CND-coated cotton exhibited absorptions at 205 and 266 nm, indicating a blue shift from 220 and 280 nm, respectively, which can be attributed to the interactions between conjugated C=C bonds in CNDs and silane molecules. The presence of functional groups (OH, CO, NH) associated with absorption at 266 nm remained unchanged. At lower concentrations, a secondary peak at 205 nm was detected, likely due to unreacted organic silane, which disappeared in the 0.5% CND-coated fabric. The higher UV absorption observed in CND-treated samples compared to silane-treated cotton indicates enhanced UV-absorbing properties. The CND-coated cotton exhibited significantly increased absorbance, with increasing CND concentration and broader absorption in the UV region up to 400 nm. The CND-coated fabric exhibited enhanced light absorption in the UV region.

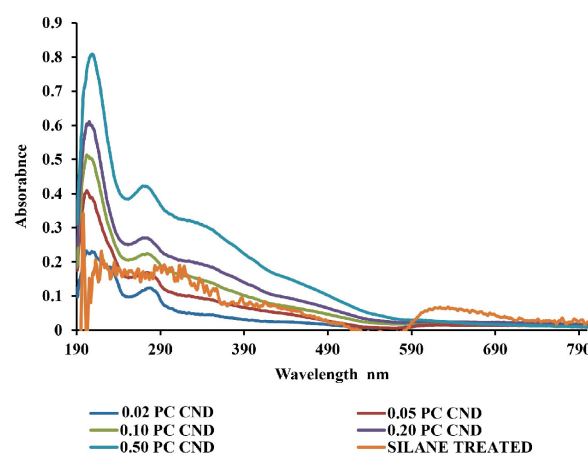


Fig. 1. UV-Visible spectroscopic analysis of cotton fabric, silane-treated cotton, and silane-CND-treated fabric

Fourier transform infrared spectra of CND, cotton fabric, silane-coated cotton, and silane-CND-coated cotton are shown in Fig. 2. The characteristic Si-O peaks in silane-coated cotton, initially observed at 979 and 982 cm^{-1} , exhibited a red shift to 990 and 996 cm^{-1} upon CND integration, indicating a strong interaction between silane and CNDs. Similarly, the C-H in-plane bending vibrations of CNDs, originally at 1235 and 1245 cm^{-1} , shifted to 1214 and 1217 cm^{-1} in the silane-CND cotton composite, confirming conjugated C-C interactions. Further spectral shifts were observed in the 1520–1580 cm^{-1} range,

with absorption bands shifting to 1574 and 1631 cm^{-1} , providing additional evidence for the interaction between the conjugated C=C system in CNDs and silane. A significant shift in absorption bands was noted when comparing silane-coated cotton with the silane-CND composite, highlighting the effective integration of CNDs. Additionally, shifts in N-H and O-H stretching vibrations suggested steric interactions and potential hydrogen bonding, further supporting the successful formation of the composite material. These FTIR findings were consistent with the results of the UV-Vis spectral studies. The modified cotton fabric samples displayed distinct peaks at 1058, 985, and 836 cm^{-1} , corresponding to the stretching vibrations of Si-O-C groups (Li et al., 2016; Pourhashem, Vaezi, Rashidi, & Bagherzadeh, 2017). Furthermore, bands at approximately 1116 and 896 cm^{-1} were attributed to Si-O-Si vibrational modes, confirming the effective anchoring of the silane coupling agent onto the cotton fabric (Gan et al., 2015).

In addition to silane-specific interactions, the absorption bands between 900 and 1500 cm^{-1} corresponded to characteristic vibrations of C-H, O-H, C-O, and C-O-C groups from cotton cellulose. Notably, bands at 1156 and 900 cm^{-1} were assigned to C-O-C stretching vibrations of the β -D-glucoside

linkage, characteristic of the cotton cellulose structure (Zhu et al., 2012). These findings collectively confirm successful chemical modification and strong binding of silane and CNDs onto the cotton fabric, enhancing its structural and functional properties. Shi et al. (2019) reported using silane coupling to link graphene oxide to cotton, where the modified fabrics exhibited enhanced UV absorption and hydrophobicity.

The UV-Vis spectra of untreated cotton, silane-treated cotton, and silane-CND-treated cotton after up to 30 washing cycles with water are shown in Fig. 3. The untreated cotton fabric after 30 washing cycles exhibited lower absorption around the 300 nm region, whereas the absorption increased in the 190–200 nm region (Fig. 3(T0)). In contrast, CND-coated samples maintained substantial UV absorption (0.15–0.35 range) across multiple wash cycles. The highest absorption was observed for the 0.5% CND-treated samples, indicating excellent long-term UV-blocking ability.

The 0.02% CND-treated cotton was subjected to freshwater washing, and the results are shown in Fig. 3. The UV region showed significantly higher absorbance than the control. The absorbance ranged from 0.15 to 0.31, and no noticeable change was observed even after 30 washing cycles. T2 and T3 exhibited similar behaviour. No appreciable increase in UV absorbance was observed with an increase in CND concentration from 0.05% to 0.10%. In both treatments, the maximum absorbance was around 0.3. The T4 and T5 treatments, which contained higher CND concentrations, exhibited only a marginal increase in absorbance, with the maximum absorbance in the 0.5% CND-treated cotton. For both treatments, the maximum absorbance was up to 0.35. The average absorbance was comparatively higher after 30 washing cycles. The results indicated that CND-treated cotton possesses excellent UV absorption, and increasing the CND concentration beyond 0.2% did not influence any further improvement in UV absorption. Notably, the CND coating remained adhered to the cotton even after 30 washing cycles, indicating its potential for industrial applications. Among the tested concentrations, the 0.5% CND-treated sample showed the highest absorption at both 200 and 266 nm, while the 0.2% sample showed lower absorption.

The absorbance ratio at 200 nm and 266 nm was analysed to assess the stability and degradation of

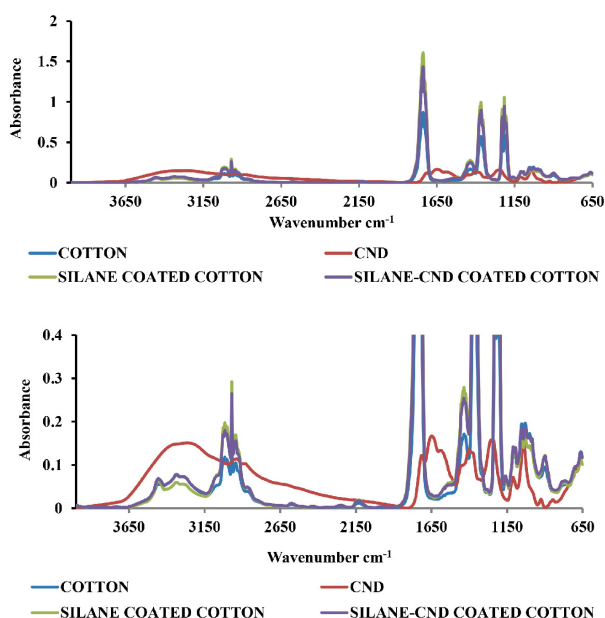


Fig. 2. FTIR spectra of cotton fabric, CND, silane-coated cotton, and silane-CND-coated cotton

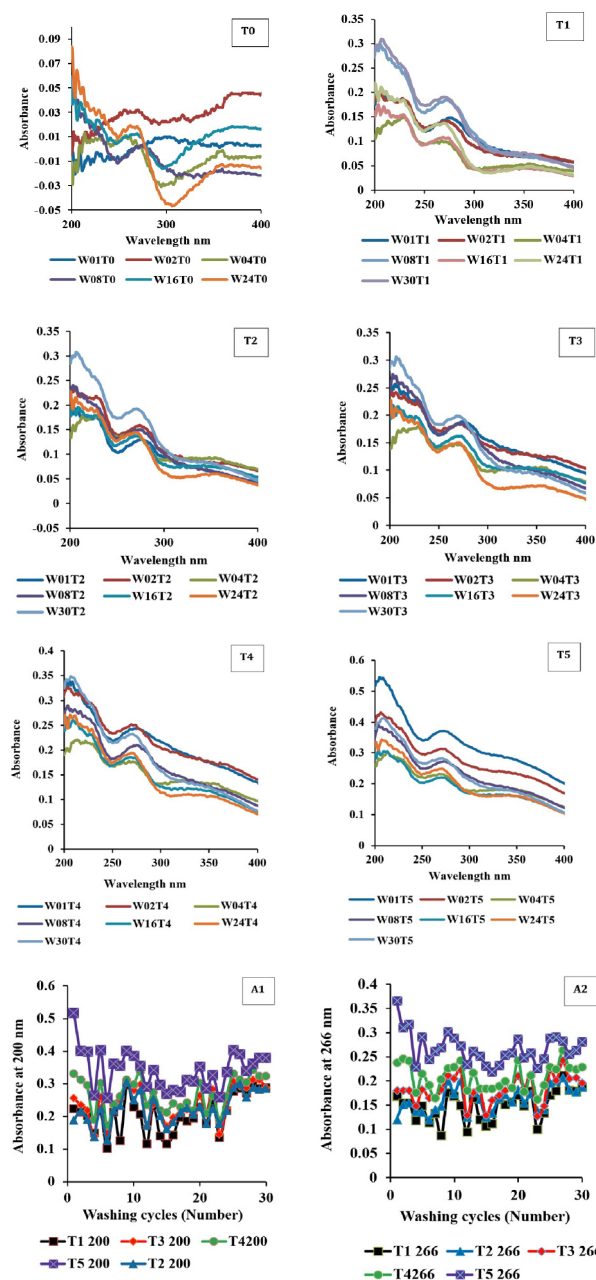


Fig. 3. The UV-Visible spectra of cotton fabric with varied treatments during 30 washing cycles. T0, control; T1 0.02% CND coated fabric; T2, 0.05% CND coated; T3 0.10% CND coated; T4 0.5% CND coated; T5 1.0% CND coated. Figs. A1 and A2 depict the changes in absorbance at 200 nm and 266 nm in treated and control fabric samples during washing.

carbon nanodots (CNDs) during the washing cycles, as shown in Fig. 4. These wavelengths correspond to the $\pi-\pi^*$ transition (200 nm) and $n-\pi^*$ transition (266 nm). The absorbance ratio was evaluated across

the different washing cycles. The results indicated that the ratio remained largely consistent, with only minor deviations observed. This suggests that the CNDs exhibited high stability and minimal degradation throughout the washing process, reinforcing the durability of the coating on the cotton fabric.

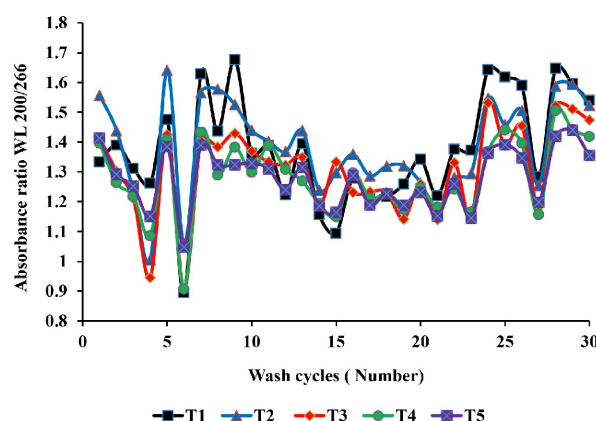


Fig. 4. The ratio of absorptions at 266/200 nm in varied CND-coated cotton fabrics in 30 washing cycles

Scanning electron micrographs of cotton, silane-coated cotton, silane-CND-coated cotton, and silane-CND-coated cotton after 30 washing cycles are shown in Fig. 5. The silane was successfully coated onto the cotton, as evidenced by the results of the micrographs. The CNDs were embedded in the matrix and uniformly distributed over the cotton

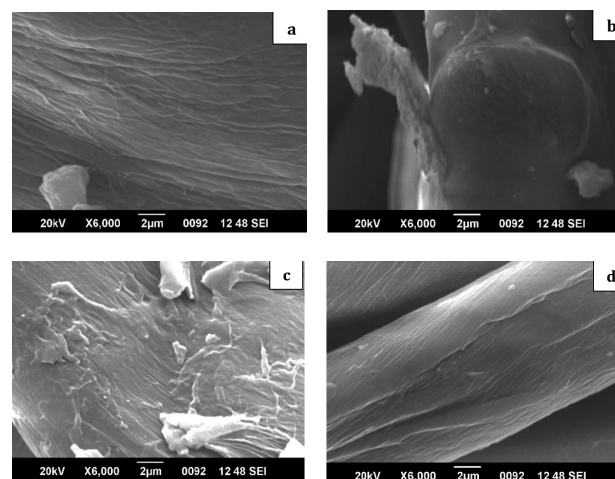


Fig. 5. Scanning electron micrographs of cotton fabric, silane-treated fabric, silane-CND-coated fabric, and silane-CND-coated fabric after 30 washing cycles; a) Control b) Silane-coated c) Silane-CND-coated d) Silane-CND-coated after 30 washes

surface. Both the silane and CNDs strongly adhered to the cotton polymeric fibres. Fig. 5d shows the condition of the treated cotton after 30 washing cycles, and the micrographs clearly show that the coating remained intact even after repeated washing. The results clearly confirm the successful formation of silane-CND coating over the cotton fabric.

Based on the previous results, the highest UV absorption efficiency was observed in the 0.2% and 0.5% CND-treated cotton samples. To evaluate the

stability of the CND coatings under seawater conditions, these treated fabrics underwent 30 washing cycles in seawater. The results revealed a reduction in UV absorption, likely due to partial delamination or leaching of CNDs caused by interactions with various ions in seawater. This effect was more pronounced in the 0.5% CND-treated samples, with a significant decrease in absorption observed.

The T200/T266 absorbance ratio remained almost constant for both the 0.2% and 0.5% samples (Fig. 6B), indicating that the overall structural integrity of the CND coating was maintained despite exposure to seawater. However, the distinct absorption peak at 200 nm diminished, suggesting possible ion adsorption or interaction with the conjugated C=C bonds, leading to minor structural modifications.

This study successfully demonstrates the potential of carbon nanodots (CNDs) synthesised from fish scales as an environmentally sustainable UV-blocking coating for cotton textiles. The integration of silane as a coupling agent significantly improved the durability of CND coatings, ensuring sustained UV absorption even after multiple washing cycles. Spectrophotometric analysis confirmed increased UV absorption as CND concentration increased, while FTIR and SEM analyses provided strong evidence of effective chemical binding and uniform nanoparticle distribution. The washing durability tests revealed minimal loss of UV-blocking efficiency in freshwater conditions, though slight degradation was observed in seawater. These findings provide a baseline for utilising biowaste-derived CNDs in textiles, offering a green and cost-effective alternative for UV-absorbing clothing, particularly for individuals exposed to prolonged sunlight, such as fishermen. Future research should further explore large-scale applications and alternative cross-linking strategies to enhance stability and performance in diverse environmental conditions.

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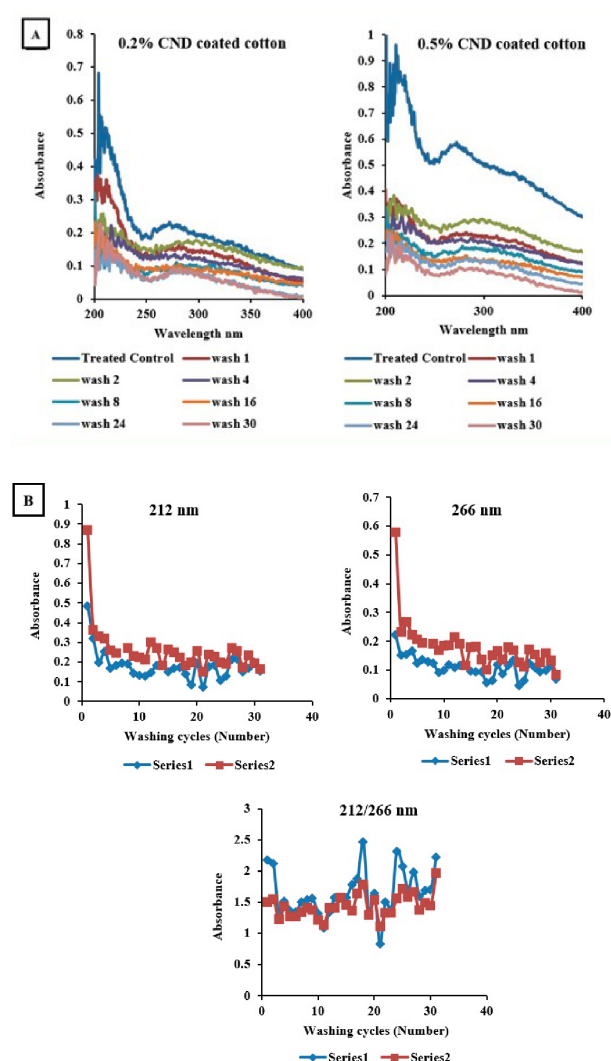


Fig. 6. A) UV-Visible spectra of 0.02% and 0.5% Silane-CND-coated cotton fabric after washing with seawater in 30 washing cycles. B) The absorption ratio at 212 and 266 nm in varied washing cycles by 0.2 and 0.5% CND-coated cotton fabric

References

- Agrawal, N., Low, P. S., Tan, J. S. J., Fong, E. W. M., Lai, Y., & Chen, Z. (2020). Durable easy-cleaning and antibacterial cotton fabrics using fluorine-free silane coupling agents and CuO nanoparticles. *Nano Materials Science*, 2(3), 281–291. <https://doi.org/10.1016/j.nanoms.2019.09.004>
- Ashraf, P. M., Sahla, V. A., Anjana, C. S., & Binsi, P. K. (2025). Carbon dot graphene composite: A novel biocide for marine biofouling control in aquaculture cage nets. *Aquacultural Engineering*, 111, Article 102586. <https://doi.org/10.1016/j.aquaeng.2025.102586>
- Ashraf, P. M., Stephen, S., & Binsi, P. K. (2021). Sustainable process to co-synthesize nano carbon dots, nano hydroxyapatite, and nano β -dicalcium diphosphate from fish scales. *Applied Nanoscience*, 11(6), 1929–1947. <https://doi.org/10.1007/s13204-021-01875-8>
- Diffey, B. L. (2002). Sources and measurement of ultraviolet radiation. *Methods*, 28(1), 4–13. [https://doi.org/10.1016/S1046-2023\(02\)00204-9](https://doi.org/10.1016/S1046-2023(02)00204-9)
- Fouassier, J. P., & Lalevée, J. (2012). *Photoinitiators for polymer synthesis: Scope, reactivity, and efficiency*. Wiley-VCH.
- Gan, W., Gao, L., Sun, Q., Jin, C., Lu, Y., & Li, J. (2015). Multifunctional wood materials with magnetic, superhydrophobic and anti-ultraviolet properties. *Applied Surface Science*, 332, 565–572. <https://doi.org/10.1016/j.apsusc.2015.01.206>
- Li, J., Cui, J., Yang, J., Ma, Y., Qiu, H., & Yang, J. (2016). Silanized graphene oxide reinforced organofunctional silane composite coatings for corrosion protection. *Progress in Organic Coatings*, 99, 443–451. <https://doi.org/10.1016/j.porgcoat.2016.07.008>
- Pourhashem, S., Vaezi, M. R., Rashidi, A., & Bagherzadeh, M. R. (2017). Distinctive roles of silane coupling agents on the corrosion inhibition performance of graphene oxide in epoxy coatings. *Progress in Organic Coatings*, 111, 47–56. <https://doi.org/10.1016/j.porgcoat.2017.05.008>
- Shen, Y., Zhen, L., Huang, D., & Xue, J. (2014). Improving anti-UV performances of cotton fabrics via graft modification using a reactive UV-absorber. *Cellulose*, 21, 3745–3754. <https://doi.org/10.1007/s10570-014-0367-3>
- Shi, F., Xu, J., & Zhang, Z. (2019). Study on UV-protection and hydrophobic properties of cotton fabric functionalized by graphene oxide and silane coupling agent. *Pigment & Resin Technology*, 48(3), 237–242. <https://doi.org/10.1108/PRT-09-2018-0098>
- Wang, Q., & Hauser, P. J. (2010). Developing a novel UV protection process for cotton based on layer-by-layer self-assembly. *Carbohydrate Polymers*, 81(2), 491–496. <https://doi.org/10.1016/j.carbpol.2010.03.008>
- Wong, Y. W. H., Yuen, C. W. M., Leung, M. Y. S., Ku, S. K. A., & Lam, H. L. I. (2006). Selected applications of nanotechnology in textiles. *AUTEX Research Journal*, 6(1), 1–8. <https://doi.org/10.1515/aut-2006-060101>
- Xie, Y., Hill, C. A. S., Xiao, Z., Militz, H., & Mai, C. (2010). Silane coupling agents used for natural fiber/polymer composites: A review. *Composites Part A: Applied Science and Manufacturing*, 41(7), 806–819. <https://doi.org/10.1016/j.compositesa.2010.03.005>
- Zhu, J., Wei, S., Gu, H., Rapole, S. B., Wang, Q., Luo, Z., Haldolaarachchige, N., Young, D. P., & Guo, Z. (2012). One-pot synthesis of magnetic graphene nanocomposites decorated with core@double-shell nanoparticles for fast chromium removal. *Environmental Science & Technology*, 46(2), 977–985. <https://doi.org/10.1021/es2014133>
- Zuo, D., Liang, N., Xu, J., Chen, D., & Zhang, H. (2019). UV protection from cotton fabrics finished with boron and nitrogen co-doped carbon dots. *Cellulose*, 26, 4205–4212. <https://doi.org/10.1007/s10570-019-02365-5>