Investigation on Nano-Structural Color for Fabric Printing Applications.

Sapni Thara Chandrasekara
Department of Textile and Apparel Engineering
University of Moratuwa
Katubedda 10400 Sri Lanka
chandrasekaraadst.20@uom.lk

Dakshika Jayamindi
Department of Textile and Apparel Engineering
University of Moratuwa
Katubedda 10400 Sri Lanka
jayamindipkd.20@uom.lk

Dasuni Kaushalya Maddumage
Department of Textile and Apparel Engineering
University of Moratuwa
Katubedda 10400 Sri Lanka
kaushalyamd.20@uom.lk

Irushika Maheshi Lakshani
Department of Textile and Apparel Engineering
University of Moratuwa
Katubedda 10400 Sri Lanka
irushikam@uom.lk

Chathuranga Senarathna
Department of Biosystems Technology
Uva Wellassa University
Sri Lanka
chathuranga@uwu.ac.lk

Gayani K. Nandasiri
Department of Textile and Apparel Engineering
University of Moratuwa
Katubedda 10400 Sri Lanka
gayanin@uom.lk

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I. INTRODUCTION

In nature, colors are created either by pigments or by structural coloration, where light interacts with micro- or nanostructures to produce vivid hues seen in butterfly wings and peacock feathers [1],[2]. Structural colors can be iridescent, changing with viewing angle, or non-iridescent, remaining consistent regardless of angle [3],[4]. Due to their durability and brilliance, structural colors offer a sustainable alternative to traditional textile dyes, which consume large amounts of water, energy, and chemicals [5],[6]. However, applying structural coloration to textiles is challenging because fabric surfaces are flexible and porous, causing poor nanoparticle adhesion, uneven coatings, and reduced color intensity [7],[8]. Additionally, the effects of fabric characteristics like weave tightness and surface texture on structural color formation remain underexplored.

This research addresses these limitations by developing a method for producing angle-dependent structural coloration on polyester satin fabric using silica (SiO_2) nanoparticles synthesized via a modified Stöber method. The approach facilitates the self-assembly of nanoparticles into photonic crystal-like structures that generate pigment-free colors. By precisely controlling synthesis parameters, silica nanoparticle sizes are tuned to produce a spectrum of non-iridescent structural colors. The resulting coated fabrics are analyzed for their morphological and optical properties to better understand the mechanisms of color formation.

II. LITERATURE REVIEW

Previous studies have explored structural coloration on textiles using silica nanoparticles (SNPs) synthesized via Stöber-based methods, with particle size control enabling a range of hues. In 2018 Gao et al. [7] demonstrated that adjusting SNP diameters from approximately 200 nm to 350 nm produced colors from blue to red on cotton, nylon, and silk fabrics. Woven fabrics generally yielded more uniform colors than knitted ones due to their tighter structure, yet issues such as short-range order, visible gaps, and patchy coloration persisted. The flexible, porous, and rough surfaces of textiles disrupted the ordered nanoparticle arrangements required for vivid structural colors, leading to reduced intensity and non-uniform optical effects.

Attempts to enhance coating stability have included Zhu et al.'s [9] use of dopamine to form a PDA-melanin bilayer on silk, which improved mechanical stability and reduced cracking. However, challenges remain in achieving high color uniformity and vividness comparable to results on smooth substrates, as well as preventing defects caused by fabric movement, folding, or surface irregularities.

Despite advances in structural coloration on textiles, challenges such as poor nanoparticle adhesion, inconsistent color uniformity, and reduced vividness due to fabric surface properties remain unresolved. These limitations highlight the need for innovative approaches that improve coating durability and control nanoparticle assembly on flexible, porous fabrics. This study addresses these gaps by developing a method to produce vivid structural colors on polyester satin fabric using through controlled silica nanoparticle synthesis and drop casting techniques, promoting short-range ordered arrays that enhance color visibility.

III. MATERIAL AND METHODS

The chemical reagents used throughout the experiments are tetraethyl orthosilicate (TEOS, 99%, Research Lab Fine Chem Industries, India), ammonia catalyst (25% w/w, Glorchem Enterprise, Colombo), pure ethanol solvent (99%, Breckland Scientific Suppliers, UK), and distilled water (University of Moratuwa), all used as received. Black polyester satin fabric (200 GSM, EPI 280, PPI 180, Lean Textile Co., China) was used without modification. Glassware was cleaned with distilled water and ethanol, then air-dried. A hot-box laboratory oven (SDL Atlas Textile Testing Solutions) provided elevated temperatures to accelerate self-assembly.

A. Synthesis of uniform SiO_2 nanoparticles

Silica nanoparticles were synthesized via a modified Stöber method. In a 250 ml beaker, 73 ml ethanol was stirred at 600 rpm and heated to 60 °C. TEOS (6 ml) was added dropwise, followed by a dropwise addition of 8 ml ammonia and 3 ml distilled water. The reaction continued at 60 °C under constant stirring for three hours.

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B. Self-assembly of silica nanoparticles on fabric

To prevent solution absorption and promote thin film formation, fabrics were pre-wetted with ethanol. A measured volume of unpurified suspension was drop-cast onto polyester satin fabric and oven dried at 60 °C to promote photonic crystal film with a periodic silica nanoparticle array.

C. Characterization of SiO_2 photonic crystals

Scanning Electron Microscopy (SEM; Carl Zeiss Evo 18) was used to analyze the thin film morphology and average nanoparticle size. Structural color visibility of coated fabrics was evaluated in a standardized lightbox to ensure color consistency and reliability.

IV. RESULTS AND DISCUSSION

A. Formation of structural color via particle arrangement

In the preliminary experiments, the films deposited on glass substrates exhibited agglomeration and poor uniformity, resulting in a whitish appearance (Figure 1). This issue was resolved by optimizing solvent volume, stirring speed, and reagent addition rate, as well as maintaining a sealed reaction environment.

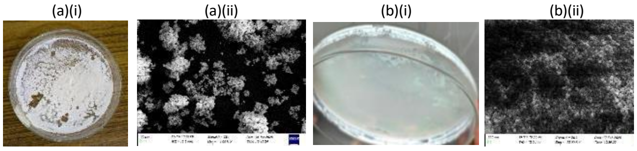

Fig. 1. Nanoparticle thin film (a)(i) agglomerated, (a)(ii) SEM image 50K magnitude, (b)(i) partially agglomerated, (b)(ii) SEM image 50K magnitude

Modifications to the synthesis process produced self-assembled periodic arrays that generated visible structural colors on specific regions of the petri dish. Analysis of the SEM images revealed irregular nanoparticle arrangements, which were attributed to uneven coating thickness on the glass substrate. To address this issue, different coating thicknesses were investigated by varying the volume of the synthesized solution (1ml, 3ml, 5ml, 7ml, 10ml and 15ml). The results confirmed that film thickness significantly influences color formation by minimizing agglomeration and improving the uniformity of the nanoparticle arrays.

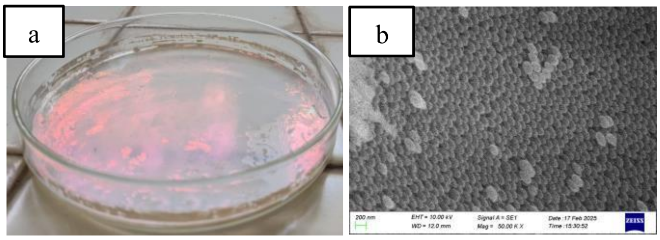

Fig. 2. Ordered silica nanoparticle thin film (a)petri dish, (a)SEM image 50K magnitude

Building on these findings, silicon dioxide nanoparticles were successfully prepared using a modified Stöber method, creating uniform, spherical particles that self-assembled into ordered thin films producing iridescent colors. The vividness of structural colors depends on both uniform particle size and periodic arrangement within the photonic crystal. When these conditions are not maintained, the structural order is disturbed, leading to weaker color formation. SEM images confirmed a close-packed, well-ordered regions, enabling constructive light interference and angle-dependent color (Figure 2). In contrast, agglomerated or irregular regions appeared white (Figure 1).

B. Different colors achieved by structurl color

The generation of different colors through the photonic crystal mechanism is primarily driven by the diameter of the silica nanoparticles. Once spherical and uniformly sized silica particles were synthesized, further adjustments to the process enabled the formation of monodisperse particles with different average diameters. These particles were coated onto glass substrates to produce structural colors (Figure 3).

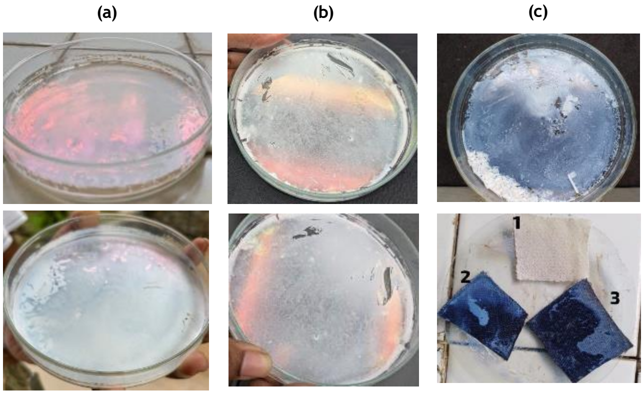

Fig. 3. Visible colors corresponding to silica nanoparticle diameters of (a) 385 nm, (b) 313 nm, (c) 145 nm

The particle diameters were measured by analyzing the SEM images, and a clear correlation was identified between particle size and the resulting visible color, as summarized in Table 1. An increase in particle diameter led to a red-shift in the visible color, whereas a decrease in particle size caused the observed color to shift toward the blue region.

TABLE I. STRUCTURAL COLOR VISIBILITY WITH RESPECT TO AVERAGE PARTICLE SIZE

Observation	Average diameter (nm)
Red to orange angle-dependent color shift	385.971
Red to yellow angle-dependent color shift	313.623
A single shade of blue on both glass and fabric surfaces	145.041

The experimental findings indicate that to achieve visible colors varying from blue to red, the silica nanoparticle diameter must be varied within the range of approximately 145–390 nm. This observation is consistent with literature reports on photonic crystal-based coloration.

C. Structural color on fabric surfaces

During trials, it was identified that achieving structural color on fabrics depends strongly on fiber type, surface structure, and background color. The results are summarized in Table 2.

TABLE II. SELECTION CRITERIA FOR FABRIC SUBSTRATES

Type	Identified reason
Synthetic polyester	Smooth filamentous surface enables uniform nanoparticle deposition compared to staple fibers.
Satin weave structure	Provides a more stable and uniform surface than knitted fabrics. Offers high cover factors and minimal surface texture, making it more suitable for nanoparticle deposition than plain or twill weaves.
Black color fabric	White fabrics reflect excessive light, interfering with Bragg diffraction and diminishing visible structural color. Black fabrics maximize contrast by absorbing background light and providing a low-reflection background. This maximizes contrast, allowing the structural color generated by the photonic crystal and enhances color vibrancy.

As shown in Figure 4, no visible structural color was observed on white fabric. In contrast, black satin and black twill fabrics displayed clear structural colors. Under a standardized lightbox, a slight shift from blue to white was noted with changes in the viewing angle for both satin and twill fabrics, indicating the presence of short range ordered particle deposition. The structural colors were most vibrant under UV and fluorescent lighting, highlighting the unique nature of structural color, which arises from the underlying photonic crystal structure rather than chemical pigmentation. Among the tested fabrics, black satin showed the best results due to its smooth surface and high contrast, which maximizes the visibility of structural colors.

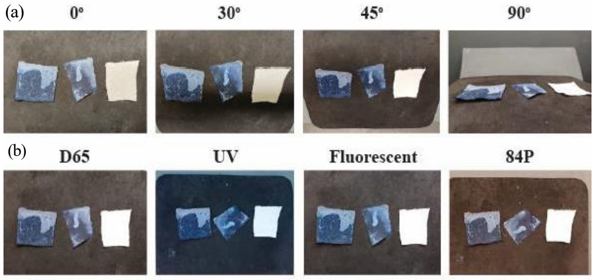

Fig. 4. Black twill, black satin, white fabric respectively in (a) D65 light box images with respect to viewing angle, (b) Lightbox images under different light sources

V. CONCLUSION

This study demonstrated the successful fabrication of nano-structural color on polyester satin fabric using silica (SiO_2) nanoparticles synthesized via a modified Stöber method. The nanoparticles self-assembled into ordered photonic crystal films, producing vivid, dye-free colors with iridescent effects. A clear relationship between particle diameter and visible color was identified, where smaller particles yielded blue hues, while larger particles shifted the color toward red. By controlling particle size within the 100–400 nm range, structural colors including red-orange, red-yellow, and blue, was achieved. Among the tested fabrics, black polyester satin provided the most favorable surface for uniform nanoparticle deposition and enhanced color visibility.

Future work should focus on evaluating the durability of structural coloration under washing and abrasion and on optimizing application methods to improve coating uniformity and scalability. These steps will help advance nano-structural coloration as a sustainable, pigment-free alternative for textiles.

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