

Effects of Nano-Coating, Nanocomposites, Biocomposites to Develop UV Protective Knit Fabrics: A Synergistic Review

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Abstract

Nanotechnology is transforming the textile industry by embedding UV-blocking and antimicrobial agents into fabric fibres at the molecular level. This study explores the development of biocomposites and nanocomposite materials for UV protection and microbial resistance in clothing. Nanoscale UV-blocking agents enhance the protection of textiles against harmful ultraviolet radiation. Recent studies on composites such as ZnO/carboxymethyl chitosan, polyacrylonitrile with UV absorbers and TiO₂ nanoparticles, and lignin-TiO composites have shown significant improvements in UV protection and some antibacterial activity. Techniques such as electrospinning, hydrothermal synthesis, and natural fibre welding were used to create these composites, focusing on ZnO and TiO₂ nanoparticles for dual functionality. Research on nanoscale UV-blocking agents could revolutionise sun protection in clothing and offer better safety against ultraviolet radiation. Multifunctional composites with UV-blocking and antibacterial properties could advance the use of protective clothing in various industries and outdoor activities. Emphasising natural fibres and sustainable materials aligns with the global trend towards eco-friendly solutions, leading to more environmentally friendly products. This literature review aims to comprehensively review and analyze current research on UV protective knit fabrics using nanotechnology, nanocomposites, and biocomposites. It seeks to identify research gaps, evaluate different approaches, and provide insights for future developments in this field.

Keywords

Knitted Fabrics, Biocomposites, Nanocomposites, UV-Protection, Antibacterial Property

1. Introduction

The textile industry is undergoing a groundbreaking shift, driven by cutting-edge nanotechnology that integrates UV-blocking properties into fabrics at the molecular scale. Attire engineered to shield wearers from the sun's detrimental ultraviolet rays is referred to as ultraviolet protection factor (UPF) clothing or sun-protective apparel. Solar ultraviolet radiation is the primary cause of skin damage, leading to sunburns, melanoma, and non-melanoma skin cancer [1] [2]. This pioneering textile technology has the potential to revolutionise the apparel industry by offering enhanced UV protection and microbial resistance in both common and specialised garments through the application of nanotechnology and biocomposites to knitted fabrics. Addressing crucial health issues associated with sun exposure and harmful microorganisms could significantly reduce the risk of skin damage, including sunburns and various types of skin cancer. The widespread adoption of these advanced textiles might improve public health and alter consumer preferences toward more protective and functional attire. This groundbreaking advancement in textile technology has the potential to revolutionise sun protection in clothing, offering consumers enhanced UV protection without compromising their comfort or style. The integration of nanotechnology into fabric production could lead to a new era of functional and protective clothing, potentially reducing the risk of skin damage and related health issues associated with ultraviolet (UV) exposure. Furthermore, this innovation may spark widespread changes in the fashion industry, encouraging the development of more technologically advanced and health-conscious apparels. This review paper aims to understand the potential influence of various knitted structures, nanocomposites, and composites on the development of textiles that offer UV protection and microbial resistance. The application of nanotechnology to imbue knit fabrics with UV-blocking properties highlights the importance of UV protection in clothing, especially in protecting against mild to severe skin damage. This review explores how this cutting-edge textile innovation can revolutionise the apparel industry by offering improved protection against ultraviolet radiation and bacterial growth. Understanding these research advances is essential for implications on public health, technological innovation, environmental considerations, and market dynamics. It informs future investigations, influences interdisciplinary fields, optimizes performance metrics, enhances cost-efficiency, improves product longevity, and ensures adherence to regulatory standards. Nanotechnology and biocomposites present innovative approaches for developing UV-protective textiles, addressing public health concerns and meeting consumer requirements in outdoor and athletic apparel sectors. Furthermore, it examines the broader implications of this innovation on public health and individuals' apparel choices. This study also elaborates on the current challenges and limitations faced by the technological solutions analysed.

2. Need for UV Protection

Fabrics provide UV protection through radiation reflection, absorption, and

scattering. Their effectiveness depends on characteristics such as structure, porosity, thickness, mass, fiber type, color, and finishing treatments [3] [4]. Contrary to common belief, many fabrics offer inadequate UV protection. A study of 236 apparel textiles revealed, 33% had a UV protection factor below 15. Light, colorless materials worn in summer typically provide the least protection [4] [5]. Regular fabrics may provide UV protection, but effectiveness varies based on composition, weave, and color. Wool, polyester, and blends offer better protection than cotton, linen, and viscose. For adequate protection, choose fabrics with UPF 30+ as per European standards [4]. Despite the availability of UV-protective fabrics, there's a need for consumer education. Consumers should be aware that not all summer clothing provides sufficient UV protection, highlighting the importance of proper fabric selection and potential UV-protective treatments.

3. Impact of Knit Fabric Parameters

3.1. Effect of Surface Treatments

It was examined that the ultraviolet (UV) protective properties and antibacterial effectiveness of cotton knit fabrics against *Staphylococcus aureus* and *Escherichia coli*. The research found that the ultraviolet protection factor (UPF) values were influenced by various factors, including the fabric structure, pretreatment history, type of softening agent, incorporation of UV absorbers, sequence of addition, and nature of the deposited metal oxide. The antibacterial efficacy was enhanced by the fabric structure, substrate condition, finishing additives and process, and deposited metal oxide. Optimal UV protection and antibacterial properties were achieved through a combination of soft finishing, UV cutting, and in situ deposition of metal oxides. This comprehensive approach to enhance fabric properties demonstrates the potential for developing multifunctional textiles that offer both UV protection and antimicrobial benefits, opening new avenues for innovation in the textile industry. The study's controlled laboratory conditions may limit its real-world applicability, as they might not accurately reflect the diverse environmental factors and bacterial strains encountered in everyday cotton fabric use [6]. Focusing on only two bacterial species may not provide a comprehensive understanding of the overall antibacterial effectiveness of the fabric against a broader range of pathogens. Despite this, research advances multifunctional textile development, potentially revolutionising the industry with fabrics offering enhanced UV protection and antimicrobial properties through an innovative approach combining soft-finishing, UV-protection, and metal oxide deposition. However, further studies under real-world conditions with a wider pathogen range are necessary to fully validate the practical applicability of these enhanced fabrics.

3.2. Role of Fibers on UV Protection

Research conducted on the UPF of weft-knitted textiles produced from 20 Ne cotton yarn, Coolmax yarn, and their blends under various conditions. The samples were divided into three groups based on the fibre composition. The UPF

prediction model incorporates both yarn and fabric characteristics. The findings revealed that in Group I, the UPF ratings were dependent on the spinning technique and fibre type, with combed Supima cotton yarns providing superior UV protection. For Group II, the combination of the two combed Supima cotton yarns yielded a higher UPF than the other combinations. Group III, comprising Coolmax/cotton blends, demonstrated the highest UPF values, which was attributed to the enhanced UV protection offered by Coolmax [7]. Another investigation correlated between UV protection and the composition of cotton knitted textiles. They manufactured 15 types of knitted fabrics, including single-knitted (e.g. plain knit, lacoste) and double-knitted fabrics (e.g. Half Milano, Full Cardigan). This study examined the fabric weight, thickness, and count (stitch density). The results showed a positive correlation between fabric weight per unit area and its Ultra Violet Protective Factor (UPF) [8]. However, the UPF values for the single- and double-knitted fabrics did not consistently increase with thickness. Although a higher stitch density increases the loop count, different loop types affect fabric appearance and UV radiation transmission. The knit structure of a fabric significantly influences its ultraviolet (UV) protection properties. This study has shown that fabrics with miss-stitches generally exhibit higher Ultraviolet Protection Factor (UPF) values compared to those with tuck stitches, while double-knitted fabrics typically offer superior UV protection than single-knitted structures [9]. They further explored how different knit structures, including knit, tuck, and miss stitches, affect the ultraviolet protection factor (UPF) of knitted fabrics. They evaluated the UPF and structural properties such as thickness, weight, stitch density, and porosity of the greige and bleached fabrics using factorial analysis of variance. This study found that fabrics with missed stitches exhibited a higher UPF than those with tuck stitches. Generally, double-knitted fabrics offer better UV protection than single-knitted fabrics do.

However, bleaching affects the UPF of single- and double-knitted fabrics. The findings suggest that UV protection in knitted fabrics cannot be solely determined by thickness or weight, but that fabric porosity is a reliable indicator for UV protection when comparing fabrics of the same weight and thickness but different structures or fibre compositions. Building on these findings, further research could explore how different knitting patterns and fibre blends can be optimised to enhance UV protection in lightweight breathable fabrics suitable for various applications. Furthermore, the examination of whether biopolishing and UV absorber treatments affect the UV protection of cotton-knitted fabrics made from torque-free ring-spun yarn. Following scouring and bleaching, biopolishing and UV absorber treatments were applied. UV protection was measured using the UV protection factor (UPF) and UV ray transmittance standards. The results indicated that the torque-free ring-spun yarn fabric had a higher UPF than the conventional ring-spun yarn fabric, both untreated and biopolished. However, the conventional ring-spun yarn fabric demonstrated a better UPF than the torque-free ring-spun fabric after UV absorber and combined UV absorber and

biopolishing treatments [10]. Another study explored how fabric attributes, such as weight, thickness, and stitch density, affect the UV protection of knitted textiles. Various knitting structures, such as plain, pineapple, lacoste, and combinations of knit, tuck, and miss stitches, as well as half Milano, full Milano, half cardigan, full cardigan, 1 × 1 rib, and interlock were analysed. The findings showed that weight had the most significant impact on UV protection, whereas thickness and stitch density were less influential [11].

Further research examined the relationship between the bursting strength of knitted fabrics and their UV protection properties. The study included various single-jersey and double-jersey structures, such as plain, pineapple, lacoste, knit-tuck-miss combinations, half Milano, full Milano, half cardigan, full cardigan, 1 × 1 rib, and interlock. The results demonstrated a strong correlation between the UV protection factor and the variation in bursting strength across different structures [12]. Furthermore, it was examined that [13] how constructional parameters and dyeing techniques affect the ultraviolet (UV) protection of cotton knitted fabrics. The UV protection of the dyed cotton fabrics was assessed using a spectrophotometre for *in vitro* testing. Among the six parameters, yarn fineness and dye concentration were the most influential on the UPF, while colour had the least impact. The findings showed that dyed textiles from combed cotton generally have a higher UPF than those from combed Supima cotton because the shorter fibres in combed cotton block or absorb more UV radiation. Fabrics from twisted yarn, like ring-spun yarn, typically exhibit higher UPF values compared to torque-free yarn (ESTex) because they shrink during wet processing, resulting in a denser structure.

3.3. Influence of Yarn Characteristics on UV Protection

Textiles made from 30 Ne yarn also have higher UPF values than those made from 40 Ne yarn because of their greater thickness and lower porosity. The fabrics dyed with lower dye concentrations had the lowest UPF values. Sulfur-dyed samples provided inferior UV protection compared to reactive and direct-dyed samples. No significant differences in the UPF were found among the red, yellow, and blue fabrics. This study also found a negative correlation between fabric lightness and UV protection. The dyed 100% cotton-knitted fabrics using direct dyes with different colour intensities. The CIE L*a*b* values and dye uniformity of the fabrics were analysed to assess their colour properties. This study examined the correlation between colour characteristics and UV protection. The results showed that the colour depth and dye concentration were the primary factors influencing the UV protection of cotton fabrics [14]. Another study analysed that the UV protection of plain-knitted fabrics made from three types of ring-spun cotton yarns with varying twist levels and staple lengths. They found that yarn characteristics affect UV protection differently before and after washing. Low-twist yarns create porous fabrics, increasing UV radiation (UVRI) transmission, whereas long-staple yarns produce uniform fabrics that enhance UVR reflection. However, the

uniformity of long-staple yarns also reduced fabric shrinkage during washing, making the UV protection improvement less significant than that of short-staple yarns [15].

Additionally, it was evaluated that the UV protection factor of various weft-knitted structures using grey 100% Organic Cotton yarns, Ne 30/2, with 330 twists per meter, on a 7-gauge flat knitting machine. The study showed that thicker yarns (3-ply instead of 2-ply) improve UV protection. The knit fabric structure had the most significant impact on the UPF, with Miss-Stitch stitches improving the UV blocking. All the structures with missed stitches had high UPF values. The effect of tuck stitches on the UPF varies based on their combination and repetition. Seven knit structures, including Half Cardigan, Complete Milano, Rib 1 × 1, KM11, KM22C, KM22W (3-ply yarn), and Interlock (2-ply yarn), achieved UPF values above 40, with some exceeding 50. These structures are likely to maintain a high UPF, even at higher gauges, and colouration and washing treatments could further enhance the UPF [16]. Likewise, a study examined that bi-layer knitted fabrics, highlighting their flexibility, stretchability, and comfort. Known for their stretch, recovery, porosity, and air permeability, knitted fabrics are prevalent in sportswear, summer clothing, underwear, and children's apparel [17].

3.4. Effect of Fibers and Fabric Construction

Weft-knitted fabrics are easier and more cost-effective to produce than woven fabrics. This study assessed weft-knitted fabrics with different construction parameters for UV protection in sportswear. Bamboo fabrics demonstrated superior UV protection over cotton and modal fabrics, and the knit structure significantly affected the UPF parameters. Tuck stitches, although generally linked to lower UPFs, vary based on their combination and repetition. Tuck stitches improved the air permeability but reduced the bursting strength. All samples had UPFs above 15, with six samples (D2, D3, D4, H2, H3, and H4) surpassing UPF 40, influenced by the varying bamboo content. Further analysis showed a high UPF in knitwear, which was enhanced by colouration and wet treatments. Sample D4 excelled in producing UV-resistant sportswear fabric. This review paper discusses several contributions concerning knit structures, focusing on the impact on the Ultraviolet Protection Factor (UPF) and its effectiveness. This study examines how different knitting techniques and patterns can enhance the UV-blocking properties of fabrics. Additionally, this paper also delves into the role of fibre blends and finishes in optimising the UPF rating of knitted garments. There are several contributions concerning knit structures that this review paper discusses, focusing on the impact on UPF (Ultraviolet Protection Factor) and its effectiveness. It examines how different knitting techniques and patterns can enhance the UV-blocking properties of fabrics. Additionally, the paper also delves into the role of fiber blends and finishes in optimizing the UPF rating of knitted garments. This opens an avenue for the comprehensive analysis of yarn characteristics, fabric parameters, and nano-finishes, shedding light on how these factors collectively

influence UV protection. This review further investigates emerging innovations in nanotechnology in knit fabrics to further maximise UV-blocking capabilities while maintaining wearer comfort and breathability. Moreover, it examines the potential of integrating smart textiles and wearable technology into UPF knitted garments, paving the way for advanced sun-protection solutions [18]. Moreover another research aimed to compare and analyze the UV protection properties of fabrics made from various cellulose fibers, emphasizing hemp fibers' potential for sustainable and UV-protective textiles. The five knitted fabrics from different cellulose-based fibres were pure hemp, pure cotton, pure viscose, and blends of hemp with either cotton or viscose. A plain weft knitting technique was used on a double jersey (rib structure) in a circular knitting machine with consistent settings for all samples to ensure structural uniformity. In blended fabrics, hemp yarn is directly combined with cotton or viscose yarn on the machine before feeding into the needles. Pure fabric samples were prepared using two assembled yarn components to maintain uniformity across the specimens. Fibre preparation, knitting parameters, and relaxation procedures were consistent to minimise structural variations that could influence the UV protection results, enhancing the reliability of comparisons across cellulose-based fabrics [19]. However, they did not explicitly justify this decision as to why only the rib structures were used. Key findings include the significant UV protection potential of cellulose-based fabrics, particularly cotton. This study suggests that hemp shows promise but requires further research to enhance its UV-blocking capabilities for textile use.

3.5. Studies on Dyed Cotton Knit Fabrics

Notably, only CIE L^* values were significantly correlated with the UV protection factor (UPF), whereas CIE a^* and CIE b^* values were not. However, dyeing uniformity affects the UV protection of the coloured 100% cotton-knitted fabric. In the research it was investigated that the ultraviolet protection capabilities of various knitted fabric structures, including those with knit, tuck, and miss stitches when exposed to stretching and moisture. The study revealed that black knitted fabrics experienced an average reduction of 53% in their UV protection factor when stretched by 10%. Notably, fabrics incorporating miss stitches in their knit structure demonstrated sustained UV protection efficacy even when elongated to 20% beyond their initial dimensions [20]. The optimized quality parameters of single jersey and 1×1 rib knitted fabrics using a desirability function framework. This adaptive approach integrates and optimises the key characteristics by targeting an overall desirability index from zero to one. Comfort attributes such as air permeability, thermal conductivity, and UV resistance were combined to achieve this goal. The overall desirability was optimised based on the desired values for these characteristics. Experimental validation confirmed the method's effectiveness in designing knitted fabrics with the desired comfort and UV resistance properties [21].

4. Nanocoating

Nanocoating is an advanced surface treatment technique that involves applying thin films with nanoscale dimensions to materials, enhancing their functionalities and protective properties. It combines nanotechnology with conventional coating methods to create smart finishes that offer superior protection and performance [22] [23].

Synthesis of Nanoparticles:

Nanoparticle synthesis is a critical process that determines the size, properties, and applications of these tiny particles ranging from 1 to 100 nm in size [24]. Traditional methods of nanoparticle synthesis often involve hazardous chemicals and high energy consumption, prompting researchers to explore more sustainable alternatives [25]. Green synthesis has emerged as a promising approach, utilizing biological entities such as bacteria, fungi, algae, and plant extracts to produce nanoparticles in an eco-friendly and cost-effective manner [26] [27]. Interestingly, while green synthesis offers numerous advantages, including improved safety and minimal environmental impact, it is not without challenges. Maintaining consistent structure, size, and yield of particles during biosynthesis can be difficult, requiring careful monitoring of parameters such as temperature, pH, and reaction period [28].

1) Sol-gel technique: A wet-chemical method for producing solid materials from small molecules [22] [29].

2) Layer-by-layer technique: A process of depositing alternating layers of oppositely charged materials.

3) Cross-linking by polymers: Using polymers to create a network structure in the coating [22].

4) Thin film deposition: Methods like chemical vapor deposition (CVD) and physical vapor deposition (PVD) for applying thin films [29].

5) Plasma spraying: A thermal spraying technique used for applying nanostructured coatings.

6) Electroless deposition: A method for depositing nanocomposite coatings, particularly Ni-P based coatings [30].

7) Electro-spark deposition and electrochemical deposition: Techniques for applying nanocoatings using electrical current.

8) Laser beam surface treatment: Using laser technology for nanocoating application [29].

These approaches can incorporate various nanomaterials such as metal oxides (ZnO, TiO₂, SiO₂), graphene, and carbon nanotubes to create specialized nanocoatings with enhanced properties [31] [32].

4.1. Benefits of Nano-Coating

Nanocoatings offer numerous benefits, including improved mechanical properties, wear resistance, corrosion protection, and the ability to impart specific functionalities like self-cleaning, UV protection, and anti-fouling properties [29] [33].

The versatility and effectiveness of nanocoatings make them promising candidates for next-generation protective systems in various industries, including marine, building, defense, and food preservation [29] [34] [35].

4.2. Classification of Nanomaterial Based on Dimensionality

Nanomaterials, including nanorods, solid and hollow nanoparticles, and 2D and 3D structures, exhibit unique properties due to their size and shape at the nanoscale. Semiconductor nanorods, for instance, offer tunable absorption and emission properties based on their size, aspect ratio, and composition [36]. These nanorods demonstrate polarized and directional emission, with potential applications in light-emitting and lasing devices. Hollow nanoparticles present intriguing characteristics compared to their solid counterparts. They often exhibit improved catalytic properties due to their large surface area, as demonstrated in the case of hollow nickel and cobalt nanoparticles synthesized using aluminum nanoparticles

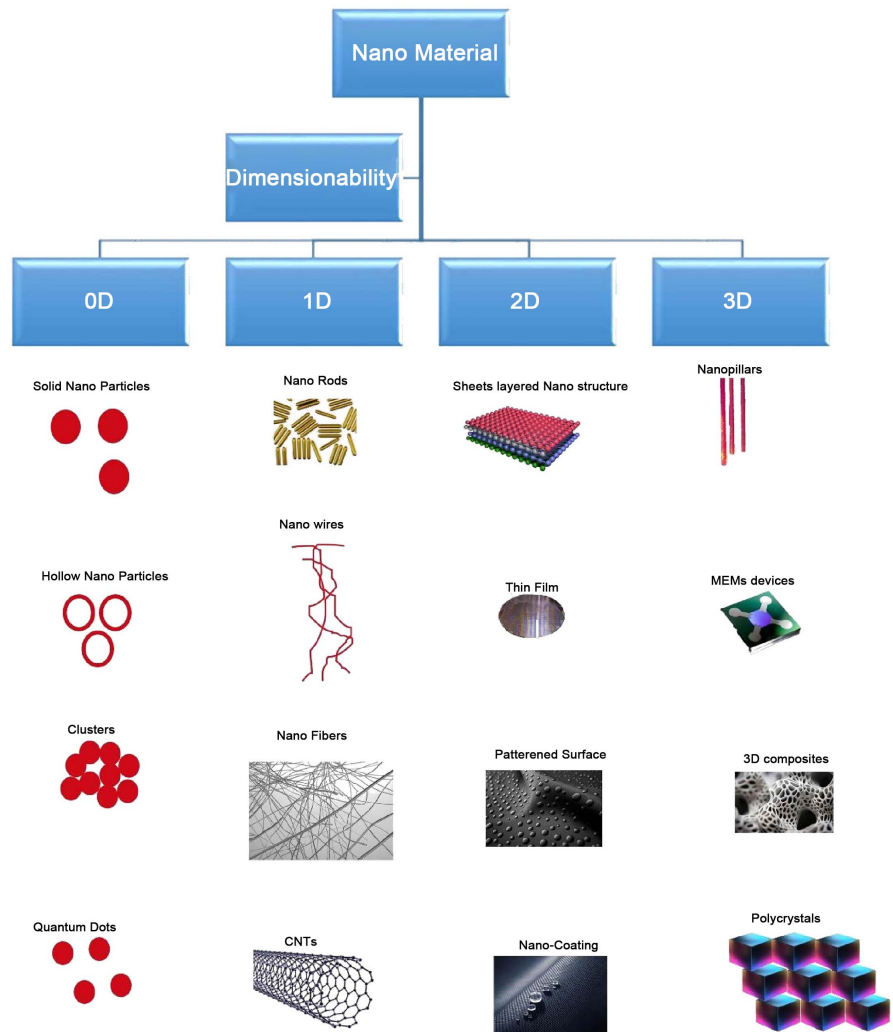


Figure 1. Schematic Illustration of the Classification of nanomaterials Based on Dimensionality [41].

as templates [37]. Interestingly, hollow ZnO nanorods show a larger optical band gap and enhanced visible emission compared to solid ZnO nanorods, attributed to quantum confinement effects and multiple scattering [38]. The internal structure of hollow nanoparticles can be manipulated, as shown in the case of AgAu nanorods, allowing for reversible shape and near-field control with potential applications in reprogrammable sensors and optical memory units [39]. In summary, nanomaterials in various forms, from 2D sheets to 3D structures like hollow nanoparticles, offer a wide range of unique properties and potential applications. The ability to tune these properties through size, shape, and composition makes them versatile candidates for diverse fields, including catalysis, sensing, drug delivery, and optoelectronics [40]. As research in this area continues to advance, we can expect further innovations and applications leveraging the distinct characteristics of these nanomaterials (Figure 1).

Nano-Coating Fixation:

These innovative nanocoatings not only offer superior protection but also pave the way for enhanced performance and sustainability across multiple sectors, highlighting their potential to revolutionize traditional surface treatment methods. The process of fixing nanocoatings involves applying an ultra-thin layer of nanoparticles or nanostructured materials to a surface, typically ranging from 1 to 100 nanometers in thickness.

Nano coating can be applied to fabrics using various methods, often involving adhesives or binders to fix the coating: The pad-dry-cure method is commonly used for applying nanoparticle coatings to fabrics. For instance, encapsulated nanosilica particles were coated on fabric surfaces using this technique to impart properties like antibacterial activity and wrinkle resistance [42]. Direct electrospinning of nanofibers onto padded fabrics is another approach, which creates an interconnected nanofibrous structure on the fabric surface [43]. Adhesives and binders play a crucial role in fixing nano coatings to textiles. Water-based adhesives are used as coatings for electromagnetic shielding textiles [44] [45]. Commercial binders are employed to disperse metal oxide nanoparticles like TiO₂ and ZnO before coating textiles [46]. Polymeric binders such as TEXPRINT ECOSOFT N10[®] and WST SUPERMOR[®] are used to incorporate phase change material (PCM) microcapsules into fabrics [47]. Nano coating application on fabrics involves various techniques, with adhesives and binders being essential components for fixing the coating. The choice of method and adhesive depends on the desired properties and the specific nanoparticles or materials being used. These techniques allow for the development of multifunctional textiles with enhanced properties such as antibacterial activity, flame retardancy, and electromagnetic shielding [42] [46] [48]. The fixation of nanocoatings requires precise control over environmental conditions and application parameters to ensure consistent and effective results. This advanced surface treatment technique offers numerous benefits, including improved durability, enhanced functionality, and reduced material consumption

compared to traditional coating methods.

4.3. Impact of Nano Coating on UV Protection

✓ CaO and CaO-SiO₂ Nanocoating

The study examines the enhancement of UV protection in jute fabrics using CaO and SiO₂ nanoparticles through a dip-coating method. They assessed the UV protection of treated fabrics using the EN13758-1 standard, which computes the Ultraviolet Protection Factor (UPF), UVA, and UVB blocking [49].

Results showed a significant increase in UV protection. Untreated jute fabric had a UPF of 8, indicating minimal protection, whereas CaO nanoparticle-treated fabric exhibited a UPF of 159, offering excellent protection. Further enhancement was observed when SiO₂ nanoparticles were added to the CaO coating, though the precise UPF value was not detailed. The study attributes the improved UV protection to metal oxide nanoparticles' ability to reflect, scatter, and absorb UV radiation, owing to their semiconducting properties that enable electron excitation from the valence band to the conduction band. In short, the above study demonstrates that CaO and CaO-SiO₂ nanoparticle coatings significantly enhance the UV protection of jute fabrics, potentially broadening their use in UV-protective textiles. There were two studies that explored enhancing UV protection in fabrics using nanoparticle coatings. In the research, jute fabrics were treated with CaO and SiO₂ nanoparticles. The results showed a significant improvement in the Ultraviolet Protection Factor (UPF), which rose from 8 for the untreated jute to 159 for the fabric treated with CaO nanoparticles [49]. The application of nano-zinc oxide coatings to cotton, polyester/cotton, and polyester fabrics led to notable improvements in UV protection [50]. Furthermore, fabrics treated with nano-ZnO demonstrated considerable increases in their Ultraviolet Protection Factor (UPF) [50].

The methodologies employed in these studies differed significantly. One approach utilized dip-coating [49] and adhered to the EN13758-1 standard for measuring Ultraviolet Protection Factor (UPF). In contrast, another study [50] employed hydrothermal synthesis and followed the AATCC test method for UPF evaluation. This latter research also investigated the impact of nanoparticle morphology on UV protection. The findings revealed that rod-shaped nano-zinc oxide particles provided superior UPF values compared to star or sphere-shaped particles. Notably, the UPF values remained durable even after multiple wash cycles.

✓ Activated Nanocarbon (ANC)

The enhanced UV protection is attributed to the nanoparticles' ability to reflect, scatter, and absorb UV radiation. These findings indicate that nanoparticle coatings are a promising approach for developing UV-protective textiles across various fabric types. In line with the growing interest in sustainable and eco-friendly textile treatments, the study by [51] presents a methodology to enhance ultraviolet (UV) protection in cotton fabric utilising a hybrid coating of activated nanocarbon

(ANC) derived from Teff hay and polyaniline (PANI). The process encompasses the synthesis and functionalisation of ANC, followed by *in-situ* polymerisation of PANI on cotton fabric with functionalised ANC. Response Surface Methodology optimised the ANC and PANI percentages for maximum UV protection. The optimised coating significantly increased the Ultraviolet Protection Factor (UPF) from 3.7 to 64.563, representing a 17-fold improvement. This enhancement is attributed to the synergistic effect of ANC absorbing UV radiation and PANI functioning as a UV absorber and radical scavenger. The optimal coating composition was determined to be 24.585% PANI and 3.307% ANC. The study presents a sustainable, cost-effective method for creating highly UV-protective cotton fabrics utilising agricultural waste. The findings have significant implications for UV-protective clothing in the textile industry. Enhancing cotton fabric's UV protection with a hybrid coating of activated nanocarbon from Teff hay and polyaniline offers a promising, environmentally-friendly approach that could potentially reduce UV-related skin damage. This method aligns with circular economy principles, presenting new opportunities for sustainable innovations in textile manufacturing.

✓ **TiO₂ Coating**

The research examined the utilisation of TiO₂ nanoparticles to enhance UV protection in workwear fabrics. Employing an *in-situ* synthesis method, the researchers applied TiO₂ nanoparticles to fabrics and subsequently measured their Ultraviolet Protection Factor (UPF). The findings demonstrated a significant increase in UPF values for coated fabrics in comparison to uncoated specimens. Notably, the coating did not adversely affect the fabrics' comfort and performance properties, including air permeability, thermal resistance, and water vapour resistance. The study concludes that TiO₂ nanoparticle coating constitutes an efficacious method for augmenting UV protection in workwear fabrics without compromising their intrinsic properties. Nanocoating technology has revolutionized fabric protection by providing exceptional UV shielding and durability. Studies indicate substantial increases in Ultraviolet Protection Factor (UPF), with some treatments enhancing UPF from single digits to over 150. These coatings, using materials like CaO, SiO₂, ZnO, and TiO₂, efficiently reflect, scatter, and absorb UV radiation. They can be applied to various fabrics, including natural fibers like cotton and jute and synthetics like polyester, while preserving comfort and performance.

TiO₂ nanoparticle coatings on workwear fabrics have shown promising results, spurring further research into nanocoating technology. This research is yielding even greater UPF improvements across diverse fabrics. For instance, Rabiei *et al.* (2022) demonstrated the feasibility of maintaining comfort and performance while enhancing UV protection. Innovative methods, such as using activated nanocarbon from agricultural waste, are advancing sustainable, eco-friendly textile treatments. This technology not only boosts UV protection but also supports circular economy principles, potentially revolutionizing the textile industry and reducing UV-related skin damage risks [52].

5. Bio Composite

Biocomposites are materials made from a combination of natural fibers and polymers, designed to harness the beneficial properties of both components. They typically consist of natural fibers as reinforcement embedded in a polymer matrix, which can be either synthetic (e.g., PP, PE) or bio-based (e.g., starch, PLA, PHA) [53] [54]. These materials are gaining popularity due to their environmental advantages compared to traditional synthetic composites. The primary components of biocomposites are: 1) Natural fibers: These provide reinforcement and can include plant-based fibers like flax, hemp, or wood flour. They offer benefits such as biodegradability, low weight, low cost, and improved thermal and mechanical properties [55] [56]. 2) Polymer matrix: This can be either synthetic thermoplastics or bio-based polymers. The matrix binds the fibers together and provides protection from environmental factors. Interestingly, while biocomposites offer numerous environmental benefits, they can present challenges at the end of their lifecycle. Current recycling streams are not well-suited for these materials, leading to increased focus on “eco-friendly” composites based on biodegradable polymers and fillers. Additionally, the quality of the fiber-matrix interface is crucial for optimal performance, often requiring surface modifications of natural fibers to improve adhesion. In conclusion, biocomposites represent a promising class of materials that combine the strengths of natural fibers and polymers [54] [56]. They offer potential solutions for reducing environmental impact while maintaining or even enhancing performance in various applications, from automotive to biomedical sectors [55] [57]. However, ongoing research is needed to address challenges in manufacturing, durability, and end-of-life management to fully realize their potential as sustainable alternatives to conventional composites. Biocomposites are innovative materials that combine natural fibers or particles with synthetic or bio-based polymers, offering an environmentally friendly alternative to traditional composites. These materials have found applications across various industries, showcasing their versatility and potential for sustainable development. In the automotive sector, biocomposites are utilized for interior components, panels, and structural parts, contributing to lighter and more fuel-efficient vehicles. The construction industry has embraced biocomposites for building materials, insulation, and decking, leveraging their thermal and acoustic insulation properties.

Impact of Biocomposites on UV Protection

✓ ZnO/carboxymethyl chitosan

As the second most prevalent biopolymer in nature, chitin derived from the exoskeletons of crustaceans and insects serves as the primary constituent of, as well as the cell walls of, certain bacteria and fungi. This substance is extensively distributed worldwide. Notably, the biodegradable and biocompatible properties of chitin have elicited considerable interest in its potential applications for UV protection in textiles, analogous to the utilisation of ZnO nanoparticles [58]. Moreover, another research investigated a ZnO/carboxymethyl chitosan bionano-

composite to enhance the antibacterial and UV protection properties of cotton fabric. The composite, synthesised at various temperatures and characterised using UV spectroscopy, FTIR, and TEM, was applied to cotton fabric via pad-dry curing. Treated fabric analysis, including SEM, XRD, UPF rating, and antibacterial assessments, showed successful composite formation with significant antibacterial activity against Gram-positive and Gram-negative bacteria, which increased at higher concentrations. The treated fabric also exhibited improved UV protection, which was further enhanced by higher curing temperatures [59].

✓ **Biocomposites—PAN-based composite nanofibrous membranes**

A study reported that a composite material combining polyacrylonitrile, UV absorber 329, and titanium dioxide nanoparticles [60]. Whereas, another research emphasised the need for further analysis to evaluate the eco-friendliness of the composite throughout its lifecycle, considering the environmental impact of raw materials (PAN, UV329, TiO₂), sustainability of the fabrication process (electrospinning), and the durability and lifespan of the composite, which influence its overall sustainability [61]. This study aims to develop a PAN-based composite nanofibrous membrane with enhanced UV protection and filtration performance. Researchers have used electrospinning to create composite membranes incorporating UV329 for UV absorption and TiO₂ nanoparticles for UV shielding. The results showed that combining UV329 and TiO₂ significantly improved the UV protection capabilities of the PAN membranes, resulting in high UV absorption and blocking efficiency. The inclusion of TiO₂ nanoparticles also enhanced the filtration performance of small particles. The synergistic effect between UV329 and TiO₂ led to superior UV protection and filtration compared with membranes with only one additive.

A PAN/UV329/TiO₂ composite nanofibrous membrane was successfully developed, offering potential applications in protective clothing and air filtration systems that require both UV protection and efficient filtration. PAN, a synthetic polymer, is known for its strength, heat resistance, and fibre fabrication capabilities. UV329, a benzotriazole-based compound, absorbs harmful UV radiation, particularly UVB rays, and converts it into less harmful thermal energy [61]. TiO₂, a naturally occurring titanium oxide is an effective white pigment used in paints, coatings, sunscreens, food colouring, and photocatalytic processes [62]. It provides opacity, brightness, UV absorption, and self-cleaning properties [63] [64].

The combination of PAN, UV329, and TiO₂ to create a novel composite material resulted in a synergistic effect, leading to enhanced properties that surpassed those of the individual components. In this composite, each constituent plays a distinct role: PAN provides the structural framework, UV329 acts as a UV absorber, and TiO₂ enhances both the UV shielding and filtration performance. The integration of these materials into a cohesive structure yields a composite with improved UV protection and filtration capabilities compared with using any of the components individually. The study presented offers promising findings, but like many research articles, it leaves room for further investigation in several areas

[61]. Potential gaps that could be explored include long-term performance and durability. Focusing on the initial properties of the composite membrane and evaluating its long-term performance and durability, particularly the persistence of UV protection and filtration efficiency after prolonged exposure to UV radiation, washing, or mechanical stress, could provide valuable insights.

a) Environmental impact: Evaluating the environmental impact of a composite material throughout its life cycle, including raw material sourcing, manufacturing, use, and disposal, is vital to ensure sustainable technology.

b) Cost-effectiveness: Comparing the production cost of composite membranes with current UV protection and filtration solutions is important for assessing their practical viability and market adoption.

c) Scalability: Investigating the scalability of the fabrication process to meet industrial demands is crucial for successful implementation of the technology. A nanofibrous membrane is a composite material envisioned as a thin, flexible layer made of extremely fine fibres. This composite can be applied to fabrics, as indicated by its potential use in protective clothing.

However, this study primarily focused on the development and characterisation of the membrane itself, without addressing specific fabric coating methods or the performance of various fabrics. However, further research is required to investigate these aspects. Notably, the properties of the final composite membrane may differ from those of individual components. Although pure PAN typically has low air and water permeability owing to its dense molecular structure, researchers have used electrospinning to create nanofibrous structures. This technique can produce a membrane with a high surface area and minute pores between the fibres, potentially affecting the air and water permeability of the composite. The specific permeability characteristics of the composite membranes are not detailed in this article, warranting further study of these properties and their relevant applications.

Biocomposites offer several advantages, including biodegradability, reduced environmental impact, and utilization of renewable resources [65]. Their lightweight properties and good strength-to-weight ratio make them attractive for various applications. Additionally, biocomposites contribute to reduced dependence on petroleum-based materials and often provide improved thermal and acoustic insulation. In some applications, they may also offer lower production costs compared to traditional materials [57].

However, biocomposites are not without challenges. The natural fiber components can lead to variable material properties, requiring careful quality control measures. Moisture sensitivity and potential for degradation in certain environments pose limitations on their use [66]. Biocomposites may also exhibit limited high-temperature performance compared to traditional composites, restricting their application in some high-heat scenarios. Achieving consistent quality control can be challenging due to the inherent variability of natural materials [67]. Despite these limitations, ongoing research and development efforts continue to

address these issues, expanding the potential applications of biocomposites across various industries [68] [69]. Biocomposites, combining natural fibers with synthetic or bio-based polymers, have gained traction in textile applications. These materials offer eco-friendly alternatives to traditional textiles, providing improved sustainability and biodegradability. In textile manufacturing, biocomposites are used to create fabrics with enhanced properties such as strength, durability, and moisture-wicking capabilities. They find applications in clothing, upholstery, and technical textiles. Biocomposites also contribute to reducing the environmental impact of textile production by utilizing renewable resources and potentially lowering energy consumption during manufacturing processes [70] [71].

While biocomposites demonstrate significant potential for improving UV protection in knitted textiles, their impact extends beyond just UV-blocking capabilities. The integration of natural fibers and biodegradable polymers in biocomposites aligns with growing sustainability demands in the textile industry, potentially revolutionizing how we approach UV protection in clothing and other fabric applications. However, realizing the full potential of biocomposites requires addressing key challenges, particularly in scaling up production processes and ensuring consistent performance under diverse real-world conditions. As research progresses, biocomposites may emerge as a versatile solution that not only enhances UV protection but also contributes to more environmentally friendly and multi-functional textile products.

6. Nanocomposites

Nanocomposites are advanced materials that incorporate nanoscale fillers or reinforcements within a matrix material, typically a polymer. These nanoscale components, such as nanocellulose, nanosilica particles, or other nanofillers, have dimensions in the nanometer range (1 - 100 nm) and provide unique properties to the composite due to their large surface area and high aspect ratio. While nanocomposites and biocomposites differ in their reinforcing elements, both represent innovative approaches to material design that aim to enhance performance and sustainability in various applications. Interestingly, the combination of nanofillers with natural fiber-reinforced composites has led to the development of hybrid bio-based composites or nanobiocomposites. These materials aim to leverage the benefits of both nanocomposites and biocomposites, enhancing mechanical properties while maintaining environmental appeal [72] [73]. For example, the addition of nanofillers to natural fiber composites has been shown to improve tensile, flexural, and compressive strengths, as well as thermal stability [74]. The emerging field of nanobiocomposites combines both nanotechnology with biocomposites, which create high-performance, environmentally friendly materials suitable for various applications in industries such as automotive, aerospace, and packaging [75].

6.1. Impact of Nanocomposites on UV Protection

✓ **Lignin-TiO₂ composites - ZnO-TiO₂ composite films**

A study developed a biodegradable, sustainable UV-shielding material via the hydrothermal synthesis of a lignin-TiO₂ composite facilitated by nanofibrillated cellulose. This synthesis method, conducted under high temperature and pressure in aqueous solutions, allows control over the particle size and morphology, yields highly crystalline products, and ensures environmentally friendly reaction conditions [76].

The lignin-TiO₂-NFC composite, synthesised using an eco-friendly method, exhibited optimal nanoparticle characteristics and thermal stability. When incorporated into an unmodified hand cream, the composite demonstrated excellent UV-shielding properties, absorbing nearly 90% of the UV radiation across the spectrum. In this study, TiO₂ and lignin were selected as the raw materials for the nanocomposites based on specific rationales. Furthermore, another study developed a transparent polyethylene terephthalate (PET) film with enhanced UV-blocking properties. They synthesised a ZnO-TiO₂ composite using a hydrothermal method followed by ball milling, and applied it with a UV stabiliser to PET films via dip coating. The addition of the ZnO-TiO₂ composite significantly improved UV blocking, achieving less than 20% UV transmittance while maintaining 90% visible light transmittance, indicating its potential for applications that require transparency and UV protection, such as packaging for UV-sensitive products [77].

✓ **Zinc oxide - Titanium di Oxide Nanocomposite**

Researchers synthesized ZnO-TiO₂ composite nanoparticles via a hydrothermal method, controlled the size and crystallinity, and used ball milling to reduce particle size and enhance

dispersion. These steps are critical for achieving a transparent film by minimising light scattering from large agglomerates. Two strategies were employed to address nanoparticle agglomeration: modifying ZnO and TiO₂ nanoparticle surfaces with 3-chloropropyl trimethoxy silane to enhance wettability, compatibility with organic solvents, and reducing surface energy, thus minimising aggregation. Hydrothermal synthesis and ball milling improved nanoparticle dispersion by narrowing size distribution and breaking weak agglomerates. These combined methods produced nanocomposites with well-dispersed nanoparticles, enhancing the transparency of the PET film.

The 3-chloropropyl trimethoxysilane coupling agent effectively bonded inorganic ZnO-TiO₂ nanoparticles with the organic polymer, strengthening the material interface [78]. The eco-friendliness of 3-chloropropyl trimethoxysilane raises concerns. Some silane coupling agents may emit harmful volatile organic compounds during processing. In addition, their environmental impact and potential for bioaccumulation require further research. Scientists are investigating bio-based coupling agents from renewable resources as sustainable alternatives [79], [80]. A review paper [81] examined the synthesis and uses of zinc oxide nanoparticles highlighting their antimicrobial and UV protection properties in healthcare. Although not primarily focused on textiles, it discusses textile applications in

these areas.

Specifically, the paper discusses the integration of ZnO NPs into the

a) Wound dressings: Their antimicrobial activity makes ZnO NPs suitable for antibacterial wound dressings, and their incorporation into various polymer matrices was examined.

b) UV-protective textiles: This study briefly acknowledges the potential of ZnO NPs for developing textiles with enhanced UV protection properties.

ZnO NPs offer a promising solution to the growing need for effective antimicrobial and UV protection methods in healthcare, thanks to their dual functionality.

This review explores various synthesis methods, including chemical, physical, and biological techniques, and examines how the synthesis conditions affect the properties of ZnO NPs. The antimicrobial mechanisms of ZnO NPs, such as reactive oxygen species generation and cell membrane disruption, are described, along with evidence of their effectiveness against various microorganisms. This review also discusses UV absorption and scattering properties of ZnO NPs, their incorporation into products for UV protection, and their applications in wound dressings, drug delivery, and dental materials. The potential of ZnO NPs to address antibiotic resistance and prevent infections is highlighted, while challenges related to toxicity, stability, and large-scale production are addressed, emphasising the need for further research to optimise their properties and ensure their safe and effective use in healthcare.

✓ **Mesoporous Cellulose Nanocomposite**

“Natural Fiber Welding” was used for creating mesoporous cellulose structures by reorganizing cellulose fibers into an interconnected pore network. The high surface area of the nanoscale pores makes mesoporous cellulose suitable for filtration, catalysis, and drug delivery. It is produced by altering cellulose fibres to induce porosity and enhance textile properties, such as UV protection [82]. Mesoporous cellulose can be fabricated into powders, fibres, films, beads, or 3D scaffolds, with the form chosen based on specific applications and desired properties [83] [84]. Researchers have endeavoured to develop UV-protective textiles using mesoporous cellulose as a scaffold for titanium dioxide nanoparticles (TiO₂NPs). The steps involved in synthesising the nano composite are:

a) Creating Mesoporous Cellulose: Researchers have used natural fibre welding on Aida cloth (cotton fabric) to form a mesoporous structure within the cellulose fibres.

b) Incorporating TiO₂NPs: Mesoporous cellulose was then immersed in a TiO₂NP solution, allowing effective nanoparticle entrapment within the cellulose matrix.

c) Testing UV Protection: The UV protection factor of the resulting fabric was measured using standardised tests and compared to that of control samples (untreated and non-mesoporous NFW cloth).

A range of analytical methods were utilised to investigate the characteristics of the material, including electron microscopy and spectroscopy, and to evaluate their concentration within the cellulose framework.

6.2. UV Protection Performance

The mesoporous cellulose fabric with TiO₂NPs achieved an FDA-rated “Excellent” UPF of 200+, significantly outperforming the control samples. The mesoporous structure enabled a high TiO₂NP loading (approximately 1.6 wt%) while maintaining fabric flexibility and breathability. TiO₂NPs were incorporated within approximately 60 s. Encapsulation within the mesoporous structure likely enhances TiO₂NP durability and reduces leaching during washing. Further it was demonstrated that an innovative method for creating UV-protective textiles by leveraging the properties of mesoporous cellulose and TiO₂NPs, promising comfortable and durable fabrics with superior UV protection [82]. Future research should investigate the long-term performance and sustainability of fabric treatments. Despite advances in the UV protection of textiles, key gaps remain in their long-term performance, environmental impact, scalability, and application. To the best of our knowledge, this is the first synergistic review of recent advancements in ultraviolet protection through nanotechnologies for knitted textiles via nanocomposites and biocomposites.

Recent advancements in nanotechnology have opened new possibilities for enhancing UV protection in knit fabrics. However, despite significant progress, several critical areas require further investigation to fully realise the potential of these innovative solutions. This review examines the current state of nano-UV-protective technologies for knit fabrics, highlighting their key achievements. However, previous studies do not address the following gaps or identify crucial research voids that need to be addressed for widespread adoption and long-term effectiveness.

1) Durability: The long-term performance of UV-protective treatments and materials requires further investigation to ensure sustained effectiveness under real-world conditions.

2) Cost-effectiveness: More research is required to develop economically viable solutions for large-scale implementations.

3) Environmental impact: Studies on the ecological footprint of UV-protective technologies, including their production processes and end-of-life disposal, are necessary.

4) Toxicity and biocompatibility: The potential health risks associated with UV-protective materials, particularly those incorporating nanoparticles, require thorough examination.

5) Real-world usage: Controlled laboratory studies should be complemented by field tests to assess the performance under various environmental conditions.

6) Fabric properties: The impact of UV-protective treatments on other textile characteristics, such as air permeability and comfort, requires further explo-

ration.

7) Scalability: Research on scaling up the production processes for commercial viability is essential.

9) Standardisation: The development of uniform testing protocols and industry standards for UV protection of textiles and materials is crucial.

10) Mechanism of action: A deeper understanding of the underlying principles of UV protection of various materials could lead to more effective solutions.

11) Clinical translation: For healthcare applications, more research is required to bridge the gap between laboratory findings and practical medical use.

12) Multifunctional materials: Exploration of materials that combine UV protection with other desirable properties (e.g. antibacterial and self-cleaning) could yield versatile solutions.

13) Sustainability: The focus on developing eco-friendly, biodegradable UV-protective materials aligns with global sustainability goals.

14) Interdisciplinary approach: Collaboration across the materials science, textile engineering, and healthcare sectors could accelerate innovation in UV protection technologies.

7. Classification of Nano-Coating, Nanocomposites, and Biocomposites in Textile Application

Nano-coated textiles, nanocomposites, and biocomposites constitute three distinct categories of advanced materials utilised in textile applications, each exhibiting unique characteristics and advantages. Nano-coated textiles involve the application of an extremely thin layer of nanoparticles (1 - 100 nm) to textile surfaces, enhancing properties such as water repellency and UV protection. nanocomposites combine a polymer matrix with nanoscale fillers, resulting in improved mechanical and thermal properties. Biocomposites, conversely, utilise bio-derived matrices and natural or synthetic fibres, offering biodegradability and reduced environmental impact. These materials differ in composition, production methods, and functional properties. Nano-coated textiles are produced through coating techniques, nanocomposites through various mixing and polymerisation processes, and biocomposites through moulding and extrusion. While nano-coated textiles and nanocomposites find applications in high-performance and protective textiles, biocomposites are particularly valued for their eco-friendly attributes. Each category presents unique environmental considerations, from potential nanoparticle release to biodegradability and reduced carbon footprint.

To provide a comprehensive overview of the key characteristics and applications of these advanced materials in textile applications, **Table 1** below presents a comparative analysis of nano-coated textiles, nanocomposites, and biocomposites.

8. Advantages of the Recent Innovations

Textiles incorporating nanocoatings, nanocomposites, and biocomposites exhibit

Table 1. Classification of distinct advanced material [included].

ATTRIBUTES	NANO-COATED TEXTILES	NANO-COMPOSITES	BIOCOMPOSITES
1. Definition	An extremely thin film or coating of nanoparticles with a thickness ranging from 1 to 100 nanometers (nm) on textile material	Materials with nanoscale fillers (1 - 100 nm) in a polymer matrix	Materials created by combining bio-derived matrices with natural or synthetic fibers, often characterized by biodegradability and a reduced environmental impact compared to conventional composites.
2. Material composition	Base textile material + nanocoating material	Polymer matrix + nanoscale fillers or reinforcements	Bio-based matrix + reinforcing fibers (natural or synthetic)
3. Production method	Coating techniques (e.g., dip-coating, spray coating, electrospinning)	In-situ polymerization, melt blending, solution mixing	Compression molding, injection molding, extrusion
4. Functional properties	Water repellency, UV protection, antimicrobial properties	Enhanced mechanical properties, thermal stability, barrier properties	Biodegradability, renewable resource utilization, lightweight
5. Application areas	Protective clothing, sportswear, medical textiles	High-performance textiles,	Bio-degradable High-performance fabrics
6. Environmental impact	Potential nanoparticle release, durability of coating	Recyclability, potential environmental risks of nanoparticles	Biodegradability, reduced carbon footprint
7. Scale of reinforcement	Surface modification at nanoscale	Nanoscale reinforcement throughout the matrix	Macro to microscale reinforcement
8. Performance characteristics	Surface-dependent properties	Enhanced bulk properties due to nanoscale interactions	Bulk material properties, often with anisotropic behavior

significantly enhanced UV-blocking efficacy in knitted materials, achieving UPF levels of 40+ or even 200+. Numerous technologies in this domain confer both UV protection and antimicrobial properties, resulting in multifunctional textiles. The incorporation of nanoparticles into the structure of the fabric can yield more persistent UV protection than surface treatments. Many of these innovations enhance UV shielding while maintaining the breathability, flexibility, and wearability of the fabric. Biocomposites and solutions derived from natural fibres are sustainable alternatives. The degree of UV protection can be modulated by altering nanoparticle concentration or composite formulations.

This review paper highlights the research gaps in long-term performance, environmental impact, and real-world applications of UV protection for textiles and materials. The multidisciplinary nature of this field, involving materials science,

textile engineering, and healthcare, offers opportunities for cross-sector collaboration and innovation. The focus on sustainability aligns with global trends towards eco-friendly solutions. The review aims to drive the development of more sustainable UV protection methods that benefit both consumers and the environment, potentially leading to engineered fabrics that provide UV protection without compromising comfort and breathability.

9. Limitations of the Recent Studies

Further research is necessary to investigate the potential risks and ecological implications of nanoparticle utilisation in textiles. State-of-the-art methodologies may prove prohibitively expensive or challenging to implement on a scale. Numerous experiments are conducted under controlled laboratory conditions rather than in practical, real-world environments. Understanding the application of ultraviolet finishes on other textile properties is to be studied for improved functional clothing. The process of incorporating nanoparticles or developing nanocomposites may increase manufacturing complexity. Newly developed nanomaterials may encounter regulatory barriers before market introduction.

10. Results

Evaluating the Effects of Nano-Coating, Nanocomposite, Biocomposite Materials to Develop UV Protective Knit Fabrics

As the textile industry moves towards more sustainable practices, these innovations align with eco-friendly goals. These innovative approaches not only address UV protection but also offer additional benefits. This section of the review paper addresses key evaluating features of innovative textile technologies for enhanced UV protection. It highlights three main approaches: nano-coatings, nanocomposites, and biocomposites. These technologies not only significantly improve UV blocking capabilities, achieving high UPF ratings, but also offer multifunctional properties such as antimicrobial activity. The durability of UV protection is enhanced, particularly in nanocomposites. Importantly, these innovations maintain essential fabric properties like breathability and flexibility. The passage also touches on sustainability aspects, noting that biocomposites and green synthesis methods offer more environmentally-friendly options. Additionally, the versatility of these technologies allows for modulation of UV protection levels. It is observed from **Table 2** that the synergistic effects are observed in certain combinations, such as ZnO and TiO₂ nanoparticles, leading to superior UV protection and antibacterial activity.

Various researchers have predominantly focused on advanced technical aspects and improved multifunctional properties of fabrics while neglecting the development of final products. The advancements in textile technology to improve UV-protection of fabrics result in the development of high-performance fabrics with improved shielding and antibacterial qualities.

Table 2. Key features of the advanced material.

S. No.	KEY EVALUATING FEATURES	REMARKS
1.	Enhanced UV protection	<ul style="list-style-type: none"> - Nano-coatings and nanocomposites incorporating materials like ZnO and TiO₂ nanoparticles significantly improve UV blocking, achieving UPF ratings of 40+ or even 200+. - Biocomposites using natural fibers and UV absorbers also show improved UV protection compared to untreated fabrics.
2.	Multifunctional Properties	<ul style="list-style-type: none"> - All three technologies discussed above confer UV protection and antimicrobial properties, resulting in multifunctional textiles. - Some composites also improve mechanical properties like strength and durability.
3.	Durability	<ul style="list-style-type: none"> - Incorporation of nanoparticles into the fabric structure can yield more persistent UV protection. - Studies suggest improved durability of the UV protective properties in nanocomposites. - While nanocomposites appear to offer improved durability in terms of UV protection, the durability of biocomposites is not explicitly discussed.
4.	Fabric Properties	<ul style="list-style-type: none"> - Various studies in this review proved that innovations improved UV protection while maintaining breathability, flexibility, and wearability of the fabric.
5.	Sustainability	<ul style="list-style-type: none"> - Biocomposites derived from natural fibers offer more environmentally-friendly alternatives. - However, the use of green synthesis to develop nanoparticles was reported as an eco-friendly approach.
6.	Versatility	<ul style="list-style-type: none"> - The degree of UV protection can be modulated by altering nanoparticle concentration or composite formulations.
7.	Synergistic Effect	<ul style="list-style-type: none"> - Nanocomposites between ZnO and TiO₂ can lead to superior UV protection compared to single additives. - The ZnO/carboxymethyl chitosan bionano-composite showed significant antibacterial activity - PAN-based composite nanofibrous membranes incorporating UV329 and TiO₂ nanoparticles demonstrated enhanced UV protection - Mesoporous cellulose fabric with TiO₂ nanoparticles achieved an FDA-rated “Excellent” UPF of 200+, significantly outperforming control samples.

11. Conclusion

Research on UV protection for textiles and materials has made significant progress, elucidating promising avenues for innovation and improvement. These studies have established a robust foundation for future advancements in the field by identifying key areas that require further investigation. The diverse range of approaches examined, from fabric treatment to nanoparticle applications, illustrates the field’s dynamic nature and potential for growth. This research on

advanced materials with UV protection and antibacterial properties in textiles has substantial implications for various industries and applications. The development of novel composites combining synthetic polymers, natural fibres, and nanoparticles presents promising solutions for enhancing textile functionality. However, several challenges remain unaddressed. As this field progresses, it has the potential to revolutionise textile manufacturing, leading to the development of multifunctional knitted fabrics that offer superior protection against UV radiation and microbial contamination, while maintaining comfort and sustainability. This could significantly impact public health, particularly by reducing UV-related skin damage and preventing the spread of infections in various settings.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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