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Fabrication and Applications of Textile-Based Structurally Colored Materials

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ABSTRACT

Textile-based structurally colored materials have emerged as a captivating field of research and innovation, presenting unparalleled prospects to revolutionize the realm of textiles and their diverse applications. This review paper provides a comprehensive overview of the progress made in the manufacturing methods and applications of structurally colored textiles. Based on the principles of Bragg diffraction and its extended theorems, the mechanisms behind the generation of structural colors in textiles are explored, revealing the underlying principles that enable coloration. The versatile and effective strategies adopted for the fabrication of textile-based structurally colored materials, such as gravity sedimentation, spray coating, vertical deposition, screen printing, shear-induced assembly, additive manufacturing or three-dimensional (3D) printing, dip coating, electrophoretic deposition, and electrospinning methods are discussed. The applications of textile-based structurally colored materials are discussed, with a specific focus on anti-counterfeiting measures, the biomedical field, and radiative cooling applications. This review aims to drive the progress of fabricating and functionalizing textile-based structurally colored materials, with the ultimate goal of expanding their applications in diverse fields.

1 | Introduction

Colors play a fundamental and indispensable role in the evolution and survival of plants and animals [1–4]. Structurally colored materials have garnered considerable interest in the past few decades due to their captivating aesthetics and versatile applications across industries [5–9]. Structurally colored textiles with intricate patterns and photonic crystals [10–14], renowned for their vivid structural colors, draw inspiration from the natural phenomenon of structural coloration found in living organisms like butterfly wings [15, 16], peacock feathers [17, 18], beetle exoskeletons [19, 20] and kingfisher feather barbs [21], as illustrated in Figure 1. Textile-based structurally colored materials present a compelling opportunity for the development of visually stunning and functional materials. Structural coloration is a captivating optical phenomenon that occurs when the color of an object is not determined by pigments or dyes but rather by the physical structure and properties of the material. In contrast to traditional coloration methods, which rely on the absorption and reflection of specific wavelengths of light, structural coloration arises from the interaction of light with microscopically structured surfaces or materials within the scale of visible wavelengths [22], leading to unique optical effects and vibrant colors that are not achievable with traditional dyes. Except for

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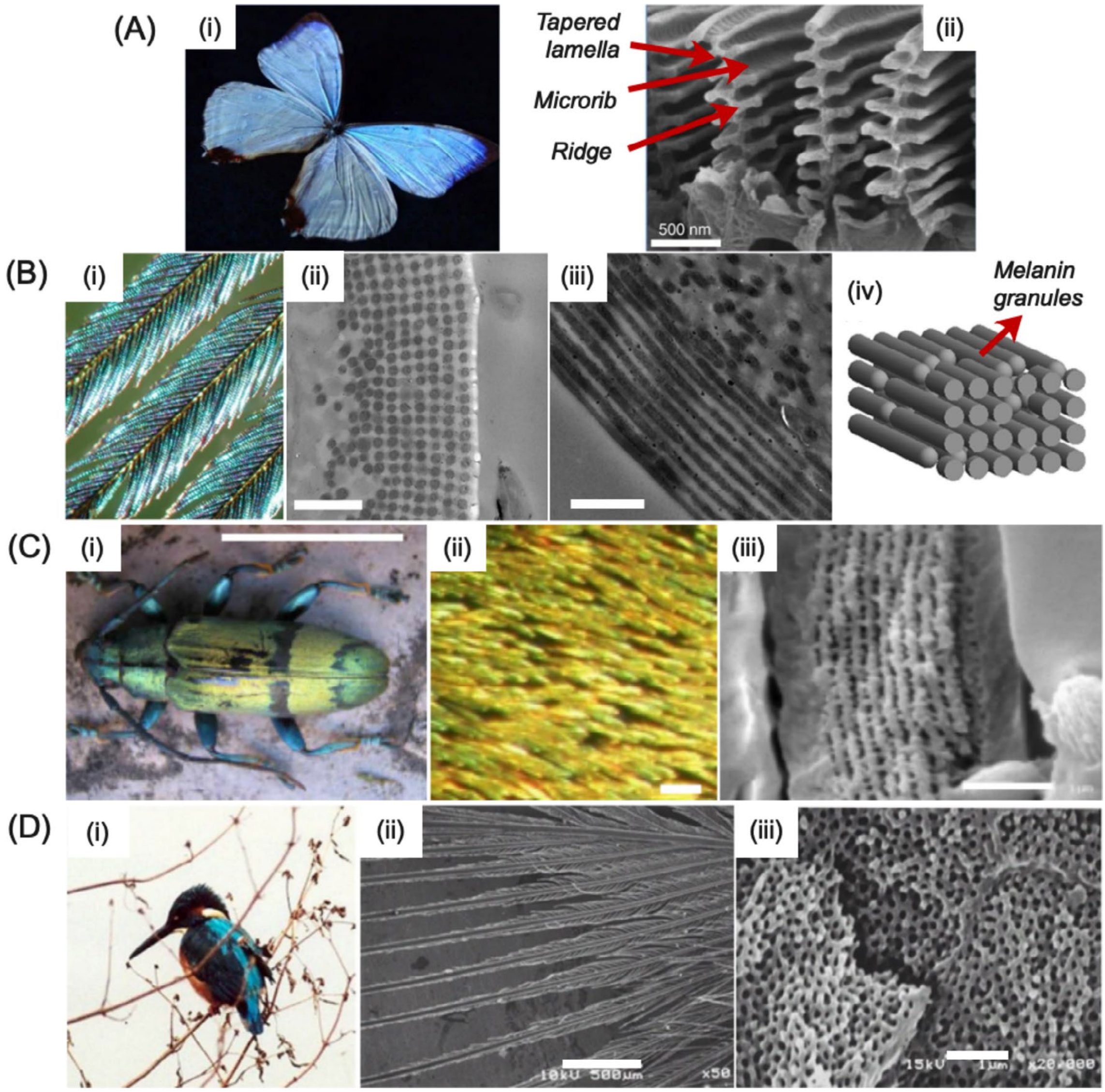

FIGURE 1 | Structural coloration inspired by various creatures (A) Butterflies: (i) Photo of Morpho butterflies and (ii) tree-like tapered structure on their scales. Scale bar: 500 nm. Reproduced under the terms and conditions of Creative Commons Attribution 4.0 International (CC BY) license [16]. Copyright 2015, The Authors. Published by Springer Nature. (B) Peacocks: (i) Optical image of the feather barbule of a peacock, TEM images of (ii) cross-section and (iii) longitudinal section of feather barbule, and (iv) Schematic diagram illustrating the organization of melanin granules in peacock feather barbules. Scale bars: (ii) and (iii) 1 μm. Reproduced with permission [18]. Copyright 2021, Springer Nature. (C) Beetles: (i) Photos of beetle *Tmesisternus isabellae*, (ii) Close-up of the golden-colored region on the elytra, where the surface is densely covered with colored scales, and (iii) Cross-section of a scale showing a clear multilayer structure inside. Scale bars: (i) 10 mm, (ii) 100 μm, and (iii) 1 μm. Reproduced with permission [20]. Copyright 2009, Optica Publishing Group. (D) Kingfishers: (i) Photo of a Kingfisher, (ii) SEM images of its feather barbs, and (iii) the cross-section of a barb. Scale bars: (ii) 500 μm and (iii) 1 μm. Reproduced with permission [21]. Copyright 2005, Wiley-VCH.

different mechanisms of coloration between structurally colored textiles and traditional dye-based coloration, it also offers other distinct advantages and differences. In terms of environmental impact, traditional dye-based coloration processes often rely on the utilization of chemicals, substantial water consumption, and energy-intensive procedures. Conversely, textile-based structurally colored materials offer potential environmental benefits. By reducing reliance on chemical dyes and minimizing water usage during the coloration process, textile-based structurally colored materials have the potential to foster more sustainable and eco-friendly manufacturing practices [23]. Textile-based structurally colored materials can exhibit a broader range of colors and higher color vibrancy compared to traditional dye-based coloration. By engineering the size, shape, and arrangement of structures, it is possible to achieve vivid and dynamic colors that can be angle-dependent, iridescent, or possess other visually captivating properties [24]. Furthermore, better durability and colorfastness of structural colored textiles can be achieved without damaging the periodic crystal structures due to the structural color generation mechanism. Structural colors are not susceptible to fading or washing out since they are not reliant on chemical dyes that may degrade over time [25, 26]. This makes textile-based structurally colored materials exhibit enhanced resistance against fading, washing, and environmental factors such as sunlight or harsh chemicals. Most textiles possess high flexibility and can readily return to their original shape after

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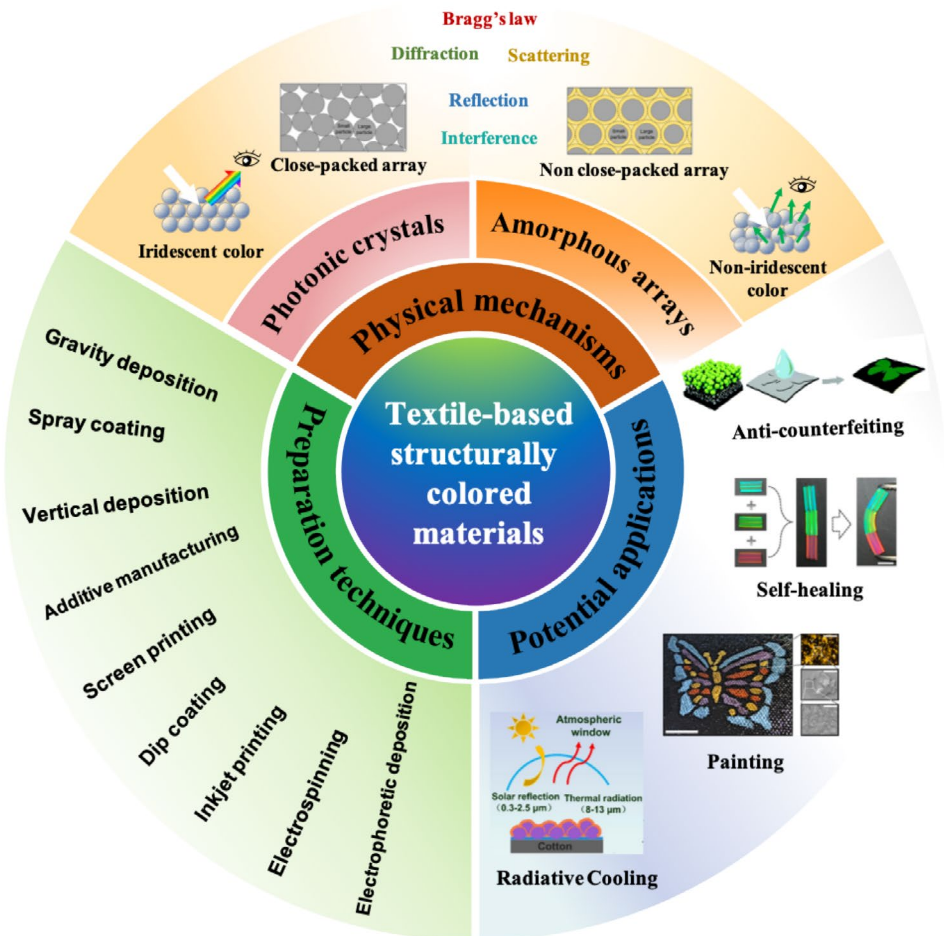

FIGURE 2 | Physical mechanisms, preparation techniques and applications of textile-based structurally colored materials. Close-packed arrangement in a gas medium and non-close-packed arrays in a liquid medium. Reproduced with permission [31]. Copyright 2019, Wiley-VCH. The structure of anti-counterfeiting labels and the water-assisted emerging process of the encrypted butterfly pattern with structural color. Reproduced with permission [32]. Copyright 2019, Royal Society of Chemistry. Self-healing process of three kinds of hydrogel microfibers with different structural colors. Reproduced with permission [33]. Copyright 2017, The Authors. Published by National Academy of Sciences. A multicolor butterfly pattern photographed on a black canvas painted with plasmonic paints based on linseed oil. Insets show a microscope image and SEM micrographs. Reproduced with permission [34]. Copyright 2023, American Association for the Advancement of Science (AAAS). A cotton fabric that is both self-cleaning and spectrally selective for passive radiative cooling. Reproduced with permission [35]. Copyright 2021, Elsevier.

being bent or crumpled [27]. Stimuli-responsive textiles with shape-changing and recovery properties [28], which are also applicable to photonic crystal-based structurally colored textiles, offer significantly enhanced design flexibility. In a recent study, it has been confirmed that once the appropriate adhesive is employed, structurally colored textiles can endure any degree of folding and kneading with negligible impact on color visibility while still presenting clear patterns [29]. Moreover, through structural coloration, precise control over the arrangement, size, and geometry of structures can be exercised, allowing for the attainment of specific visual effects. The customizable patterned fluorescence-responsive photonic crystals have been designed and synthesized by the emulsion polymerization method to embed aggregation-induced emission molecules into core-shell colloidal nanospheres, and then constructed on textile substrates by screen printing technology using the nanospheres as building blocks, achieving excellent optical properties and sensitive anti-counterfeiting properties, providing a reference for sustainable structural coloring in the textile industry [30]. Textile-based structurally colored materials provide an environmentally friendly alternative to traditional coloration methods, reducing dependence on chemical dyes and realizing sustainable coloration in textile production.

In this review, we opt to give a brief concept of structural coloration, summarize the research progress in construction techniques of textile-based structurally colored materials, and highlight their applications in various promising fields (Figure 2) [31–35]. The unique visual appeal, optical effects, and functional properties of textile-based structurally colored materials make them suitable for diverse applications such as smart textiles, multi-responsive materials, biomedical, and radiative cooling purposes. This is what is expected to be seen that by studying the progress in construction and applications of textile-based structurally colored materials due to its potential impact on textile technology, sustainability, design innovation, functional textiles, cross-disciplinary collaborations, and industrial applications, this research serves a dual purpose: illuminating the technological strides made in the realm of structural color textiles while simultaneously contributing to the development

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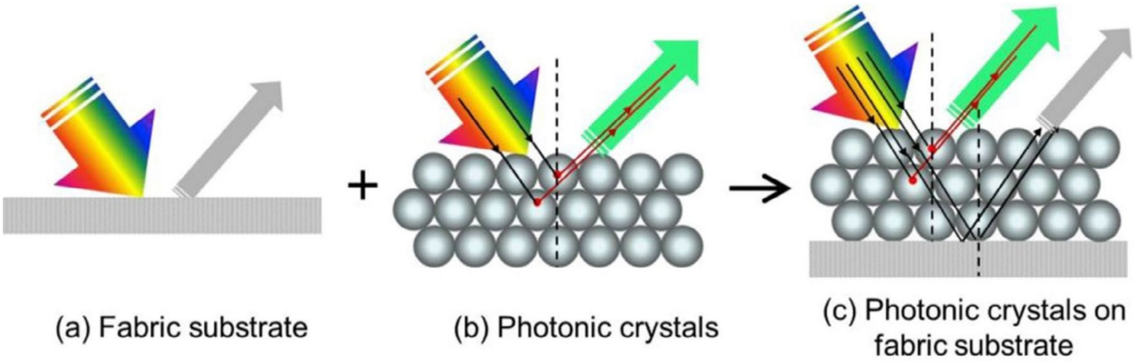

FIGURE 3 | Illustration of white incident light on textile substrates. Reproduced with permission [42]. Copyright 2016, Elsevier.

of visually striking, environmentally friendly, and functionally enhanced textiles for a wide range of industries.

2 | Mechanisms of Structural Color Generation on Textiles

The phenomenon of structural coloration arises from the interplay of interference, diffraction, scattering, and selective reflection mechanisms on micro- or nanostructures [36]. When light interacts with a structured surface, it experiences constructive or destructive interference, giving rise to unique structural colors [37]. The specific arrangement and spacing of these structures determine which wavelengths of light are enhanced or suppressed, ultimately determining the observed color [38]. Photonic crystals, which possess two- and three-dimensionally periodic structures, have the ability to manipulate the propagation of light [39]. When light encounters a photonic band gap, a portion of it will be reflected at the same angle as the incident angle. However, outside of the band gap, some light can be transmitted or refracted, propagating at different angles within the photonic crystal. The presence of additional reflected and/or refracted waves depends on factors such as frequency, interface periodicity, and the overall band structure. This phenomenon is known as Bragg diffraction. When materials in a crystal have diverse dielectric constants and low light absorption, light interactions at interfaces mimic electron behavior. Photonic crystals, as low-loss dielectric mediums with photonic band gaps, offer a solution for optical control, preventing light propagation in specific directions with defined frequencies [40]. The color exhibited by photonic crystals in long-range order stems from the periodic arrangement of nanoparticles [41]. Photonic crystals in long-range order showcase varying angle-dependent and iridescent colors based on the observation angle due to the periodic arrangement of particles. If the photonic band gap aligns with the visible light spectrum, specific wavelengths of visible light are prevented from propagating within the photonic crystal structure, leading to their selective reflection, as depicted in Figure 3 [42]. Light scattering, unlike the photonic crystal type, serves as another source of structural colors and is derived from the irregularity of the structure [43]. Those short-range ordered photonic structures are usually stacked randomly with quasi-amorphous arrays. They do not display any color change with respect to the detection angle, exhibiting noniridescent and angle-independent colors, which have been reported to exist ubiquitously in natural organisms [25, 44]. By incorporating photonic crystal structures into textiles, the textile-based structurally colored materials subsequently become possible to selectively reflect specific wavelengths, resulting in the generation of various structural colors. Although the fibrous and porous nature of textiles can affect the uniformity of the photonic crystal structure, when colloidal particles contact photonic crystals on fabric substrates, they initially fill fiber gaps during the self-assembly process. Once these gaps are filled, subsequent colloidal particles self-assemble into an ordered crystalline structure on the flat surface [45]. The subsequent photonic crystal formation process is similar to that on conventional smooth and rigid substrate materials. Substrate flexibility and the good binding strength between the photonic crystal, especially using soft polymer colloidal particles and the fabric substrate, provide more potential practical applications in wearable smart clothing [46]. To display vibrant structural colors, light must exhibit high reflectance within the photonic band gap and high transmittance at other wavelengths. Black textile substrates exhibit significant absorption of transmitted and scattered light beyond the photonic band gap, effectively enhancing the chroma of structural colors [42].

In general, the positions of the reflection peak (λ_{max}) of textile-based structurally colored materials can be estimated by the Bragg-Snell diffraction law [23, 47].

$$\lambda_{\max} = \frac{2d}{m}\left(n_{\text{eff}}^2 - \sin^2\theta\right)^{1/2} \quad (1)$$

where λ_{max} represents the wavelength corresponding to the wave with the highest reflected intensity from the photonic crystal, d is the spacing between crystal planes, m is the diffraction level and θ is the incidence angle. n_{eff} denotes the effective refractive index of the crystal array which can be further expressed as

$$n_{\text{eff}} = \left(\Sigma n_i^2 f_i^2\right)^{1/2} \quad (2)$$

where n_i represents refractive indices of each component in photonic crystal array and f_i is the relative proportions or fractions of each component within the photonic crystal structure.

According to the above equation, it is proved that the wavelength of coherent diffraction changes generally depending on the observation angle, and there is a correlation between the maximum wavelength and micro-/nano-particle diameter governed by the diffraction property, which approximately follows Bragg's law [48].

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In order to develop the functionality of photonic crystal-based arrays, functional polymer matrices are usually added to the photonic crystal structures to generate non-close-packed colloidal arrays endowed with functional performances like mechanically reinforced or multiple responsive properties. The arrangement of nanoparticles in long-arranged colloidal crystal arrays is widely recognized as face-centered cubic (fcc) lattices [49]. The peak positions (λ_{max}) observed in non-close-packed fcc lattices loaded with colloidal nanoparticles could be calculated. The dependence of λ_{max} on the diameter is approximately in accordance with Bragg's diffraction equation for (111) planes of a non-close-packed fcc lattice [31, 50–52].

$$\lambda_{111} = 2d_{111}n_{eff} = \left(\frac{\pi}{3\sqrt{2}\phi}\right)^{1/3}\left(\frac{8}{3}\right)^{1/2} d\left(n_{\text{particle}}^2\phi + n_{\text{matrix}}^2(1-\phi)\right)^{1/2} \quad (3)$$

where d_{111} is the distance between two neighboring (111) planes, which is affected by the filling ratio (ϕ) and diameter of nanoparticles (d), respectively. The effective refractive index of the composite, n_{eff}, is estimated using the Maxwell-Garnet average of the refractive indices of the micro- or nano-particles (n_{particle}) and the polymer matrix (n_{matrix}).

Based on underlying principles and the mechanisms of structural color generation, idea and controllable textile-based structurally colored materials could be achieved for their potential applications by controlling the multiple factors influencing the formation of structural colors. The choice of materials is significant because different materials possess unique surface hydrophobicity/hydrophilicity and optical properties. The size, shape, and composition of colloidal micro- or nano-particles, the interaction between the structured material and the incident light determines which wavelengths are selectively reflected or scattered, and the geometry, arrangement, and uniformity of the structures on or within the material also play a significant role in color formation [53, 54]. As indicated in Equations (1) and (3), the refractive index contrast between the material and its surrounding medium affects the interference effects and color intensity. Some structural colors can exhibit angle-dependent effects; the color formation is accordingly influenced by the characteristics of the incident light source. In other words, the structural color will shift with the change of incident light [55]. Additionally, environmental factors like humidity, temperature, and exposure to light can cause variations in structural coloration [56].

3 | Preparation Techniques for Textile-Based Structurally Colored Materials

Generating structural colors on textiles involves various methods and techniques that manipulate the surface or structure of the textile materials including fibers or fabrics woven from fibers, which can be classified into several distinct categories. These methods include gravity sedimentation, spray coating, vertical deposition, 3D printing, screen-printing, dip coating, ink-jet printing, electrospinning, and electrophoretic deposition. These techniques, as exemplified in Figure 4, are frequently employed to achieve vibrant structural colors within the visible light spectrum on textiles [57–62].

3.1 | Spray Coating

The biomimetic creation of amorphous photonic crystal patterns on a substrate surface can generate distinct noniridescent structural colors, suitable for diverse applications in textiles, paints, and other industries [63, 64]. Spray coating has been utilized for the rapid larger-scale application of amorphous photonic crystals with excellent colorfastness onto textiles, enabling high-speed production [65]. When employing the spray coating technique, the extensive atomization of the emulsion prompts the rapid evaporation of the solution, facilitating the swift assembly of colloidal particles into short-range ordered yet long-range disordered amorphous photonic crystal structures [66]. During this process, the textile surface is coated by atomizing and spraying a specially formulated solution or suspension that contains photonic dyes, colloidal nanoparticles, or other photonic materials capable of producing colors (Figure 4A). The spray coating method is versatile and can be applied to a diverse range of textile materials, encompassing natural fibers, synthetic fabrics, and blended textiles [25, 57, 67, 68]. It is seamlessly compatible with various textile manufacturing processes and can be easily incorporated into existing production lines. The scalability of this method makes it suitable for a wide range of applications, from small-scale research projects to large-scale industrial production [69, 70]. It can be readily adjusted to accommodate different sizes and quantities, enabling efficient and cost-effective manufacturing processes. Fu et al. [57] presented a common spray coating technique for producing iridescent structural colors on fabrics like cotton, polyester, viscose, and polyamide on versatile textiles by the usage of poly(St-MMA-AA) particles. The photonic crystal patterns on textiles were of high quality and the resulted fabric had a flexible and tough character. In Tang's research, an innovative spray coating method was introduced for constructing noniridescent structural color coatings that exhibit high color visibility, excellent structural stability, and possess self-healing abilities [71]. Li's work demonstrated that noniridescent and structurally stable vibrant colors were successfully created on textile substrates using a straightforward spray coating technique. The resulting textiles exhibited amorphous photonic structures that resembled the amorphous nanostructures found in avian feathers [72].

3.2 | Gravity-Based Methods

3.2.1 | Gravity Sedimentation

Gravity sedimentation occurs as particles naturally settle under the influence of gravity, driven by their own weight, which has been a common fabrication method used to create vivid structural colors on different textiles like carbon fiber fabrics (Figure 4B) [58, 73], cotton fabrics [74, 75], polyester fabrics [76] and silk fabrics [77]. In the gravity sedimentation process, suspended particles within a liquid medium settle gradually under the influence of gravity, leading to the formation of well-organized structures. By precisely controlling factors such as particle size, concentration, and suspension conditions, desired structural arrangements that give rise to vibrant and iridescent colors in the textiles can be achieved. This method allows for meticulously controlling particle behavior, enabling the generation of visually stunning and captivating structural color

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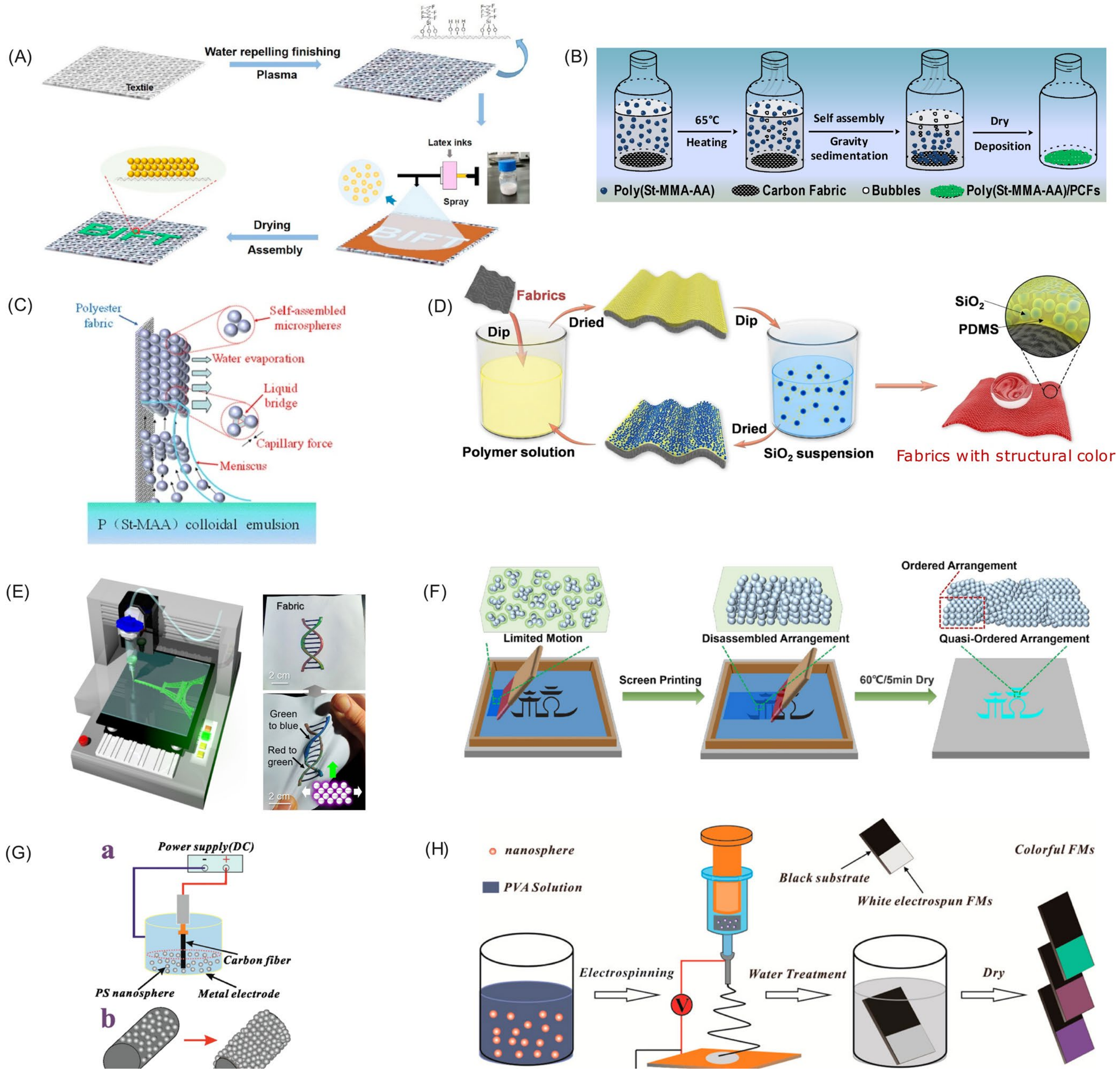

FIGURE 4 | (A) Spray coating process of photonic crystal patterns on textiles. Reproduced with permission [57]. Copyright 2021, Elsevier. (B) Schematic diagram of preparation process of photonic crystal films on fabric by thermal assisted gravity sedimentation method. Reproduced under the terms and conditions of Creative Commons Attribution 4.0 International (CC BY) license [58]. Copyright 2020, The Authors. Published by MDPI. (C) The mechanism behind the vertical deposition of colloidal micro-particles on fabric substrate. Reproduced with permission [59]. Copyright 2016, Springer Nature. (D) Dip coating process of photonic crystal coated fabrics with angle-independent color. Reproduced with permission [41]. Copyright 2023, Springer. (E) Left part is the dispenser for line drawing with a moving nozzle and the right part is the nucleic acid double helix drawn on fabric using phenyl ether acrylate (PEA) inks. The insets represent lattice deformation by stretching. Reproduced with permission [60]. Copyright 2021, American Association for the Advancement of Science (AAAS). (F) Preparation process and the mechanism of screen-printed photonic crystal patterns. Reproduced with permission [13]. Copyright 2022, American Chemical Society. (G) The preparation of structurally colored carbon fibers by electrophoretic deposition. (a) Set-up of electrophoretic deposition process. (b) Assembly of colloidal nanoparticles on fibers. Reproduced with permission [61]. Copyright 2013, American Chemical Society. (H) Fabrication of structurally colored fibers by electrospinning technique. Reproduced with permission [62]. Copyright 2015, American Chemical Society.

effects. Durable, washable, steam-permeable fabrics exhibiting solvatochromic structural color shifts were created using poly(styrene–butyl acrylate–acrylic acid) (P(St–BA–AA)) microspheres [78]. Upon wetting the fabric, its color alters. Once the wet fabric dries entirely, its original black color reappears (Figure 5A). When the colloidal suspension seeped into the fabric, the fabric appeared light green initially (Figure 5A-i) due to the high concentration of colloidal latex and the negatively

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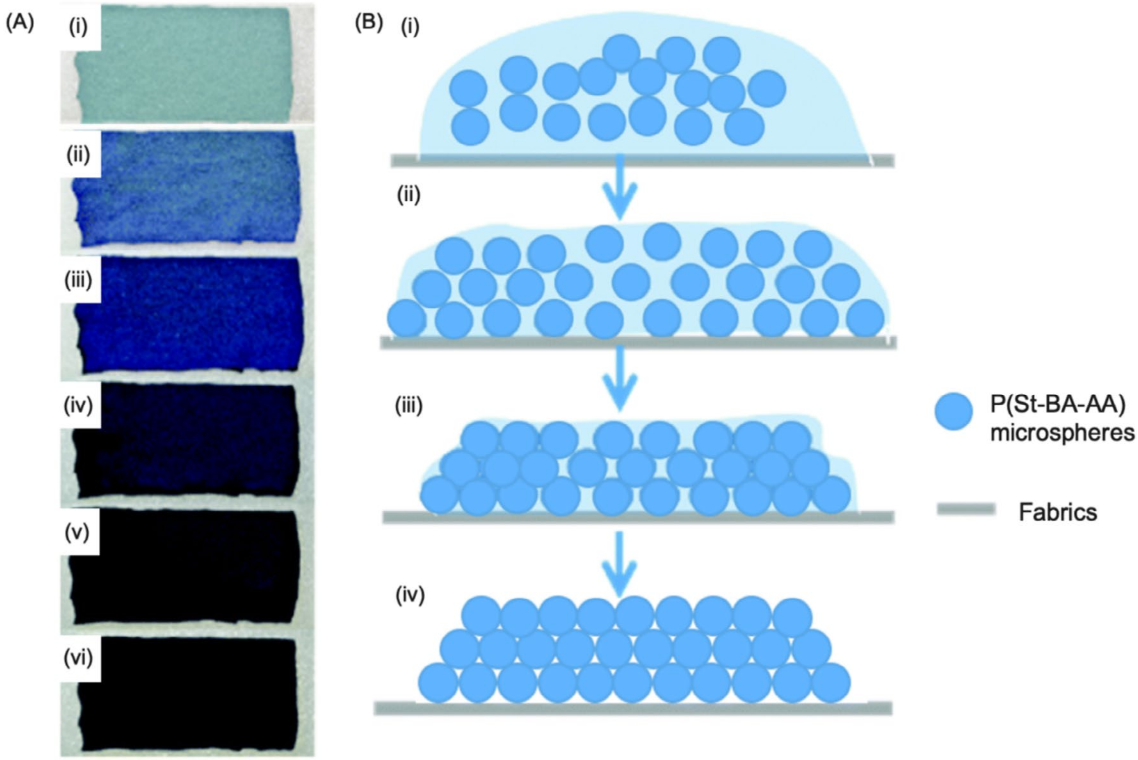

FIGURE 5 | (A) Photos of the self-assembly process of the P(St–BA–AA) core-shell colloidal microspheres measuring 206 ± 50 nm in diameter on a woven fabric, (i–vi) color change of the colloidal suspension on the fabric shifting from green to green-blue, then to blue, blue-black, and finally to black. (B) Proposed mechanism of (i–iv) the assembly process of colloidal microspheres on individual yarns. Reproduced with permission [78]. Copyright 2019, Royal Society of Chemistry.

charged surface of the P(St–BA–AA) microspheres, which repel each other, forming regular arrangements within the latex. As the solvent evaporates, the color at the edge of the fabric undergoes the initial change. Ultimately, the color returns to black once the suspension completely dries (Figure 5A-ii–vi). The proposed mechanism for microsphere self-assembly is shown in Figure 5B; high-density colloidal emulsion with negatively charged surfaces initiates crystal formation. Concentration rises as solvent evaporates, inducing a coffee ring effect, leading to edge-first crystal formation. Evaporation results in a compact crystal structure on yarn surfaces, transforming into a dense polymer film post-evaporation. Shao's group successfully fabricated polyester fabrics adorned with high-quality silica (SiO_2) photonic crystals exhibiting a fcc array by gravitational sedimentation self-assembly [45]. Full structural colors of SiO_2 photonic crystals on polyester fabrics were obtained. The fabrication of photonic crystals using colloidal microspheres of various sizes on polyester fabrics results in distinct structural colors that span the entire visible spectrum. Li et al. [77] fabricated SiO_2 photonic crystals on silk and polyester fabrics in different textures by gravitational sedimentation self-assembly method, and they found that textile fibers that possess fewer polar groups and water-soluble groups on their macromolecular chains have the potential to facilitate the filling of voids and gaps between fibers and yarns by colloidal microspheres during the initial self-assembly process. Moreover, such fibers can ensure the availability of a greater number of residual colloidal microspheres in colloidal dispersion, thereby enabling their active involvement in the subsequent self-assembly stages. However, Gravitational sedimentation, relying on the natural settling of particles, can be a time-consuming process to achieve the desired structure [79]. This characteristic poses limitations in terms of production speed and efficiency, especially when considering large-scale manufacturing requirements, making it less practical for mass production. Smaller particles tend to exhibit longer settling times, whereas larger particles may experience uneven settling or lead to aggregation issues.

3.2.2 | Vertical Deposition

Based on evaporation-induced colloidal assembly, the vertical deposition method offers a relatively effective method for crafting high-quality colloidal crystal structures. In this approach, a substrate is immersed vertically into a suspension containing uniform colloidal particles. As the solvent evaporates, the solvent surface moves downward, resulting in the self-assembly of colloidal particles into a photonic crystal film onto the substrate [80]. This process occurs as the solvent surface gradually declines [81]. Drawing upon the unique surface properties of the substrate material, a diverse array of structural colored fabrics or yarns can be meticulously crafted through the process of vertical deposition [82–84]. Vertical deposition has many similarities with the gravity sedimentation method, but it primarily involves the controlled process of depositing colloidal particles onto a textile substrate in a vertically oriented manner, resulting in the formation of structured patterns or layers. The capillary force effects play a crucial role in the preparation of structural color materials on textiles using the vertical deposition method. It primarily originates from the meniscus formed between the

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colloidal microspheres and the vertical polyester fabric substrate, as well as the liquid bridges between adjacent colloidal microspheres (Figure 4C) [59]. From Liu's study, poly(styrene-methacrylic acid) (P(St-MAA)) photonic crystals with fcc structure and full colors were fabricated on polyester fabrics by vertical deposition self-assembly [85]. Their work proved that the textile-based structurally colored materials obtained from this process exhibited clear fabric texture, a double-sided coloration effect and comfortable fabric handle. But the fabrication of structurally colored textiles by vertical deposition has limitations when it comes to large-scale production owing to the nature of this process, which involves the immersion and long-time evaporation of the solvent. Meanwhile, to ensure consistent and desired outcomes using the vertical deposition method, precise control and optimization of essential parameters such as suspension composition, immersion speed, and drying conditions are crucial. Based on the mastery of preparation parameters, Shao's team has successfully prepared structurally colored fabrics using the vertical deposition self-assembly method [86]. The prepared photonic crystal fabric not only exhibits vibrant structural colors but also demonstrates high hydrophobicity due to the nano-scale dual-rough morphology of the poly(styrene-methacrylic acid) (P(St-MAA)) photonic crystal encapsulated on its surface resembling lotus leaves.

3.2.3 | Dip Coating

In addition to the two gravity-based methods mentioned above, dip coating has been extensively utilized in both industrial and laboratory settings due to its simplicity, cost-effectiveness, and ability to achieve high coating quality. The straightforward process, affordability, and reliable coating results of this method have made it the preferred choice in a wide range of applications [87]. The dip coating process can be described as applying aqueous-based liquid phase coating solutions onto the surface of a substrate material [88]. It is also a common fabric coating technique where the fabric is immersed in a coating solution to achieve a uniform and controlled deposition of the functional fabrics with desired properties such as superhydrophobic or water-repellent [89–91], superhydrophobic–superoleophilic [92], superamphiphobic [93], flame-retardant [94], thermoelectric [95] and UV-resistant properties [96]. Dip coating can be divided into several types including directly solution dip coating, sol–gel dip coating, spin-assisted dip coating, multi-layered dip coating, and vacuum-assisted dip coating on fibrous materials [88]. During the evaporation of the dispersion medium and the gravity of colloidal particles in the dip coating process, the substrate absorbs or accumulates the coating material onto its surface. Subsequently, the fabric substrate is typically dried or cured to solidify the coating and attain the desired properties [41]. This construction process of wash-resistant and antifouling photonic crystal coating is described in Figure 4D. Peng's group first applied the dip coating method to textile fibers, they used hard polystyrene/poly(methyl methacrylate) (PS/PMMA) core/soft poly(ethyl acrylate) (PEA) shell microspheres to prepare continuous dyeing-free mechanochromic fibers on spandex fibers/composite fibers [97]. The obtained yarns could be woven into structurally colored fabrics or designed patterns, making them suitable for potential applications in smart wearable textiles. Subsequently, research on using this method to prepare structural color fabrics based on textile fabrics has gradually emerged. Achieving consistent structural coloration relies on the uniform distribution of coating material across fabric surfaces facilitated by smooth surfaces during the dip coating process. The surface of some textile materials, such as polyester and aramid fiber, is relatively smooth, which is conducive to the self-organization and regular arrangement of photonic crystals. Tan's team employed a dip coating method to create structurally colored fabrics based on smooth-surfaced and yellow-colored aramid fabric substrates. The resulting fabrics have angle-independent colors and wash resistance, potentially serving as a recyclable photonic catalyst [98]. Zhang et al. also successfully utilized the dip coating method to create structurally colored fabrics with angle-dependent color and hydrophobicity on a smooth polyester fabric surface by using carefully modified hydrophobic SiO_2 colloidal particles (h-SiO_2 CPs) as building blocks. The structurally colored fabrics demonstrate remarkable durability, withstanding rinsing, laundering, bending, stretching, and kneading, thereby highlighting the practicality of the dip coating method, holding extensive potential for application within the textile coloring industry [99].

3.3 | Printing Techniques

3.3.1 | Screen Printing

Screen printing has a wide range of applications across diverse industries, including flexible electronics, batteries, solar cells, the food industry, and medical applications [100–105]. Before its integration into the creation of structural color materials, screen printing has been widely employed in the textile industry for fashioning conductive textiles, sensors, and textile electrodes, showcasing its versatility and utility in various applications [106–108]. Screen printing enables the rapid and straightforward creation of large-scale patterns with high resolutions reaching hundreds of micrometers [109]. The general process of screen printing includes the following steps: a mesh screen with a stencil made from photosensitive emulsion is created and exposed to light to define the pattern; the printing pastes, containing functional color-producing colloidal particle inks like temperature/electrical/magnetic/pH responsive inks or photo-responsive inks, are applied to the screen; a squeegee or blade applies shear force to push the paste through the mesh onto the textile substrate; finally, the printed fabric is dried and cured to ensure the material adheres and maintains its structural integrity [110, 111]. The shear force applied by the squeegee and the rheological properties are crucial for the deposition of the printing paste or inks, significantly impacting the quality of the printing process [112, 113]. It refers to the frictional force created when a squeegee or blade is pulled across a screen, pushing the ink through openings in the mesh onto the substrates [114]. The color paste experiences flow and deformation when subjected to varying shear forces, and subsequently transfers onto the fabric through the mesh [13], the screen printing process is shown in Figure 4F. Shear-induced assembly involving the controlled application of shear forces such as flow, agitation, or mechanical shearing has been applied to facilitate the self-organization and alignment of particles or structures on the textile surface [115, 116]. Screen printing has gained widespread utilization

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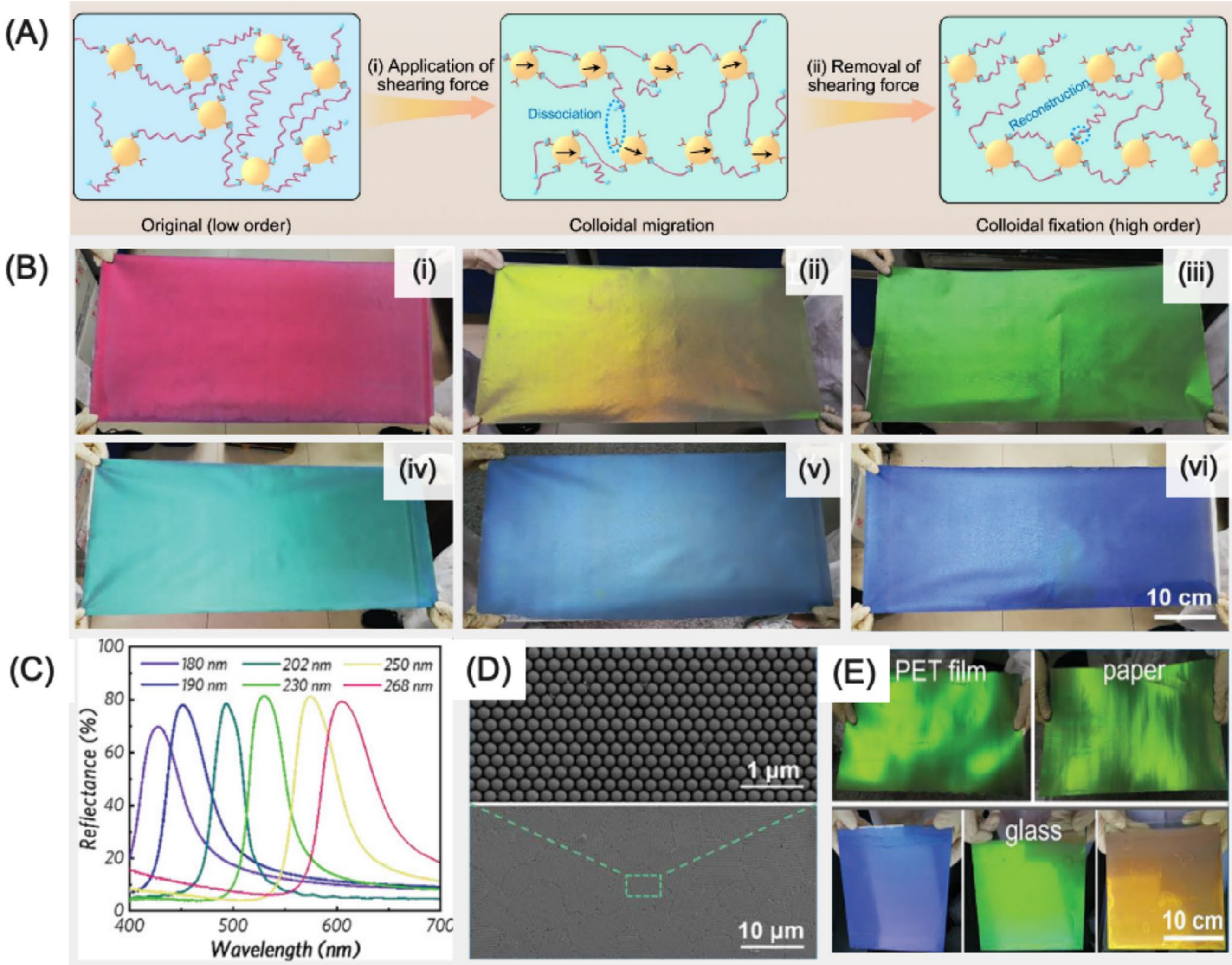

FIGURE 6 | (A) Schematic diagram illustrating colloids migrating and fixing in a supramolecular composite under shearing treatment. Reproduced under the terms and conditions of Creative Commons Attribution 4.0 International (CC BY) license [123]. Copyright 2024, The authors. Published by Springer Nature. (B) Digital photos of photonic crystal films exhibiting brilliant structural colors on a large scale on fabric substrates with the sizes of polystyrene beads decreased from (i) to (vi) (268, 250, 230, 202, 190, and 180 nm), respectively. Reproduced with permission [124]. Copyright 2021, Wiley-VCH. (C) The corresponding reflection spectra of the structurally colored fabrics in (B). Reproduced with permission [124]. Copyright 2021, Wiley-VCH. (D) SEM images of the photonic crystal film using 230 nm polystyrene beads at different magnifications. Reproduced with permission [124]. Copyright 2021, Wiley-VCH. (E) Digital photos of the structural color coatings on other substrates. Reproduced with permission [124]. Copyright 2021, Wiley-VCH.

in the realm of traditional fabric dyeing and functional modification, especially on textile fabrics [117–120]. Through this process, the particles or structures align and arrange themselves, resulting in the creation of desired structural color effects. It can be used on a wide range of substrates, such as fabrics, paper, and plastics, which offers versatility in terms of the substrate materials. The printing paste comprises vehicles encompassing solvents, resins, and additives, and inorganic powders consisting of functional powders and glass powders. Rheological characteristics, including paste liquidity, thixotropy, and viscoelastic properties, significantly impact the quality of the printing process [121]. Screen printing can be executed on a large scale with the aid of automated equipment. Nevertheless, it is also possible to perform screen printing manually on a smaller scale using more affordable equipment [122]. Zhu's group found that the utilization of supramolecular composites composed of polyethyleneimine (PEI) polymer and carboxylated polystyrene (PS-COOH) colloids with supramolecular interactions (mainly hydrogen bonding and electrostatic interactions) allows for a gentle and effective method to produce large-scale structurally colored composite films through shear-induced assembly (Figure 6A). The PEI chains slid and elongated, causing partial dissociation of supramolecular interactions between the polymer and colloids owing to the shearing force (Figure 6A-i). This facilitated directional migration of colloids in the matrix, reducing viscous resistance and improving regular arrangement of the colloids. After the shearing force is removed, the disassembled supramolecular interactions autonomously reassemble, securing the ordered colloidal structure within the polymer matrix as viscosity is restored as demonstrated in Figure 6A-ii [123]. Li et al. [124] successfully fabricated large-scale photonic crystal films on hydrophilic fabric substrates by shear-induced assembly of liquid colloidal crystals under the action

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of a magnetic field (Figure 6B). From Figure 6C, it can be obviously observed that the reflection peaks are very sharp, confirming the high bandgap intensity and saturated structural color of these large-scale photonic crystals based on precisely arranged hexagonally close-packed arrays (Figure 6D). In addition to flexible fabrics as base materials, vibrant structural color coatings can be applied on other substrates like polyester (PET), drawing paper as well as glasses, validating the universality of the current preparation strategy (Figure 6E). According to Zhang's research, a fast screen-printing technique is employed to fabricate large-scale, vivid noniridescent structural colors on white fabric, ensuring robust structural stability. Meanwhile, a similar multistep printing process enables the effortless attainment of multi-color patterns on fabrics [125]. Screen printing has been widely recognized for its exceptional mass production capabilities [122], nevertheless, screen printing can be time-consuming, especially when dealing with intricate or complex designs, and the design of screen-printing inks is subject to stringent rheological constraints throughout the printing process [126]. Screen printing poses challenges when it comes to achieving seamless color gradients or complex color blends, and the reproduction of intricate details can present challenges.

3.3.2 | Additive Manufacturing

Additive manufacturing, also named as 3D printing, builds three-dimensional objects layer by layer and enables unprecedented design freedom, which opens up possibilities for creating unique and customized textile-based structurally colored materials with intricate patterns and designs that would be challenging to achieve through other fabrication methods [127, 128]. The geometry, size, and arrangement of structures can be readily adjusted and controlled, allowing for the customization of textiles according to individual preferences or specific functional requirements. 3D printing has the capability to achieve complex and dynamic color effects in structural colored textiles. Compared to subtractive manufacturing methods, 3D printing significantly reduces waste, leading to more sustainable production processes by minimizing material waste and waste recycling [129, 130]. Furthermore, 3D printing empowers manufacturers to swiftly iterate and refine their designs, expediting the development process and conserving time and resources. The straightforward approach of merging photonic inks with 3D printing technology enables rapid application of photonic ink droplets on various substrates, creating diverse photonic patterns. 3D printing has been served as an effective strategy for manufacturing functional fabrics, offering numerous advantages in the production of textiles with specialized properties and functionalities [131–133]. But there are still relatively few studies on the use of 3D printing methods in the preparation of structurally colored fabrics. Kim's team utilized viscoelastic photonic inks to draw the double helix structure of nucleic acids on fabrics by the direct printing method (Figure 4E) [60]. When the fabric is stretched, the helix exhibits a blue shift in colors, indicating a reduction in the interparticle distance along the thickness direction.

Ink-jet printing stands as one of the primary methods for the additive manufacturing of structurally colored materials [127]. During the printing process, inks are expelled as droplets from a micro-sized printing nozzle and subsequently deposited onto the desired substrate. The ink-jet printing of patterned colloidal crystal arrays was first reported by Ko et al. [134] Typically, ink-jet printing technologies can be categorized into two types based on the mechanism of ink droplet generation: continuous ink-jet printing and drop-on-demand ink-jet printing. The former, continuous printing, due to the challenges of controlling droplet position and potential ink contamination in the recycling system, has seen limited usage in materials science applications [135]. The ink-jet printing method offers a combination of speed and efficiency, providing enhanced flexibility for the design and printing of intricate and complex structures [127]. Inkjet printing on textiles utilizing high-resolution devices and printing systems allows for the creation of fine and delicate images on fabrics, achieving exceptional levels of detail [136]. There have been many studies on using pigment-based inks to print various patterns on fabrics [137, 138], however, few studies on using photonic inks to produce structural color patterns on textiles. Shao's group successfully developed ordered photonic crystal droplets using poly (styrene-methacrylic acid) (P(St-MAA)) colloidal inks on fabric substrates by employing ink-jet printing technology [139]. The “coffee ring” effect was effectively mitigated by formamide through the generation of a surface tension gradient from the droplet's edge to its center. This gradient, resulting from formamide's higher boiling point and lower surface tension, induced an inward capillary flow along the droplet surface, directing the flow from the edge towards the center. The development of photonic ink for 3D printing stands as a pivotal technological advancement. Creating uniform structural colors with complex 3D designs is notably challenging, especially within hydrogels. Wu's group introduced ZnS colloidal spheres for Mie scattering in photocurable inks to prepare vivid, uniform structural colors in hydrogels, requiring a small amount of colloidal spheres and enabling high-throughput manufacturing. Additionally, incorporating water-soluble quantum dots into 3D-printed hydrogels allows for the customization of structural and luminescent colors, enhancing multi-channel spatial data encryption [140]. In addition to efficient ink-jet printing, there is also a simple direct ink writing (DIW) method for three-dimensional (3D) printing, which allows flexible design and provides a variety of customized patterns [141]. Kim's team fabricated elastic photonic microbeads via scalable bulk emulsification and developed photonic inks incorporating these microbeads for direct writing, which maintain high color saturation and provide improved printability and precise dimensional control on various substrates, including fabrics [142].

3.4 | Electrophoretic Deposition

In previous studies, the electrophoretic deposition method has been used for coloring a variety of materials with charged particles or colorants that migrate and deposit onto the electrode base materials under the influence of an applied electric field [143–148]. In addition to the electrophoretic deposition method requiring special equipment, the characteristics of this preparation process are determined by two groups of parameters. The first one involves parameters associated with the concentration and property of the suspension, while another one includes parameters related to the overall process, such as the electrical properties of the electrodes and the electrical conditions like

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the relationship between voltage and intensity, deposition time, etc. [149] These physical parameters play a significant role in shaping the outcomes of the electrophoretic deposition process. Creating complex patterns using electrophoretic deposition can present challenges since the primary focus of the method is on achieving uniform deposition rather than intricate patterning. Due to the limitation of the conductivity of the base material of electrophoretic deposition technology, its application in the textile field is also relatively limited because most textile materials are not conductive. Despite this, the electrophoretic deposition method has been applied to coloring textile materials in recent years. Zhou et al. [61] produced structurally colored fibers by applying electrophoretic deposition to conductive carbon fiber surfaces using polystyrene nanospheres of varying sizes; the preparation process is illustrated in Figure 4G. This technique is believed to hold potential for applications in structural coloration and the development of fabrics with radiation-proof properties. Liu et al. [150] fabricated structural colored fibers using the electrophoretic deposition method, and these fibers display structural colors achieved through the assembly of charged poly(methyl methacrylate) microspheres on the surface of conductive carbon fibers. The reflectance spectra of the obtained fibers can be adjusted within the range of 430–608 nm (within visible light region).

3.5 | Electrospinning

Diverging from the previously mentioned methods, electrospinning, alternatively known as electrostatic spinning, stands out as an exceptionally efficient methodology for meticulously crafting extended micro- or nano-scale fiber configurations, capturing considerable focus and intrigue over the course of recent decades. Electrospinning stands as a notable derivation from the electrostatic spraying process, tracing its roots back to the pioneering work of Bose in the 1740s [151]. As of now, electrospinning technology has reached a level of maturity, proving invaluable in creating a diverse array of nanofiber materials for a broad spectrum of applications including biomedical advancements [152, 153], wearable thermal regulation [154, 155], efficient wastewater treatment [156, 157] and innovative agricultural practices [158, 159]. The process involves the preparation of a polymer solution or melt, followed by setting up an electrospinning apparatus with a high-voltage power supply. The polymer solution is extruded through a small nozzle in the presence of an applied high voltage, inducing charges on the droplet. The electrostatic repulsion forces result in the formation of a fine jet or Taylor cone, which solidifies into a thin fiber as the solvent evaporates. The electrospun fibers are then collected on a grounded or rotating collector, allowing for their deposition and alignment [160, 161]. This approach is applicable to a wide range of materials, including synthetic and natural polymers as well as materials loaded with chromophores, nanoparticles or active agents [151]. Researches on fabricating structurally colored fibers by electrospinning have been summarized in the previous study [162]. In recent years, structurally colored electrospun fibers or fiber membranes are still being developed by different researchers [163, 164]. Dye-free electrospun fibrous membranes consisting of individual colloidal fibers with a diameter of a few micrometers were successfully created via electrospinning. The study showed that the colloidal fibers were composed of uniform colloidal spheres in short-range order and the resulted electrospun fibrous membrane exhibited noniridescent and adjustable structural colors [62]. The schematic diagram of electrospinning process for fabricating colorful membranes is illustrated in Figure 4H. Yuan's research demonstrated the direct writing of structural color patterns achieved by ink-jet printing water directly onto the electrospun colloidal fibers that were prepared by electrospinning an aqueous mixture containing colloidal particles made of poly(styrene-methyl methacrylate-acrylic acid) and poly(vinyl alcohol) [165]. This study bears immense importance in paving the way for the creation of cutting-edge wearable functional devices reliant on the utilization of electrospun colloidal fibers.

3.6 | Fabrication Methods for Textile-Based Inverse Opals

Apart from the surface construction of structural colors on textiles, there is also ongoing research on utilizing textiles for the preparation of inverse opal structural color materials. To create functional inverse opal structural color materials, colloidal crystal templates were usually removed by calcination or etching [166, 167]. Multiple techniques exist for fabricating inverse opal photonic crystals, with commonly employed methods including the sol–gel process, atomic layer deposition, chemical vapor deposition, and electro-deposition [168–171]. Liu's team introduced silk fibroin inverse opals with bistructural colors for humidity-responsive color sensing [172]. Colloidal polystyrene crystals were grown by the gravity sedimentation of the polystyrene nanospheres and then silk fibroin was used to fill the voids in the colloidal crystals, followed by the elimination of colloidal spheres by immersing the samples in tetrahydrofuran. Silk photonic crystals on the surface of silk fabrics with the encapsulation of silk fibroin solution were also fabricated. Li et al. effectively produced silica/polyurethane acrylate inverse opal photonic crystals on fabric substrates, exhibiting intense color saturation and robust mechanical durability. This achievement opens avenues for manufacturing flexible smart photonic devices [173]. Responsive structural colored fabrics generally have wider applications, especially by etching photonic particles; the obtained inverse opal structural colored fabrics can be endowed with different functionalities. In the past 2 years, Gong et al. [174] successfully prepared thermoplastic polyurethane inverse opal fabric by the vertical deposition method and sacrificing a SiO_2 photonic crystal template to generate polyurethane inverse opal, achieving tight adhesion to the fabric and enabling rapid colorimetric detection of volatile organic compounds (VOCs). These inverse opal fabrics exhibit high sensitivity to DMF, THF, toluene, and chloroform vapors, with the response times being 105, 62, 75, and 66 s, respectively. This work offers a new pathway to realize fast response of VOC detection. By utilizing the inverse opal structure, inverse opal fabrics are expected to be endowed with more functions for application in different fields.

4 | Applications of Textile-Based Structurally Colored Materials

According to useful and efficient manufacturing techniques, researchers have dedicated substantial efforts to investigate the application potential of those structurally colored materials. In

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this section, we provide a summary of the primary applications of textile-based structural colors and explore their future possibilities, particularly in sensing applications. Recent years have witnessed remarkable advancements in the utilization of structural color materials in many fields like sensor technology [175–178] and security industry [179–181]. This is primarily due to their easy fabrication process and the ability to modify their surfaces extensively. These bioinspired structurally colored sensors are typically fabricated using responsive materials that can be tuned by specific external stimulation including humidity [182, 183], strain [184–186], temperature [187, 188] and pH [189, 190]. The subsequent responsive properties of structurally colored sensors can be achieved by manipulating the lattice constant and refractive index of the photonic crystal. For instance, to fabricate thermochromic nonwoven membranes, temperature-responsive cholesteryl ester liquid crystal formulations were combined with either polycaprolactone or polystyrene for electrospinning. As chloroform was used as a solvent to dissolve the polymers, the mixture could be easily spun into nonwoven materials with thermochromic properties under the premise of controlling the electrospinning conditions properly [191]. Nie et al. [192] demonstrated the successful preparation of chameleon-inspired iridescent structural color textiles featuring multiple stimulus-responsive functionalities. The tuning of structural colors was accomplished by adjusting the proportion of glucose or employing alternative self-assembly methods for cellulose nanocrystals, without compromising the cellulose nanocrystal structure. Photonic crystal-based structures with various stimulus-responsive functionalities have been employed in various fields including anti-counterfeiting [193], painting [194, 195], radiative cooling [196, 197] and biomedical applications [198, 199].

4.1 | Security Industry

Counterfeiting and deceptive items including fake currency and confidential documents are global threats endangering individuals, businesses, and nations, emphasizing the importance of implementing robust anti-counterfeiting security measures for safeguarding the daily lives of individuals and the routines of the counties [200, 201]. Anti-counterfeiting nanomaterials including lanthanide doped [202, 203], quantum dots doped materials [204–206], and luminescent nanoscale metal–organic frameworks [207, 208] as fluorescent inks have been extensively studied for fast response anti-counterfeit marking. Smart textiles have attracted great attention in various fields like sensors, monitoring, data transfer, security, and protection of persons and objects, medicine and healthcare [209, 210]. They can be easily integrated into everyday items like clothing and accessories, providing a seamless and inconspicuous method for embedding security features [211]. Photonic crystal-based materials with distinct light manipulation capability, stimuli-responsive functions, and diverse encrypted patterns are anticipated to find extensive use in industrial applications, notably in security and authentication [212–214]. Particularly, optically variable inks comprising multiple layers of dielectric material films, capable of exhibiting interference colors, have been employed in the security industry for decades [215]. Optical anti-counterfeiting technology with encryption and decryption ability can prevent counterfeit products from causing serious economic, safety, and health ramifications on consumers and businesses in various countries around the world [216]. Stimulus-responsive smart textiles especially electrospun nanofibers containing the latex nanoparticles and thermochromic inks are particularly notable for their stable and easily detectable optical signals, making them suitable for double-encryption anti-counterfeiting and food security detection, and arbitrary patterns can be designed based on specific manufacturing techniques [217]. Tao and Lu [218] developed a novel dual-mode anti-counterfeiting photonic crystal structural color coating on fabric using aggregation-induced emission (AIE) organic molecules; the schematic diagram of the preparation process is shown in Figure 7. By modifying the surfaces of SiO_2 colloidal spheres with tetraphenylbenzene, the structure exhibited vibrant colors in sunlight and a photonic crystal-enhanced aggregation-induced emission effect under ultraviolet–visible light. This unique feature holds promise for dual-mode anti-counterfeiting logos. Furthermore, the photonic crystal structural color coating exhibits remarkable resistance to bending, rubbing, and water, showcasing potential applications in anti-counterfeiting trademarks. Lundin's group achieved a multi-responsive (thermochromic/photochemical response) system that allows for the adjustment of colors in core/sheath microfibers and microfibrous mats made by using coaxial electrospinning through fiber diameter, temperature, and UV–vis irradiation [164]. This thermochromic/photochemical responsive system based on colorful electrospun fibers had the potential to greatly impact covert interrogation techniques, particularly in the areas of anti-counterfeiting measures and friend-foe detection, leading to significant advancements in these fields. Recently, Wang's team prepared an anti-counterfeiting textile by depositing red-emitting carbon quantum dots (CQDs) on cotton fibers using a quick organic solvent evaporation method. The textile changes color in various metal ion solutions and retains over 75% fluorescence intensity after 100 washes or 20 h of sun exposure. This innovation advances CQD-based smart textiles, offering a robust solution for anti-counterfeiting and advanced security [219]. Textile-based materials are superior to rigid films or layered substrates because they can be bent, folded, and stretched without compromising the structural integrity of color patterns or functionality, especially in cases where the photonic crystal layer is well bonded to the textile substrate [220]. Therefore, as structurally colored smart functional textiles, they will be given more expectations as embedded products in the field of information security.

4.2 | Biomedical Field

As health monitoring and biological testing have reaped significant attention [221–223], wearable textile-based sensors have been widely studied due to their potential applications in biological signal detection and monitoring [224–226]. Photonic crystal-based biomaterials demonstrate excellence in biomolecular screening, multiplex detection, and real-time biomolecule monitoring [227]. Their responsiveness through visible color changes offers a distinct advantage, eliminating the necessity for expensive and intricate signal interpretation devices. This feature renders them invaluable for swift and portable analyses, especially in situations demanding immediate detection [228]. There have been many fundamental studies on the application of structurally colored materials for ophthalmic purposes [229–231]. These structural color contact lenses can be used as sensors for instant monitoring of ophthalmic health [232]. Qin's team prepared poly(acrylonitrile) fiber membranes by electrospinning method and found that by utilizing the parallel

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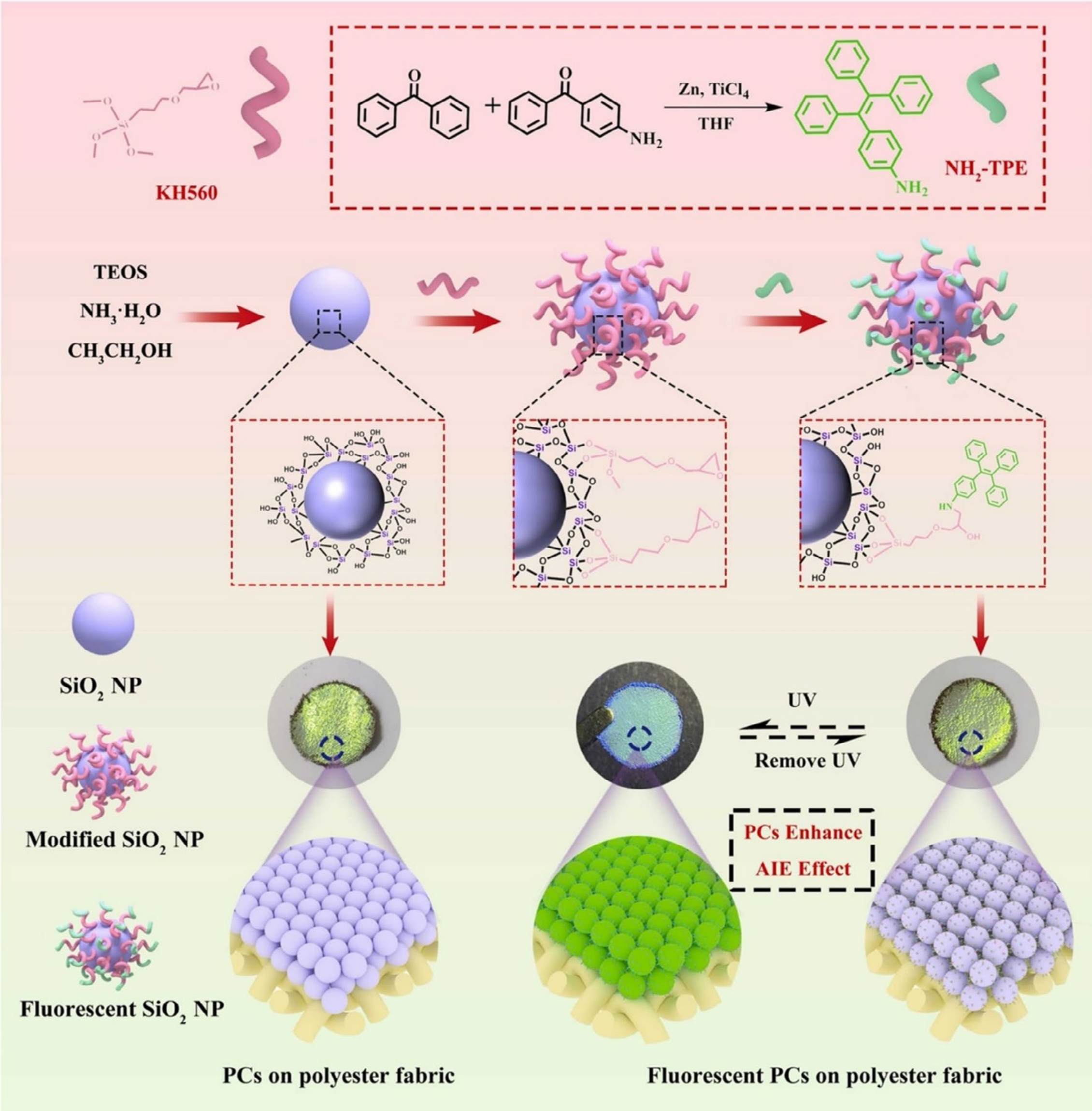

FIGURE 7 | Schematic diagram of fabricating dual-mode anti-counterfeiting photonic crystal coatings with structural color on polyester textiles. Reproduced with permission [218]. Copyright 2022, Elsevier.

transmittance effect, poly(acrylonitrile) nanofiber mats in red, yellow, and blue colors were employed to achieve colored LEDs with ideal light scattering characteristics [163]. These kinds of colored LEDs with anti-glare coatings are anticipated to offer eye protection against glare damage and also bring a visually captivating experience with vibrant colors. Kong's work introduced structural colored textiles that exhibit remarkable color visibility and stability, offering intelligent thermoregulating capabilities, which were attributed to the synergistic cooperation between the adhesion and phase change characteristics of waterborne polyurethane phase change material [233]. This research holds promise in the development of lightweight equipment for thermoregulating clothing, thus playing a significant role in alleviating the energy crisis. Chen et al. [234] have proposed a novel heterogeneous structural color microfiber designed specifically for dynamic cardiac mechanical sensing by the programmed injection microfluidic spinning method, based on the significant significance of cellular mechanics in biological functions. The microfiber, incorporating acrylamide hydrogel and a non-close-packed colloidal array segment, demonstrated high sensitivity to tension force while ensuring the preservation of cell growth without structural damage. As the cultivated cardiomyocytes regain autonomous beating cycles, the structural color section of the microfiber undergoes stretching, displaying synchronized stretch cycles accompanied by dynamic color variation and wavelength shifts.

4.3 | Radiative Cooling Field

Radiative cooling, a technology that can cool objects without energy consumption, emerges as a compelling zero-energy and eco-friendly cooling solution with remarkable potential in addressing the safety concerns related to outdoor facilities in elevated temperatures, as well as combatting the challenges posed by global warming and climate change [235–237]. Radiative cooling fabrics, capable of diffusing solar radiation, offer effective solutions to reduce light pollution while enabling

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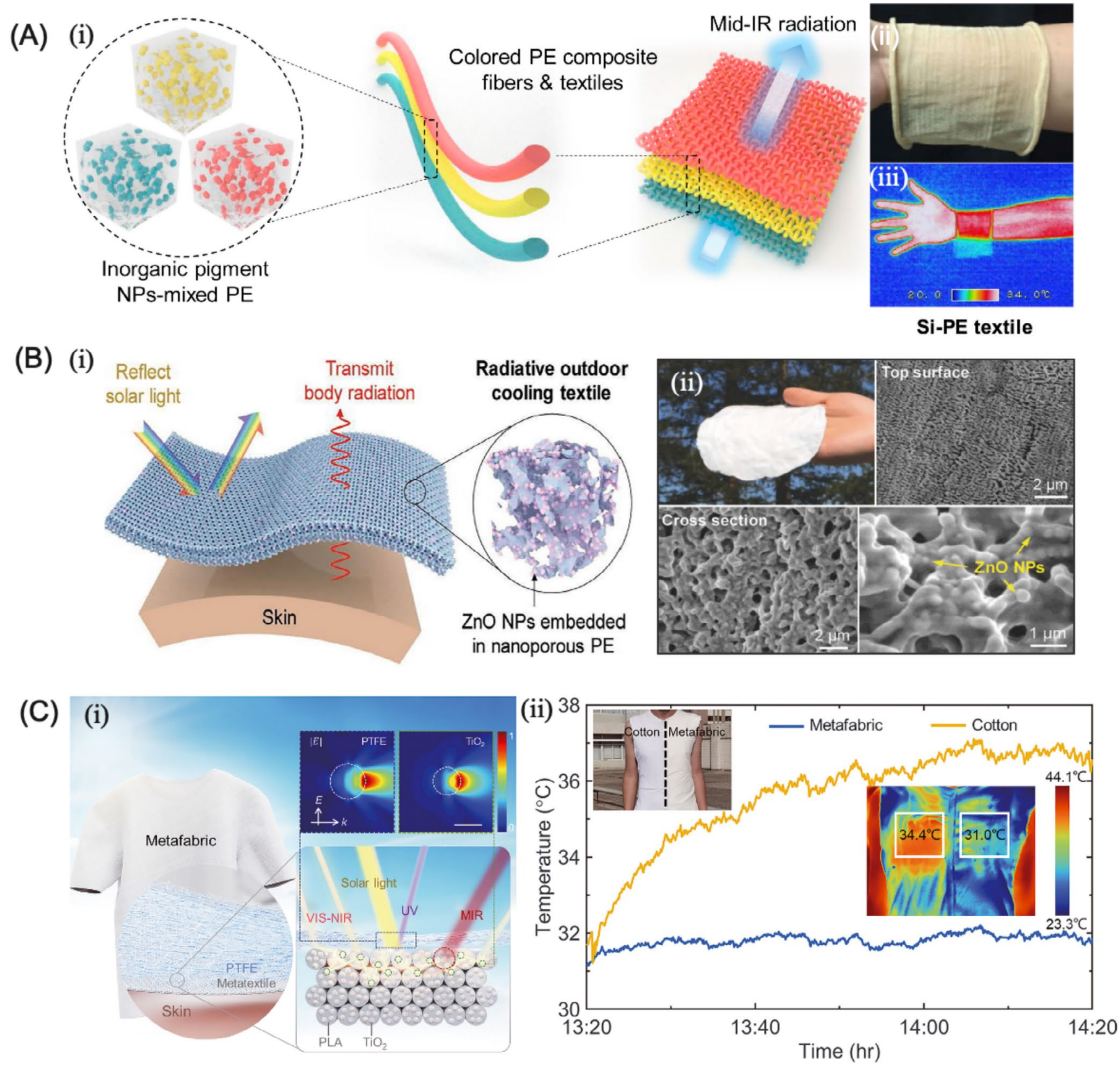

FIGURE 8 | (A) (i) Schematic diagram detailing the coloration process of radiative cooling textiles involves blending IR-transparent inorganic pigment nanoparticles with polyethylene (PE). These composite mixtures can subsequently be extruded into continuous fibers and woven into interlaced textiles using large-scale industrial methods. (ii) The photo and (iii) the infrared image of Si-PE knitted textiles on skin. Reproduced with permission [242]. Copyright 2019, Elsevier. (B) (i) Schematic illustrating the incorporation of nanoporous ZnO nanoparticles in polyethylene textiles to realize radiative outdoor cooling. (ii) Photo and SEM images of ZnO-PE textile. Reproduced with permission [243]. Copyright 2018, John Wiley and Sons. (C) (i) Schematic diagram of a metafabric for daytime radiative cooling. (ii) Temperature measurement over time in the sun wearing a vest made of cotton and metafabric. Reproduced with permission [244]. Copyright 2021, American Association for the Advancement of Science (AAAS).

large-scale production using current techniques, which garnered significant attention recently [238–240]. The focus of research on radiative cooling materials lies in optimizing photonic crystals through algorithm design. These materials utilize the resonance of phonon polarization and high refractive index in various infrared bands to enhance thermal emissivity and solar reflectivity. Silicon-related materials such as silica have been widely used to enhance thermal emissivity [241]. Cai et al. [242] introduced a novel approach employing inorganic pigment nanoparticles to colorize infrared-transparent polyethylene textiles for radiative cooling purposes, marking a significant advancement in the field of personal thermal management (Figure 8A). The pigment materials Prussian blue (PB), iron oxide (Fe_2O_3), and silicon (Si) produce basic colors of blue, red, and yellow, with minimal IR absorption, non-toxicity, and cost-effectiveness. Their experimental results confirmed the effectiveness of these infrared-transparent pigment nanoparticles for coloring radiative cooling textiles. Their group also

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prepared another selective nanocomposite textile for outdoor radiative cooling by integrating zinc oxide (ZnO) nanoparticles into nanoporous polyethylene (ZnO-PE) (Figure 8B-i) [243]. The resultant 150 μm-thick ZnO-PE film appears white when exposed to sunlight (Figure 8B-ii), suggesting significant scattering of visible light from every direction. The outdoor evaluation of the ZnO-PE radiative cooling textile demonstrated its superior cooling efficiency. The high solar reflection of this textile reduces heat absorption from the sun, while its effective transmission of human body thermal radiation maximizes radiative heat dissipation. A multilayer metafabric integrating titanium oxide polylactic acid composite with a polytetrafluoroethylene layer was innovated for passive radiative cooling. This textile offers strong mechanical features, scalability, and when fashioned into apparel or car covers, provides superior cooling compared to traditional fabrics (Figure 8C-i) [244]. The thermal characteristics of both the vest and the volunteer were observed. A substantial temperature contrast between the two sides of the vest was revealed by a thermal imaging camera, measuring 34.4°C and 31.0°C (Figure 8C-ii). These findings showcase the prospect for commercial utilization across diverse intricate settings like smart textiles. The combination of structurally colored textiles and radiative cooling enables precise regulation of the microclimate around the human body, promoting sustainable and effective personal thermal comfort. Du et al. demonstrated $ZnS@SiO_2$ colored textiles for radiative cooling by a spray coating method. By incorporating noniridescent structural color of ZnS and the core-shell structure of $ZnS@SiO_2$ micro-spheres, this colored textile achieves selective reflection of visible light for color generation while retaining high solar reflectance [245].

5 | Summary and Perspectives

In this study, we have briefly recalled the fundamental principles underlying structural colors in textiles, followed by a closer examination of the recent advancements in manufacturing these bioinspired periodic micro- or nano-structures. It extensively investigates various fabrication techniques for these materials. Effective methods such as gravity sedimentation, spray coating, and vertical deposition are examined for achieving structural coloration. Versatile printing techniques, including screen printing, shear-induced assembly, and additive manufacturing, are discussed for creating intricate patterns and designs. Additionally, the suitability of dip coating, electrophoretic deposition, and electrospinning methods for fabricating structurally colored textiles is explored. The paper also explores unique fabrication methods for textile-based inverse opals, enabling the attainment of tunable structural colors. In addition to summarizing these available preparation methods, this work delves into the applications of textile-based structurally colored materials, with a particular focus on anti-counterfeiting measures, the biomedical field, and radiative cooling. These materials exhibit significant potential in anti-counterfeiting, as their distinctive structural colors can serve as instant visual indicators of authenticity. In the biomedical field, they offer opportunities for ophthalmic health monitoring systems. Moreover, their remarkable performance in radiative cooling contributes to efficient thermal management and energy conservation.

Despite textile-based structurally colored materials have presented a promising avenue for innovative applications in various industries, several challenges still lie ahead in their widespread adoption and optimization. To begin with, the durability and colorfastness of these color materials are still a major issue that needs to be improved. It is essential to maintain the structural coloration through multiple wash cycles and environmental conditions in textiles. Research and innovation are vital in creating coatings or treatments that prolong color retention without diminishing their distinctive optical characteristics. Another challenge involves the scalability and cost efficiency of manufacturing processes for structurally colored textiles. Although intricate fabrication techniques can produce impressive visual results, scaling these methods for mass production without substantial cost escalation presents a challenge. Finding efficient and economical manufacturing methods that maintain the quality and integrity of the structural coloration is essential for commercial viability. Besides, incorporating these materials into practical textile applications poses a challenge. The fusion of structural coloration with functions such as sensing, energy harvesting, or light manipulation requires interdisciplinary research endeavors to guarantee compatibility and optimize performance.

Advancements in fabrication methods and innovative applications are key to enhancing the utilization and commercialization of structurally colored materials. We hope this mini-review will attract more attention and research from experts in the fields of material science, textile engineering, design, and manufacturing, prompting their collaboration to drive innovation, overcome challenges, and realize the diverse potential of these materials across various industries.

Author Contributions

Jiali Yu: conceptualization, literature collection and analysis, visualization, writing – original draft preparation, writing – review and editing. **Chichao Xia:** conceptualization, writing – review and editing. **Wenyi Wang:** conceptualization, writing – review and editing. **Xi Yu:** conceptualization, writing – review and editing. **Chi-Wai Kan:** supervision, writing – review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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