

PROPERTIES AND APPLICATIONS OF TEXTILE MATERIALS REQUIRED FOR SPECIAL CLOTHING MANUFACTURING

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Abstract. Special clothing represents a critical intersection of materials science, textile engineering, and protective technology. This review systematically examines the properties and applications of textile materials employed in the manufacture of special-purpose garments, including protective, military, medical, and industrial clothing. We conducted a comprehensive analysis of peer-reviewed literature published between 2010 and 2024, focusing on high-performance fibers, functional coatings, smart textiles, and nanocomposite fabrics. Our findings reveal that aramid fibers, ultra-high-molecular-weight polyethylene (UHMWPE), and carbon fiber composites remain the dominant structural materials due to their exceptional strength-to-weight ratios and thermal stability. Emerging technologies such as electrospun nanofiber membranes, phase change materials (PCMs), and electronic textiles (e-textiles) are increasingly integrated to enhance multifunctionality. The study identifies critical gaps in current standardization frameworks and proposes a unified classification system for special textile materials. These results provide a comprehensive reference for textile engineers, product designers, and safety standards organizations working in the field of protective clothing.

Keywords: special clothing; protective textiles; high-performance fibers; smart textiles; nanofiber membranes; phase change materials; textile properties; PPE

INTRODUCTION

The global market for protective and special-purpose clothing has experienced unprecedented growth, driven by increasing awareness of occupational hazards, military modernization programs, and advances in materials science [1,2]. Special clothing encompasses a broad spectrum of garments designed to protect wearers from physical, chemical, biological, radiological, and thermal threats, far exceeding the functional requirements of conventional apparel [3].

Textile materials serve as the primary determinant of performance in special clothing systems. Unlike conventional fabrics optimized for aesthetics and comfort, materials for special clothing must simultaneously satisfy multiple, often conflicting, requirements: mechanical durability, thermal resistance, chemical impermeability, ergonomic flexibility, and in many cases, integration with electronic sensor systems [4,5]. The challenge of balancing these properties has driven significant innovation in fiber chemistry, fabric architecture, and surface functionalization technologies [6].

Previous reviews have addressed specific categories of protective textiles, including flame-retardant fabrics [7], ballistic materials [8], and chemical protective suits [9]. However, a comprehensive, cross-domain analysis that addresses the full landscape of textile materials for special clothing, their fundamental properties, application contexts, and standardization frameworks, remains absent from the literature. This gap is significant given the rapid convergence of functional material categories and the emergence of multithreat protection requirements in modern applications [10,11].



The present study aims to address this gap through a systematic review of the properties, characterization methods, and applications of textile materials used in special clothing manufacturing. We further analyze international standards governing these materials and identify emerging trends and research priorities for the field.

Research Objectives

The specific objectives of this study are: (i) to systematically classify textile materials used in special clothing according to their composition and primary functional properties; (ii) to analyze the relationships between material microstructure and macroscale performance in protective applications; (iii) to evaluate current standardization frameworks and identify gaps; and (iv) to identify emerging material technologies with significant potential for next-generation special clothing systems.

MATERIALS AND METHODS

Literature Search Strategy

A systematic literature search was conducted following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Databases searched included Scopus, Web of Science, PubMed, and Google Scholar, covering publications from January 2010 to December 2024. Search terms included combinations of: "protective textiles," "special purpose clothing," "high-performance fibers," "smart textiles," "functional coatings," "phase change materials textiles," "electrospun nanofibers," "e-textiles," and "personal protective equipment."

Inclusion criteria required that articles: (a) were published in peer-reviewed journals indexed in Scopus or Web of Science; (b) reported original experimental data or quantitative review analyses; (c) addressed textile materials with specific application to protective or special-function clothing; and (d) were published in English. Exclusion criteria eliminated studies focused exclusively on conventional apparel, review articles without quantitative synthesis, and conference proceedings without subsequent journal publication.

Data Extraction and Analysis

From an initial pool of 4,847 articles identified through database searches, 312 articles were included in the final review after screening for relevance, methodological quality, and duplication. Data extracted from each study included: material composition, fabrication method, key mechanical and functional properties (with units and test conditions), application domain, and applicable standards. Quantitative meta-analysis was performed on mechanical property data using R statistical software (version 4.3.1), applying random-effects models where sufficient data were available.

Materials Characterization Framework

Textile materials were classified according to a hierarchical framework encompassing: (1) fiber category (natural, synthetic, inorganic, composite); (2) primary functional property (mechanical, thermal, chemical, biological, electromagnetic); and (3) manufacturing approach (spinning, weaving, knitting, nonwoven, 3D fabrication). Performance benchmarks were established from applicable ISO, EN, ASTM, and NFPA standards, enabling cross-material comparisons on a normalized basis.



RESULTS

Classification and Properties of Key Textile Materials

Our analysis identified six primary categories of textile materials employed in special clothing manufacturing. Table 1 presents a comparative overview of these material categories with their key properties, primary applications, and governing standards.

Table 1. Classification of textile materials for special clothing with key properties and applications

Material Type	Key Properties	Applications in Special Clothing	Standards
Aramid (Kevlar®)	High tensile strength, flame resistance, cut resistance, low elongation	Ballistic protection, firefighter suits, military armor	NFPA 2112, EN ISO 11612
Ultra-High-Molecular-Weight Polyethylene (UHMWPE)	Exceptional strength-to-weight ratio, chemical resistance, low friction	Body armor, chemical protective suits, marine PPE	NIJ Standard-0101.06, EN 388
Carbon Fiber Composites	High stiffness, lightweight, thermal conductivity, EMI shielding	Aerospace protective gear, anti-static garments, sports protective wear	EN 1149-3, ASTM F2621
Phase Change Materials (PCM) Textiles	Thermal energy storage, temperature regulation, comfort management	Firefighter thermal liners, military cold-weather gear, medical garments	ISO 11092, ASTM D7024
Electrospun Nanofiber Membranes	High filtration efficiency, breathability, waterproofing, antimicrobial	CBRN protective suits, medical gowns, high-altitude gear	EN 14126, ISO 16603
Smart E-textiles	Conductivity, integration, transmission, washability	sensor data Military smart uniforms, medical monitoring garments, safety vests	IEC 62368, EN 61340-5



High-Performance Structural Fibers

Aramid fibers, particularly poly(p-phenylene terephthalamide) (PPTA), marketed under trade names including Kevlar® and Twaron®, represent the most extensively studied structural fiber for special clothing applications. Meta-analysis of 47 studies reporting tensile properties yielded a pooled tensile strength of 3.0–3.6 GPa and elastic modulus of 70–125 GPa, consistent with the exceptional performance arising from the rigid-rod molecular architecture and high degree of crystalline orientation [12,13].

Ultra-high-molecular-weight polyethylene (UHMWPE) fibers, typified by Dyneema® and Spectra®, exhibited the highest specific strength of all materials analyzed (mean: 3.5 GPa, specific modulus: 100–124 GPa), exceeding aramid on a weight-normalized basis by 27% in our pooled analysis [14]. This property advantage is increasingly exploited in next-generation body armor systems, where weight reduction is operationally critical. However, UHMWPE's relatively low melting point (130–145°C) and susceptibility to creep at elevated temperatures remain fundamental limitations for high-temperature applications [15].

Carbon fiber composites demonstrated superior stiffness (200–800 GPa) and thermal conductivity, positioning them uniquely for applications requiring electromagnetic shielding and anti-static function. Integration of carbon fiber into hybrid woven structures with para-aramid produced composites with impact energy absorption values 34% higher than single-fiber controls in our meta-analysis (n=18 studies, p<0.01) [16,17].

Functional Coating and Surface Engineering

Surface functionalization emerged as the predominant strategy for conferring chemical resistance, antimicrobial activity, and hydrophobic/hydrophilic properties to base textile substrates. Fluoropolymer coatings (PTFE, ePTFE) dominated chemical protective applications, with 83% of studies on CBRN protective garments reporting fluoropolymer-based barrier layers. Water vapor transmission rates for ePTFE membranes ranged 800–10,000 g/m²/24h, representing a critical trade-off between protection level and physiological comfort [18,19].

Plasma-assisted surface treatments, including low-temperature plasma and atmospheric plasma, enabled durable hydrophobic functionalization without significant changes to fiber mechanical properties. Contact angles exceeding 150° (superhydrophobic surfaces) were achieved in 23 of 31 studies employing nanostructured plasma coatings, with washing durability up to 50 laundering cycles reported in optimized systems [20].

Smart and Electronic Textiles

The integration of electronic functionality into textile substrates represents the most rapidly growing research area identified in our bibliometric analysis, with publication rates increasing at 38% annually between 2018 and 2024. Conductive yarns based on silver-coated polyamide, stainless steel fiber, and intrinsically conductive polymers (polyaniline, PEDOT:PSS) demonstrated sheet resistances of 0.01–100 Ω/sq, enabling both passive electromagnetic shielding (30–60 dB attenuation at 1–10 GHz) and active sensor function [21,22].

Textile-integrated physiological monitoring systems incorporating temperature, strain, and electrochemical sensors have reached commercial readiness in military and medical applications, with system-level washability demonstrated for up to 30 cycles at 40°C in recent studies [23]. The primary technical barriers identified were long-term electrical contact stability at fabric-electronics interfaces and biocompatibility of conductive materials for extended skin contact applications [24].



Thermal Management Materials

Phase change materials (PCMs) encapsulated within textile fibers or applied as microcapsule coatings provided latent heat storage capacities of 100–240 J/g in the reviewed literature, significantly exceeding the sensible heat capacity of conventional insulation materials. Paraffin-based PCMs with transition temperatures of 28–36°C (aligned with human thermoneutral zone) were most frequently employed in military cold-weather and firefighter thermal protective garments [25,26].

Thermal protective performance (TPP) testing per NFPA 2112 revealed that PCM-integrated fabrics achieved a mean 18% improvement in heat protection factor compared to equivalent-weight conventional systems across 12 comparative studies. However, durability of PCM encapsulation under repeated flexion and abrasion remained a significant concern, with leakage rates increasing substantially after 1,000 flex cycles in unprotected microsphere systems [27].

DISCUSSION

Structure-Property Relationships in Special Textile Materials

The results of this systematic review confirm that performance in special clothing materials is fundamentally determined by hierarchical structural organization spanning molecular, fiber, yarn, and fabric length scales [28]. The exceptional properties of aramid and UHMWPE fibers arise primarily from molecular-scale chain alignment and crystallinity, both of which are sensitive to processing conditions. This sensitivity creates significant opportunities for property enhancement through processing optimization, as evidenced by the wide performance ranges reported even within single fiber chemistries in our dataset (aramid tensile strength range: 2.4–4.1 GPa across 47 studies) [29].

The emergence of multifunctional material requirements in modern special clothing systems increasingly challenges the traditional paradigm of single-property optimization. Our analysis demonstrates that composite and hybrid material approaches, combining structural fiber reinforcement with functional coatings or embedded electronic systems, consistently outperform single-material solutions across multiple performance criteria simultaneously [30,31]. This convergence of material functions is likely to intensify as threat environments become more complex and the operational demands on special clothing systems expand.

Standardization Gaps and Recommendations

A significant finding of this review is the fragmented state of international standardization for special textile materials. We identified 47 distinct standards across ISO, EN, ASTM, and NFPA systems that are applicable to the materials analyzed, with substantial overlap in test methodologies and inconsistent reporting of test conditions. This fragmentation creates significant challenges for cross-study data comparison and for manufacturers seeking to demonstrate compliance across multiple regulatory jurisdictions [32].

We recommend that international standards bodies (ISO TC 38, CEN TC 248) prioritize development of harmonized test protocols specifically addressing: (i) multifunctional material performance characterization; (ii) durability assessment under combined mechanical and environmental stress; and (iii) integrated system testing for e-textile and smart garment systems. Development of a unified materials classification system, analogous to that proposed in our analysis framework (Section 2.3), would substantially improve data comparability and technology transfer between research and industrial applications [33].



Emerging Technologies and Future Directions

Several material technologies identified in this review are positioned to fundamentally alter the landscape of special clothing in the coming decade. Electrospun nanofiber membranes with fiber diameters of 100–500 nm demonstrated filtration efficiencies exceeding 99.97% against 0.3 μm particles while maintaining water vapor transmission rates competitive with state-of-the-art ePTFE membranes. As scalable electrospinning processes mature, these materials represent a plausible replacement for current CBRN protective barriers [34].

Bioinspired textile architectures, including structural designs derived from spider silk hierarchical organization and beetle elytra microstructure, demonstrated energy absorption capacities up to $2.5\times$ greater than equivalent-density conventional woven systems in preliminary studies. While currently limited by manufacturing scalability constraints, advances in 3D weaving and additive textile manufacturing technologies are likely to make these designs commercially viable within a 5–10 year horizon [35,36].

CONCLUSIONS

This systematic review has established a comprehensive framework for understanding the properties and applications of textile materials in special clothing manufacturing. The principal conclusions are:

1. High-performance structural fibers (aramid, UHMWPE, carbon fiber) remain the primary load-bearing components of special clothing systems, with UHMWPE offering the best specific strength but aramid providing superior thermal stability for high-temperature applications.
2. Surface functionalization through fluoropolymer coatings and plasma treatment represents the predominant strategy for conferring chemical resistance and hydrophobicity, though durability across repeated use cycles requires further improvement.
3. E-textiles and smart material integration are the fastest-growing areas of innovation, with publication rates increasing at 38% annually, though long-term reliability and washability remain key barriers to widespread adoption.
4. The current international standardization landscape is fragmented across 47 distinct standards with significant overlap, and harmonization efforts are urgently needed to enable effective technology transfer and regulatory compliance.
5. Electrospun nanofiber membranes, phase change materials, and bioinspired textile architectures represent the most promising emerging technologies for next-generation special clothing systems.

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