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Nanocellulose for Military Textiles: Innovations, Applications, and Challenges

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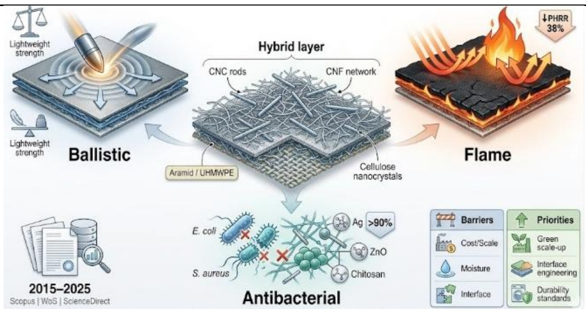
ABSTRACT



Military textiles must withstand ballistic threats, high temperatures, and chemical exposure while remaining lightweight, durable, and multifunctional. Nanocellulose, particularly cellulose nanofibrils (CNF) and cellulose nanocrystals (CNC), offers high specific strength, biodegradability, and tunable surface chemistry, making it a promising complement to conventional high-performance fibers, such as aramid. This structured review synthesizes peer-reviewed studies published from 2015 to 2025, retrieved from Scopus, Web of Science, and ScienceDirect, with a focus on ballistic resistance, flame retardancy, and antibacterial functionality. Evidence shows that CNF and CNC reinforcements improve energy dissipation and strength-to-weight ratios in composites, with several achieving benchmarks comparable to those of aramid-based materials. For flame protection, nanocellulose coatings and hybrid layers reduce peak heat release rates by up to 38% and promote the formation of dense char barriers, which limit heat and mass transfer. Antibacterial performance is typically achieved through functionalization with Ag, ZnO, or chitosan, often delivering over 90% inhibition of *Escherichia coli* and *Staphylococcus aureus*. Key barriers include production costs and scalability, as well as moisture sensitivity that can reduce long-term durability, and weak interfacial compatibility with aramid and ultra-high molecular weight polyethylene (UHMWPE). Future work should prioritize scalable green manufacturing, interface engineering for durable hybrids, and validation under military-relevant durability and laundering standards. Overall, nanocellulose is a strong candidate for next-generation sustainable military textiles.

Keywords: *Nanocellulose; Military Textiles; Ballistic Resistance; Flame Retardancy; Antibacterial Properties.*

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INTRODUCTION

Military textiles serve not only as uniforms but also as critical protective systems, used in ballistic vests, flame-retardant garments, chemical and biological protective suits, tents, and parachutes. These materials must perform reliably under extreme operational conditions, including high velocity impacts, chemical exposure, and rapid temperature fluctuations. Such environments demand textile systems that are lightweight, durable, and multifunctional, requirements that conventional fibers such as cotton and polyester, and even advanced aramids, increasingly struggle to meet [1].

Nanotechnology has therefore become a key pathway for improving military textile performance by enabling higher mechanical strength, improved chemical resistance, and added functionalities through the incorporation of nanoscale materials [2]. Although carbon nanotubes and metallic nanoparticles show strong potential, their broader deployment in defense applications is often constrained by concerns over toxicity, high production costs, and scale-up challenges [3].

Nanocellulose, available as cellulose nanofibrils (CNF), cellulose nanocrystals (CNC), and bacterial nanocellulose (BNC), has emerged as a strategic and more sustainable alternative. It combines high tensile strength (often reported above 2 GPa), low density, large specific surface area, and tunable surface chemistry, which together support effective reinforcement in textile composites [4]. Previous studies have reported improved ballistic resistance through efficient stress transfer networks and rigid percolation structures, where CNF and CNC form three-dimensional entangled architectures that enhance impact performance [3]. Nanocellulose has also been reported to reduce peak heat release rate by up to 38% in flame protection systems. In comparison, hybrid formulations incorporating metal oxide nanoparticles can achieve more than 90% antibacterial effectiveness due to increased surface reactivity [5]. Related findings by El Maaty et al. [6] and Dolez et al. [7] further highlight improved thermal stability, structural integrity, biodegradability, low toxicity, and compatibility with polymer matrices used in protective garments. These attributes position nanocellulose as a strong candidate for next-generation military textiles with mechanical, thermal, and functional advantages.

Despite these advances, research on nanocellulose for military textiles remains fragmented. Most studies focus on a single function, such as ballistic protection, flame retardancy, or antibacterial activity, without integrating these properties into a unified, multifunctional system. Practical issues also remain insufficiently resolved, including scalable production, long-term durability under humid or abrasive conditions, and interfacial compatibility with conventional fibers used in military fabrics[8-12].This review is positioned to address these gaps by focusing on nanocellulose as a core material platform for military textile applications. Recent progress is synthesized and compared across three performance domains: ballistic resistance, flame retardancy, and antibacterial functionality. Emphasis is placed on system-level integration rather than treating nanocellulose as an additive for isolated improvements [13], [14], [15]. Discussion also includes environmental stability, processing and manufacturing constraints, as well as considerations for alignment with existing defense requirements. This integrated perspective clarifies current performance trends, highlights trade-offs and design opportunities, and identifies the key barriers that must be overcome to translate them into practical protective systems. Ultimately, the review provides a unified framework for understanding how nanocellulose can support the development of next-generation military textiles that are sustainable, lightweight, and high-performance.

METHODS

1. Research Design and Approach

This study uses a structured narrative review to consolidate the fragmented literature on nanocellulose for military textile applications, where evidence on ballistic reinforcement, flame retardancy, and antibacterial performance is scattered across different material formats, testing protocols, and experimental designs. The review is guided by three questions: how nanocellulose is used to enhance protective textile functions; which mechanisms and material configurations drive these improvements; and what limitations remain regarding durability, operational reliability, and scale up for defense use.

Systematic review principles were adopted to strengthen transparency and consistency in study identification, screening, and inclusion, even though the method does not claim full PRISMA compliance. Figure 1 presents the PRISMA style flow diagram summarizing the literature selection process and the number of records retained at each stage.

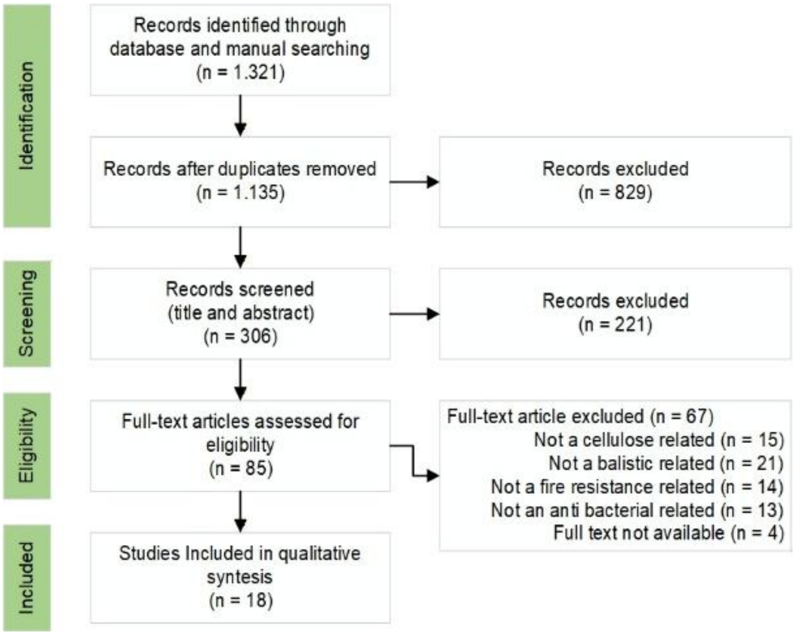

Figure 1. PRISMA Flow Diagram

2. Data Sources and Search Strategy

This study collected relevant literature using Scopus, Web of Science, ScienceDirect, and SpringerLink as primary databases, with Google Scholar used as a supplementary source. Non-peer-reviewed materials, such as theses, preprints, and conference papers, were excluded through manual screening. The search was conducted in two rounds, initially in early 2025, and was updated on 14 June 2025 to ensure completeness. Broader Boolean search strings incorporating synonyms for textiles, protective systems, and nanocellulose (e.g., textile, fabric, nonwoven, armor, ballistic, flame retardant, antibacterial, CNF, CNC, BNC) were used to capture variations in terminology across studies. Filters were applied to peer-reviewed articles published between 2015 and 2025 in English, with Google Scholar entries cross-checked for indexing to confirm peer-reviewed status. Additional studies were identified through consistent backward and forward reference tracking.

3. Data Selection and Inclusion Criteria

The selection criteria were intentionally broadened to include studies on nanocellulose (CNF, CNC, and BNC), as well as cellulose-based and natural fiber composites relevant to protective or military-oriented textile functions. This scope was adopted because several articles retained in the final dataset extend beyond the strict boundaries of nanocellulose textiles, while still providing useful evidence for performance mechanisms and design strategies. Articles were excluded when they lacked clear relevance to protective textile applications or when they focused primarily on unrelated domains, such as purely biomedical materials. Study transparency and technical adequacy were assessed using an internal checklist covering methodological clarity, experimental completeness, and the availability of quantitative results. Screening was conducted in two stages. Titles and abstracts were reviewed first, followed by full-text assessment. Two independent reviewers performed the screening, and any disagreements were resolved through discussion to reach consensus. Rayyan was used to organize references, apply tags, and document inclusion decisions, supporting a transparent workflow and maintaining PRISMA-aligned rigor in the selection process.

4. Data Analysis dan Synthesis

The included studies were synthesized by grouping their contributions into three functional themes: ballistic resistance, flame retardancy, and antibacterial performance. The dataset comprised diverse material forms, including nanocellulose systems, as well as cellulose-based and natural fiber composites, which were retained because they provide relevant mechanistic and performance insights for protective textile applications. To ensure consistent interpretation across heterogeneous study designs, each article was assessed using a simple quality assessment rubric, scored from 0 to 2, across three criteria: clarity of methodology, adequacy of experimental procedures, and availability of quantitative performance data, as summarized in Table 1.

5. Ethical Considerations

As this study is based solely on published literature, no ethical approval was required. All data were derived from publicly available, properly cited academic sources. The author maintained objectivity, avoided plagiarism, and adhered to responsible reporting practices throughout the research process.

RESULT AND DISCUSSION

Recent advances in nanotechnology suggest that nanocellulose can deliver practical benefits for military-relevant materials. However, its performance is still limited by moisture sensitivity, processing variability, and a lack of validation beyond laboratory-scale conditions. Despite being derived from renewable cellulose sources, the reviewed studies suggest that nanocellulose contributes mainly through reinforcement effects and surface reactivity, rather than solely through the general intrinsic properties discussed earlier [8]. This versatility not only supports incremental improvement of existing textile systems but also enables new design routes for advanced military equipment, uniforms, and protective gear.

Table 1. Articles were included in the review

Ref.	Material/Modification	Application Focus	Key Finding
[15]	Graphene oxide-coated natural fiber composites	Ballistic armor	Matrix–fiber adhesion ↑50%, high elastic modulus, met NIJ <44 mm standard (Kevlar ~23 mm equivalent).
[16]	Ubim fiber-reinforced epoxy composite	Ballistic, thermal, chemical	Improved thermal stability (335°C), good fiber–matrix interaction, and physical integrity maintained post-impact.
[17]	Carana fiber-reinforced epoxy composites	Ballistic & impact	Energy absorption ↑637%, average absorbed energy 48.17 J, ballistic limit (V_L) 186 m/s, good matrix–fiber bonding.
[18]	Buriti fabric reinforced epoxy composite	Ballistic armor	BFS <44 mm, absorbed 189 J, effective in multilayer and stand-alone scenarios, maintained post-impact integrity.
[19]	Salak peel fiber + epoxy + Kevlar/SiC/Al7075	Ballistic armor	BFS = 0 mm (NIJ Level II & IIA), tensile strength ↑21.46 N/mm², hardness ↑23.64 HV, superior to neat resin.
[20]	Salak peel fiber + Kevlar + carbon fiber (VARTM)	Ballistic armor (vests)	BFS 3.79 mm, passed NIJ Level II & IIA, failed at Level III (5.56 mm), moderate fiber–matrix adhesion.
[27]	Cellulose from wheat straw, corn stalk, and water reed (CMP, SE treatment)	Flame retardancy	All samples, except water reed, met the fire-resistance classification; wheat straw and corn stalk showed the best performance.
[29]	EPS-cellulose/ polypropylene composites	Flame retardancy/mechanical	Char formation ↑32%, thermal decomposition ↑71%, PHRR ↓38%, stiffness ↑83.7%, and anti-dripping were observed.
[23]	Cellulose fiber–reinforced polyurethane foams (pretreated cellulose fiber)	Flame retardancy & mechanics	T_{max} 365°C, compressive strength 1103 kPa, thermal conductivity 0.0549 W/m·K, improved thermal/mechanical stability.
[32]	Nano-fibrillated cellulose/hydroxyapatite foams	Flame retardancy	Low thermal conductivity (38–39 mW/m·K), self-extinguishing, and the highest compressive modulus, 463 kPa.
[31]	Densified cellulose-based poplar structures	Flame retardancy & mildew resistance	Hardness ↑3.9×, MOE ↑3.4×, improved dimensional stability, enhanced flame retardancy, and mildew resistance.
[34]	Cellulose board + boric acid + protein binders	Flame retardancy	Passed UL 94-HB, self-extinguishing, low density (122–164 kg/m³), improved thermal stability. *(No matching ref. in pasted.txt)*
[36]	PVA films with bacterial cellulose + ε-polylysine	Antibacterial & mechanics	Tensile strength 36.3 MPa, antibacterial activity >99% (*E. coli*, *S. aureus*), high biocompatibility, improved thermal stability.
[41]	Regenerated hemp cellulose fiber	Antibacterial	Crystallinity ↑94.7%, tensile strength 0.85 cN/dtex, antibacterial activity (*E. coli* 76.6%, *S. aureus* 46.3%).
[38]	Cellulose wipes with AgNPs	Antibacterial & antiviral	High absorption and softness, self-distributed AgNPs, vigorous antibacterial activity, 51.7% inhibition against MERS-CoV.
[40]	Amoxicillin-loaded cellulose aerogels	Antibacterial drug release	Porous 3D network, controlled drug >12 h, antibacterial activity against *E. coli*, *S. aureus*, *B. subtilis*, *C. albicans*.
[39]	Cellulose + chitosan/chitin nanostructures	Antibacterial	Strong cellulose–chitosan/chitin interaction, enhanced mechanical and antimicrobial performance, >90% microbial reduction.
[42]	Cu-coated cellulose nonwoven (magnetron sputtering)	Antibacterial & hemostatic	Antibacterial against *E. coli*, *S. aureus*, and *C. glabrata*; hemostatic effect (Cu^{2+} and Ca^{2+} ions).

Nanocellulose has also been extensively investigated in various sectors, including optoelectronics, pharmaceuticals, and healthcare. The relevance of these findings to this review lies in the transferable principles they demonstrate, particularly lightweight reinforcement, interfacial engineering, and tunable functionality, which can inform the development of military textile systems that are more durable, adaptable, and performance-oriented.

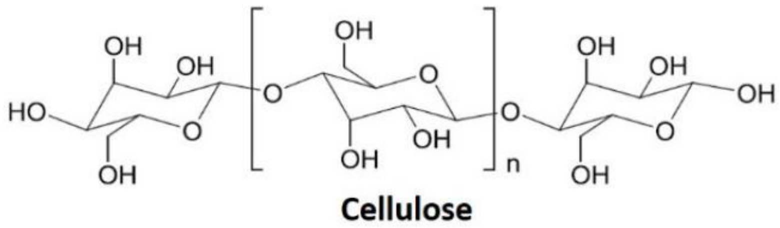

Figure 2. Cellulose Chemical Structure [5]

Chemical modification through esterification is typically carried out via esterification and etherification reactions of lignocellulosic hydroxyl groups. The reaction with organic acids or anhydrides is referred to as esterification (Figure 3). Various types of esters can be formed depending on the nature of the organic acid (or anhydride) used in the reaction.

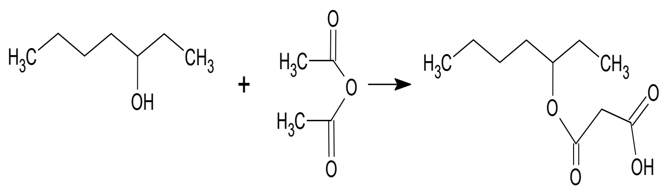

Figure 3. Esterification reaction

This process involves fiber plastification through the introduction of acetyl functional groups. Acetic acid (CH_3COOH) reacts with hydrophilic hydroxyl groups on the fiber surface, reducing moisture affinity and limiting water uptake. During acetylation, hydroxyl groups in lignocellulosic fibers are substituted with more hydrophobic moieties, which alter fiber polarity and improve compatibility with nonpolar matrices. This esterification treatment can also modify surface topography by increasing roughness and reducing void content, which may strengthen mechanical interlocking at the fiber–matrix interface. As a result, acetylation has been reported to enhance hydrophobicity, improve stress transfer during interfacial bonding, and increase laminate performance in terms of impact, flexural, and tensile properties [10].

Another chemical approach for modifying natural fibers is acrylation, which involves reacting surface hydroxyl groups with acrylic compounds to introduce vinyl functional groups. This treatment can increase interfacial adhesion by promoting stronger interactions or covalent bonding with polymer matrices. The following equation represents the acrylation reaction described in [10].

$$\text{Fiber-OH} + CH_2\text{=CH-COO-Na} \rightarrow \text{Fiber-O-}CH_2\text{-}CH_2\text{-COOH}$$

Subsequent reactions at the interface enhance the fiber–matrix interaction in composites, supporting the formation of strong interfacial bonding during curing through peroxide decomposition at elevated temperatures. The equation can be expressed as:

$$\text{RO-OR} \rightarrow 2\text{RO}^{\cdot}$$

$$\text{RO}^{\cdot} + \text{Fiber-H} \rightarrow \text{R-OH} + \text{Cellulose}^{\cdot}$$

In the reviewed studies, esterification and acrylation are primarily used to enhance the hydrophobicity of nanocellulose surfaces and improve compatibility with nonpolar matrices. These modifications have shown promise in textile-relevant systems by enhancing interfacial adhesion and stress transfer. Evidence specific to military-grade applications, particularly those involving ballistic or flame-retardant fabrics, remains limited, and further validation under realistic operational and standard testing conditions is necessary.

1. Innovations in Military Textiles

This section highlights key innovations in applying nanocellulose to enhance military textiles. Discussion is organized around three critical functional areas: ballistic resistance, flame retardancy, and antibacterial capability, which are central to meeting the demanding requirements of modern military operations. By reviewing recent advances across these domains, this section clarifies how nanocellulose can support the development of lightweight, durable, and multifunctional protective textiles designed for extreme operational environments.

a. Composite Materials for Ballistic Resistance

Lightweight materials with high mechanical performance are essential in defense and aerospace applications. Yet, ballistic impacts from projectiles, debris, and explosions remain a major design challenge that demands innovative material solutions [11], [12]. Figure 4 summarizes the common types of body armor and their fabrication techniques, providing a design context for integrating nanocellulose-based modifications into hybrid protective systems [10]. Nanocellulose has gained attention because its nanoscale building blocks can exhibit tensile strengths on the order of 1 to 2 GPa and can form percolation networks that may support energy dissipation and load redistribution within composites [13]. Interpretation of these values requires caution because nanoscale strength does not directly translate to full-scale ballistic performance, and nanocellulose should not be treated as an equivalent replacement for aramid fibers, such as Kevlar. Practical value is more realistically found in its role as a reinforcing and interfacial modifier that can improve stress transfer, restrict crack propagation, and enhance compatibility across material platforms, including conventional polymer matrices and emerging concepts such as shear thickening fluids (STFs) [5], [14].

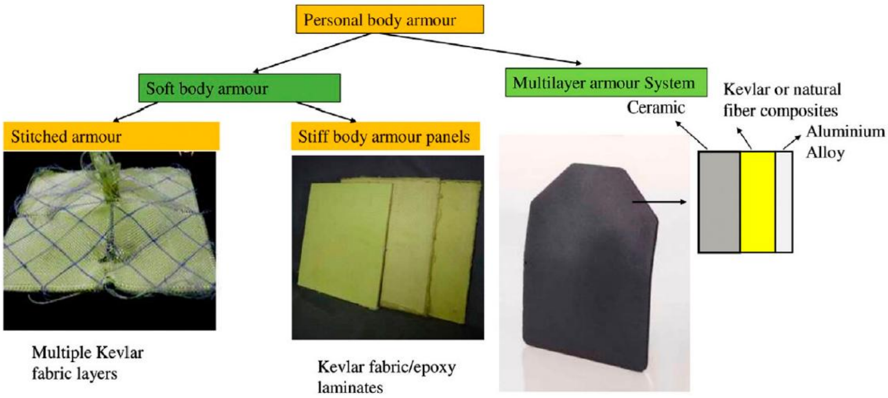

Figure 4. Different types and fabrication techniques for body armor.[10]

Empirical studies indicate several strategies to enhance ballistic performance through interface modification and hybrid laminate design. Graphene oxide coatings on natural fibers have been reported to increase fiber–matrix adhesion by more than 50% and to yield Back Face Signature (BFS) values below the 44 mm NIJ threshold under the reported test configuration [15]. Comparisons across studies should be interpreted cautiously because BFS is strongly influenced by areal density, laminate architecture, backing configuration, projectile type, and test conditions. A representative ballistic test setup that underpins BFS-based evaluation and reporting is shown in Figure 5 [21]. Epoxy composites reinforced with ubim fiber have been reported to exhibit thermal stability up to 335 °C, which is relevant for limiting thermally induced degradation during high-velocity events [16]. Energy absorption during impact has also been linked to controlled fracture mechanisms (e.g., fiber pull-out and guided delamination); therefore, interface engineering, including nanocellulose-enabled interphases, may promote more distributed and controlled damage evolution [17].

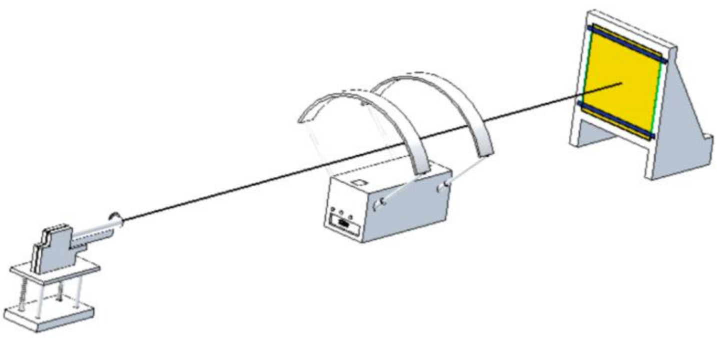

Figure 5. Ballistic Test Setup.[21]

Hybrid reinforcement strategies provide additional context for system-level design. Natural fiber composites reinforced with Kevlar or SiC have been reported to achieve BFS values within NIJ limits [18], [19]. However, these systems do not incorporate nanocellulose, and extreme BFS results, including reported 0 mm cases, should be interpreted cautiously because they depend strongly on panel architecture, backing materials, and measurement resolution. Challenges remain in optimizing reinforcement fraction and interfacial compatibility, particularly for higher protection levels (Level III and above) [20]. Nanocellulose may play a complementary role in shear thickening fluids, where improved rheological stability and impact thickening response have been reported [5], although validation in complete ballistic textile systems is still limited.

Computational modeling further supports these trends. Three-dimensional simulations have demonstrated that low-volume fiber networks can form load-bearing percolation structures that enhance impact damage resistance; however, these models represent generalized fiber architectures rather than a nanocellulose-specific system [22]. The observed agreement between experimental observations and computational predictions supports simulation-driven design as a route to optimize hybrid protective structures and reduce trial-and-error in material development[14], [22].

Challenges remain for scale-up, including production cost, consistency of nanocellulose quality, moisture sensitivity, and manufacturing process control under industrial conditions [13], [23]. Evidence to date indicates that nanocellulose is best positioned as a complementary reinforcement to enhance conventional armor systems, particularly within hybrid and multifunctional protective designs, rather than as a standalone replacement material.

b. Nanocellulose Innovation in Fire-Resistant Military Protective Clothing

Current advances in flame-resistant materials for military textiles present complex challenges that require multidisciplinary solutions. Nanocellulose, with its nanoscale architecture and tunable surface chemistry, has introduced a promising direction in protective material engineering. Recent studies report that cellulose nanofibrils (CNF) and cellulose nanocrystals (CNC) can form three-dimensional percolation networks that enhance mechanical integrity and contribute to thermal protection by promoting char formation and limiting heat and volatile transport [24], [25]. Evidence for these mechanisms is strongest in polymer composite systems rather than in woven or knitted textile architectures, so translation to fabric-based military applications should be treated as an informed extrapolation that still requires dedicated validation [26].Chemically modified cellulose used in biomass-based loose-fill thermal insulation has been reported to exhibit improved flame-resistant behavior under specific application conditions [27]. These findings provide contextual support (rather than direct evidence) for considering nanocellulose-based material strategies in military textile systems, given the differences in material form factor, service environment, and performance requirements. Cone calorimeter parameters, such as time to ignition (TTI), peak heat release rate (PHRR), and gas yield, should therefore be interpreted as composite-level indicators of general flame retardant mechanisms, rather than as direct evidence of compatibility with garment-level requirements. Table 2 summarizes the cone calorimeter results that frame this comparison at the composite scale.

Table 2. Cone Calorimeter testing result[13]

	TTI (s)	PHRR (kW/m^2)	THR (MJ/m^2)	TSR (m^2/m^2)	CO yield (kg/kg)	CO_2 yield (kg/kg)	CO production rate (g/s)	CO_2 production rate (g/s)
PP	29 ± 2	1094 ± 137	96.9 ± 14	1125.6 ± 89.2	0.03 ± 0.004	3.09 ± 0.26	0.008 ± 0.002	0.612 ± 0.07
EPS	3.5 ± 0.7	143.3 ± 4.9	143.3 ± 4.9	33.7 ± 2.1	0.034 ± 0.005	1.78 ± 0.72	0.002 ± 0.0001	0.091 ± 0.03
EPS-flax FR fiber/PP composite	20 ± 0	706.3 ± 12.7	706.3 ± 12.7	972.3 ± 25.9	0.031 ± 0.001	2.29 ± 0.014	0.004 ± 0.00006	0.392 ± 0.01
EPS-toilet paper FR fiber/PP composite	17.5 ± 0.7	680.9 ± 7.5	680.9 ± 7.5	1015.2 ± 29.8	0.031 ± 0.001	2.29 ± 0	0.004 ± 0.00005	0.357 ± 0.03

Military-relevant implementation requires controlled integration strategies that preserve textile functionality while enhancing flame resistance. Processing approaches, such as layer-by-layer (LbL) deposition and surface functionalization, have been used to produce uniform nanocellulose coatings with controllable thickness on diverse substrates [28]. Chemical modification routes, including phosphorylation and silanization, are particularly important because they can enhance flame retardancy while also improving hydrothermal stability, which is critical for operation across variable climates [30]. Preparation pathways for chemically modified cellulose and related substrates are illustrated in Figure 6, which helps clarify how modification steps are structured to support char forming and barrier effects.

Composite-oriented studies provide additional mechanistic insight that can inform textile-oriented designs. Polypropylene composites containing cellulose fibres and extracellular biopolymers derived from wastewater sludge have been reported to show a 38% reduction in peak heat release rate (PHRR), indicating potential utility for flame-retardant interlayers, padding, or stiffened composite panels. [29] However, these results do not yet confirm equivalent performance in woven or knitted military garments, where airflow, porosity, drape, and repeated flexing can substantially alter ignition, heat transfer, and char formation behaviour. The proposed fire reaction pathway in such EPS cellulose fiber and PP systems is summarized in Figure 7, which highlights how char formation and inhibited mass transfer can reduce heat release during combustion.

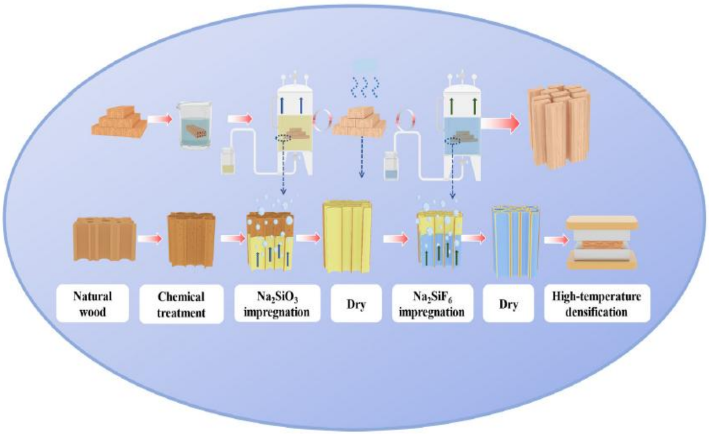

Figure 6. Schematic diagram of modified wood sample preparation[31]

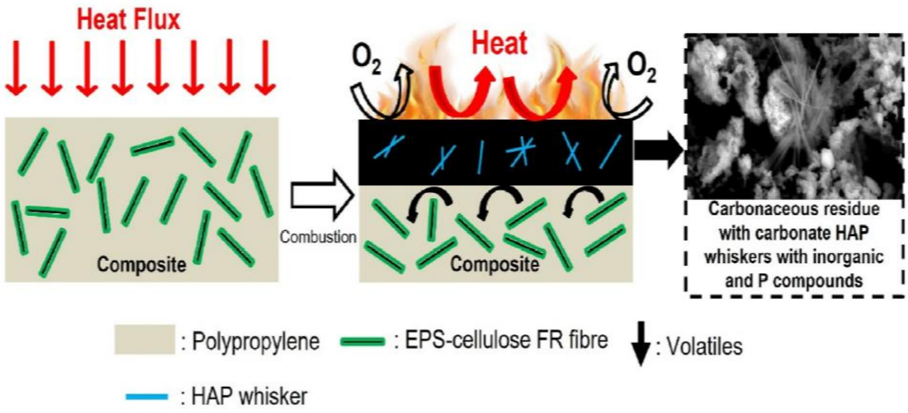

Figure 7. Schematic diagram of the fire reaction mechanism of EPS-cellulose fiber/PP composite.[29]

c. Utilization of Nanocellulose for Military Antibacterial Textiles

Nanocellulose offers promising antibacterial and mechanical functions for textile development. However, most reported systems, such as films, wipes, aerogels, and Cu-coated nonwovens, provide evidence of antimicrobial potential rather than direct validation in military uniform fabrics. Conventional antibacterial finishing can suffer from limited durability and may rely on chemicals that raise health and environmental concerns. Nanocellulose, therefore, represents an attractive alternative because it is renewable, biocompatible, and provides a high surface area with tunable surface chemistry that can support both mechanical reinforcement and antimicrobial functionality in high-performance textile platforms [32], [33].

Nanocellulose includes cellulose nanocrystals (CNC), cellulose nanofibrils (CNF), and bacterial nanocellulose (BNC), all of which offer high tensile strength, large specific surface area, and reactive hydroxyl groups that enable extensive functionalization [33]. The incorporation of metal nanoparticles, such as Ag, and metal oxides, such as ZnO or TiO_2, into nanocellulose matrices can generate strong antibacterial activity through mechanisms involving ion release and the generation of reactive oxygen species [33]. PVA films reinforced with bacterial nanocellulose (BNC) fibers and ε-polylysine have been reported to achieve a tensile strength of 36.3 MPa and to inhibit *S. aureus* and *E. coli* by more than 99%, indicating strong antimicrobial performance; however, the evidence remains limited to film-based systems and requires validation in woven or knitted garment structures [36]. Surface functionalization strategies, including silanization and phosphorylation, can enhance the bonding of antibacterial agents to nanocellulose, thereby prolonging antimicrobial efficacy, which is crucial for military applications where repeated wear and cleaning are anticipated [37]. Silver nanoparticles are widely used because Ag^{+} ions disrupt cell membranes and interfere with DNA replication, leading to bacterial death [33]. Cellulose-based wipes treated with antimicrobial/antiviral silver nanoparticles have also been reported to exhibit strong antibacterial activity against *E. coli* and *S. aureus*, as well as antiviral inhibition against MERS-CoV; nevertheless, wash durability and abrasion resistance under realistic garment conditions still require systematic assessment [38]. The synthesis route for AgNP formation and reduction steps is illustrated in Figure 8, while the resulting concept for treated textile application is exemplified in Figure 9 [38].

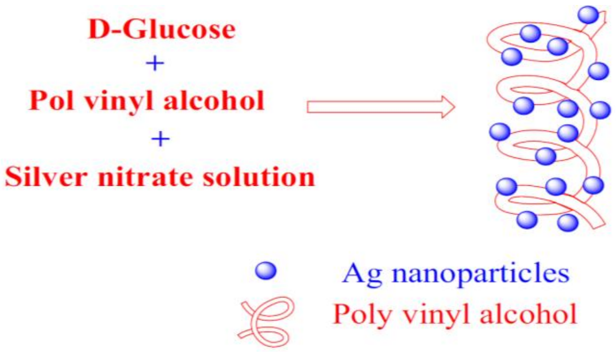

Figure 8. Preparation of silver nanoparticles via reduction of silver nitrate with polyvinyl alcohol in the presence of glucose.[38]

Figure 9. Antimicrobial and antiviral winter sweater made from cotton yarn treated with AgNPs.[38]

Beyond metallic systems, organic antimicrobial routes have also been explored. Cellulose combined with chitin nanofibrils produced films with a more than 90% reduction in microbial growth [39]. Additionally, porous cellulose aerogels loaded with amoxicillin enabled controlled release with high efficacy against bacteria and fungi[40]. These studies strengthen mechanistic understanding but are more closely aligned with medical and hygiene contexts than with military uniforms, so translation requires careful consideration of durability, comfort, and field safety requirements [32].

Textile-oriented implementation depends on fabrication methods that ensure uniform deposition and durability. Techniques such as layer-by-layer assembly, in situ reduction, and water-based coatings are increasingly used to improve adhesion and resistance to washing and abrasion. The broader manufacturing logic for nanocellulose-based nanofiber systems is summarized in Figure 10, which provides a conceptual reference for scalable processing pathways [35]. Hemp-derived cellulose fibers with a purity of 94.7% and a maximum tensile strength of 0.85 cN/dtex[41]. Magnetron sputtering to apply Cu coatings onto nonwovens, achieving both antibacterial effects and hemostatic functionality, which suggests potential relevance for protective textile layers rather than standard uniforms[42].

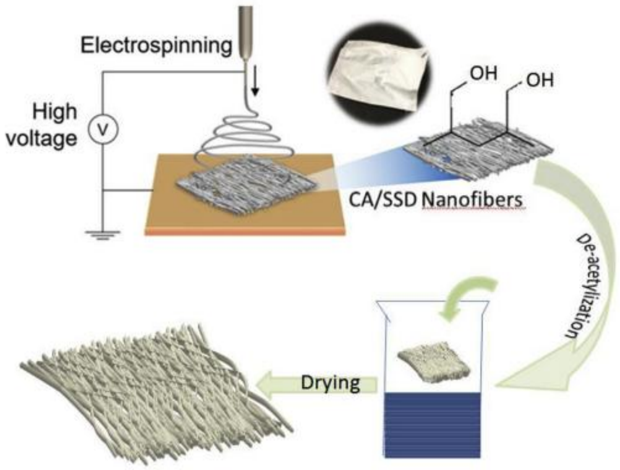

Figure 10. Schematic Illustration of CA/SSD nanofiber Manufacturing.[35]

Challenges remain, including achieving homogeneous nanoparticle distribution, managing potential cytotoxicity at higher loadings, and mitigating the high hydrophilicity of nanocellulose that can affect comfort and durability [33], [37]. Approaches such as covalent bonding, crosslinking, and optimization of nanoparticle loading and coating thickness are commonly proposed to address these limits. Continued interdisciplinary work across materials science, textile engineering, and microbiology is necessary to translate these laboratory-scale demonstrations into military-grade, scalable, and field-validated antimicrobial textile systems.

2. Challenge of Nanocellulose Integration in Military Textiles

Integrating nanocellulose into military textiles still faces substantial barriers in production and scale-up. Manufacturing cellulose nanofibrils (CNF) and cellulose nanocrystals (CNC) often requires high energy input and lengthy processing times, which increases costs and limits feasibility for large-scale deployment [9], [43]. Variability in feedstock quality and limited process standardization further contribute to inconsistent product performance, complicating quality control. Emerging approaches, such as ionic liquid processing and additive manufacturing, offer potential pathways to improve efficiency and material design flexibility; however, regulatory constraints, solvent recovery requirements, and scale-up limitations remain significant hurdles [44].

Durability is another critical concern under harsh operational conditions. Nanocellulose is inherently hydrophilic, which can lead to a gradual reduction in mechanical integrity and dimensional stability upon repeated exposure to humid environments [9]. Chemical modification strategies, including crosslinking and surface functionalization, can enhance water resistance and thermal stability; however, they must be optimized to prevent compromising flexibility, breathability, and wearer comfort, which are crucial for military garments [43]. Interfacial weakness also remains a recurring issue, because insufficient adhesion between nanocellulose phases and conventional synthetic fibers can promote debonding and delamination under cyclic mechanical loading or thermal stress [45].

Compatibility with established military fibers adds a layer of complexity. High-performance synthetics such as aramid and UHMWPE remain dominant because they provide proven strength and durability. Incorporating nanocellulose into these platforms requires interface engineering to achieve uniform dispersion and strong bonding while preserving ballistic performance and flexibility [46]. Techniques such as composite lamination, coupling agents, and surface coatings have shown promise, but challenges related to performance consistency, long-term durability, and production cost continue to limit practical adoption at scale [43]

3. Future Research Opportunities and Applications

Nanocellulose holds strong potential for designing high-performance hybrid composites in military textiles. The integration of nanocellulose with metal nanoparticles, such as Fe_3O_4, or carbon-based materials, such as graphene quantum dots, can enable multifunctional fabrics that support electromagnetic interference shielding and environmental sensing capabilities [47]. Hybridization can also enhance flame resistance and impact tolerance, which is particularly relevant for applications such as flame-resistant uniforms and ballistic protective systems [47].

Smart textile development is another promising direction. Nanocellulose composites combined with conductive polymers can be engineered into garments that respond to physiological and environmental signals, including temperature variation, humidity changes, and indicators of physical injury [49]. Self-healing nanocellulose-based systems also show potential to extend service life by repairing microcracks or surface damage, thereby reducing the maintenance burden and improving operational readiness [50].

Future work should prioritize interface engineering to strengthen interfacial bonding and maintain uniform nanoparticle dispersion, as both factors significantly influence mechanical reliability and functional stability during actual use. Computational simulations can complement experiments by predicting composite behavior under combined mechanical loading and harsh environmental exposure, supporting more efficient material optimization [48]. Collaboration among materials researchers, textile engineers, and military stakeholders will be essential to translate laboratory-scale innovations into field-ready products. With these advances, nanocellulose could support lighter, more durable, and more multifunctional military textile systems.

CONCLUSION

Nanocellulose holds significant potential to revolutionize military textiles by enhancing mechanical resilience, flame-retardant properties (through the formation of a stable char layer and a reduction in peak heat release rate [PHRR]), and robust antibacterial capabilities (via the functionalization of metal nanoparticles and organic compounds). However, challenges persist in large-scale production, durability under extreme conditions, and compatibility with existing textile materials. These limitations necessitate further innovation, particularly in fabrication techniques and chemical modification approaches (e.g., plasma treatment, layer-by-layer coating, green solvent processing), to fully realize nanocellulose's potential in military applications.

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