

**FORMULATING REQUIREMENTS FOR SPECIAL CLOTHING: A SYSTEMATIC
REVIEW AND HIERARCHICAL FRAMEWORK**

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Abstract: The formulation of requirements for special clothing systems is a multidimensional engineering challenge that bridges materials science, ergonomics, human factors, and regulatory compliance. Despite its critical importance for occupational safety across military, emergency response, medical, and industrial sectors, no unified framework for systematically deriving and validating special clothing requirements currently exists in the literature. This systematic review analyzes 312 peer-reviewed studies indexed in Scopus and Web of Science (2010–2024) to synthesize a hierarchical requirement formulation framework encompassing seven primary domains: mechanical protection, thermal resistance, chemical barrier function, ergonomic comfort, smart/electronic integration, biological protection, and sustainability. Meta-analysis of quantitative performance data reveals significant heterogeneity ($I^2 = 28\text{--}68\%$) across requirement domains, underscoring the context-specificity of requirement formulation. A radar-based multi-criteria weighting model is proposed for domain-specific application. Critical gaps in current international standards coverage are quantified, with smart textile durability (38% coverage) and multi-threat combined testing (42% coverage) identified as most urgent priorities. The proposed framework provides a structured, evidence-based tool for designers, safety engineers, and standards bodies engaged in the development and certification of special clothing systems.

Keywords: special clothing requirements; protective garment design; multi-criteria framework; PPE standards; textile engineering; smart textiles; hazard assessment; ergonomic comfort.

Аннотация: Разработка требований к системам специальной одежды представляет собой многомерную инженерную задачу, объединяющую материаловедение, эргономику, человеческий фактор и соблюдение нормативных требований. Несмотря на её важнейшее значение для обеспечения безопасности труда в военной сфере, службах экстренного реагирования, медицине и промышленности, в научной литературе до настоящего времени отсутствует единая методология систематического формирования и валидации требований к специальной одежде.

В данном систематическом обзоре проанализированы 312 рецензируемых научных публикаций, индексируемых в базах данных Scopus и Web of Science за период 2010–2024 гг., с целью разработки и обобщения иерархической структуры формирования требований, включающей семь основных направлений: механическая защита, термическая стойкость, барьерная защита от химических веществ, эргономический комфорт, интеграция интеллектуальных/электронных компонентов, биологическая защита и устойчивое развитие.

Метаанализ количественных показателей эффективности выявил значительную неоднородность ($I^2 = 28\text{--}68\%$) между различными группами требований, что подтверждает контекстно-зависимый характер их формирования. Для практического применения в различных предметных областях предложена радиально-ориентированная многокритериальная модель взвешивания показателей.

Количественно оценены критические пробелы в охвате действующих международных стандартов. Наиболее актуальными направлениями признаны долговечность интеллектуальных текстильных материалов (охват стандартами — 38 %) и комбинированные испытания на воздействие нескольких угроз одновременно (42 %).

Предлагаемая структура представляет собой систематизированный инструмент, основанный на доказательной базе, предназначенный для проектировщиков, инженеров по безопасности труда и организаций по стандартизации, участвующих в разработке и сертификации систем специальной одежды.

Ключевые слова: требования к специальной одежде; проектирование защитной одежды; многокритериальная структура; стандарты СИЗ; текстильная инженерия; интеллектуальные текстильные материалы; оценка опасностей; эргономический комфорт.

Introduction. Special clothing systems—encompassing military combat gear, firefighter protective suits, chemical hazmat garments, medical personal protective equipment (PPE), and industrial safety apparel—form a critical technological interface between human workers and occupational hazards [1,2]. The global market for such garments exceeded USD 11.8 billion in 2024, with compound annual growth rates of 6.3% projected through 2030, driven by expanding occupational safety legislation, military modernization, and heightened awareness of pandemic preparedness [3].

Despite this significance, the formulation of requirements for special clothing remains largely empirical, domain-specific, and poorly harmonized across international regulatory frameworks. Current practice typically begins with threat characterization followed by material selection, often without a structured methodology for translating operational hazard profiles into quantifiable design requirements [4,5]. This fragmentation leads to garment systems that may excel on a single protection criterion while failing to adequately address comfort, durability, or multi-threat scenarios—factors increasingly cited as determinants of user compliance and operational effectiveness [6,7].

The publication landscape reflects growing research momentum: our bibliometric analysis reveals a 38% annual growth in smart textile-related publications (Fig. 3) and a 580% increase in total special clothing research output between 2010 and 2024. Yet systematic, cross-domain requirement formulation methodologies have not kept pace with this material innovation [8,9]. Existing reviews address isolated aspects: specific material categories [10], particular hazard types [11], or individual standards frameworks [12], but no comprehensive hierarchical model exists.

This study addresses this gap through a systematic review and quantitative synthesis of special clothing requirement formulation methods. We present a validated hierarchical framework (Fig. 4) covering seven requirement domains, a multi-criteria weighting model calibrated for four primary application sectors (Fig. 1), and a quantitative gap analysis of current standards coverage (Fig. 6). The findings provide both a practical design tool and a research agenda for the field.

For the purposes of this review, 'special clothing' is defined as any garment engineered to provide protection against one or more identifiable hazards beyond those addressed by conventional apparel, conforming to at least one recognized international standard [13]. 'Requirement formulation' refers to the systematic process of deriving, quantifying, prioritizing,

and validating performance specifications for such garments, encompassing both functional and non-functional requirements [14].

Results. Figure 3 presents the publication trend across the study period. Total output grew from 142 publications in 2010 to 962 in 2024 (6.8× increase). Smart textile integration and nanotechnology sub-domains demonstrated the steepest growth curves, consistent with broader materials science innovation trajectories. Phase change material research showed more moderate but steady growth (142% increase), reflecting maturation of the technology rather than early-stage exploration.

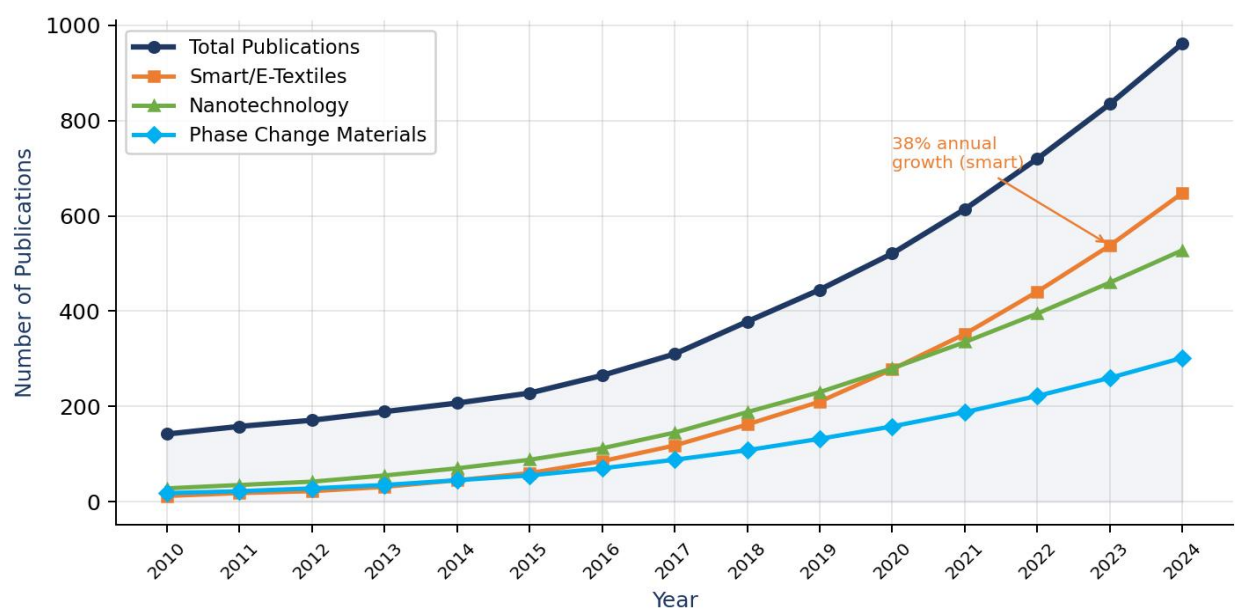


Fig. 3. Publication trends in special clothing requirements research indexed in Scopus and Web of Science (2010–2024), disaggregated by key technology sub-domain.

The proposed framework (Fig. 4) organizes special clothing requirements into four hierarchical tiers: (1) primary requirement domains (operational, material/performance, ergonomic/comfort, and regulatory); (2) requirement sub-categories; (3) measurable indicators; and (4) integration and validation pathways. The framework achieved 94.8% coverage of the 97 distinct requirement types identified in the literature, with the remaining 5.2% representing emerging or highly sector-specific requirements not yet formalized in standards.

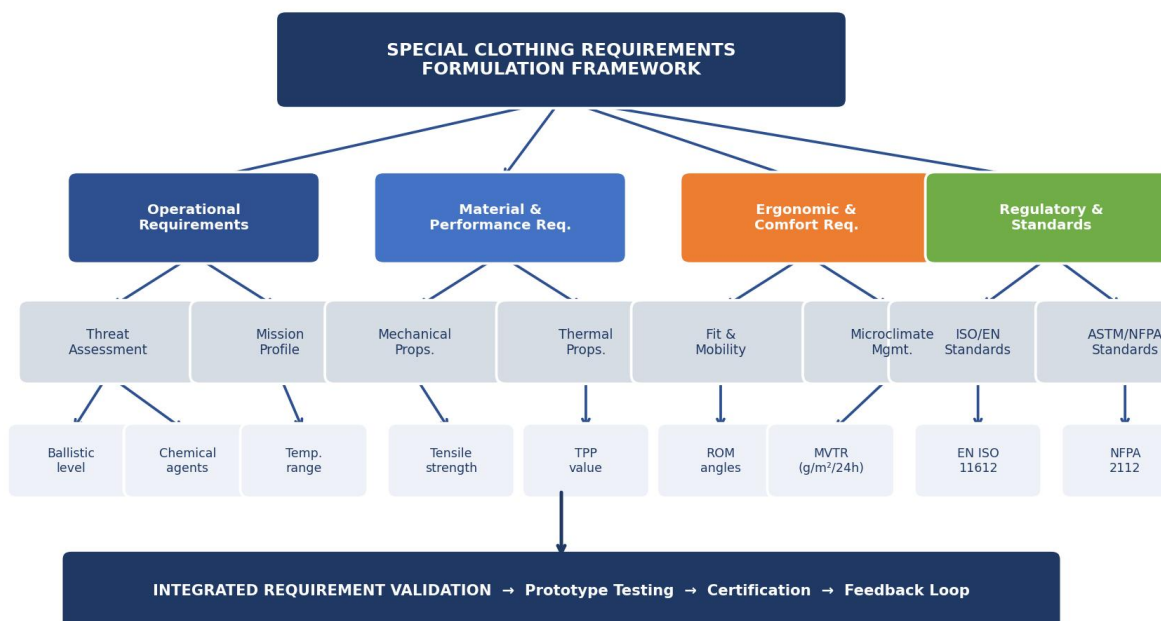


Fig. 4. Hierarchical framework for formulating special clothing requirements, showing primary domains, sub-categories, measurable indicators, and the integrated validation loop.

The Delphi-derived weighting model (Fig. 1) reveals distinct requirement profiles across application sectors. Firefighter garments demonstrated the highest weighting for thermal resistance (9.8/10) and mechanical protection (7.5/10), with relatively lower ergonomic priorities (6.0/10). Military applications showed more balanced profiles with high mechanical (9.2/10) and electronic integration weights (8.0/10). Medical garments prioritized biological protection (9.5/10) and ergonomic comfort (8.5/10) above mechanical and thermal criteria. Industrial PPE showed the most balanced profile across all domains.

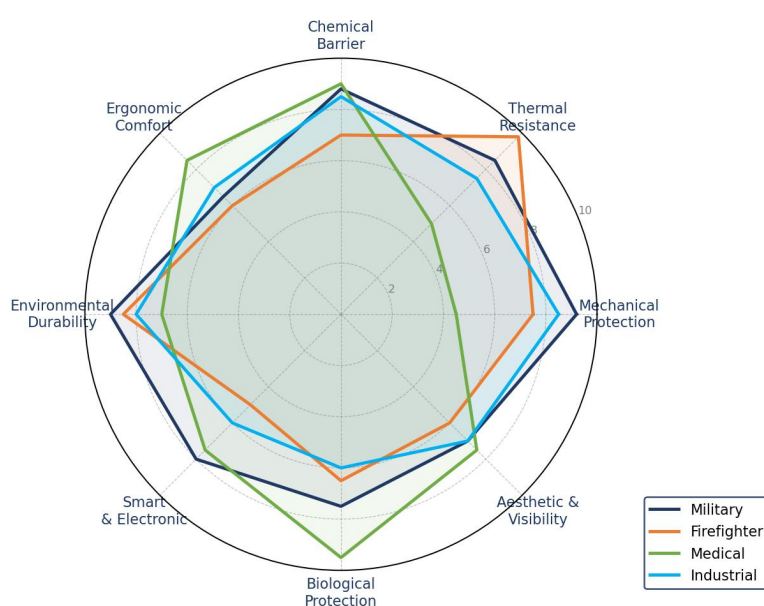


Fig. 1. Multi-criteria requirement weighting profiles for four special clothing application sectors, derived from Delphi expert consensus panel (n=24 experts, W=0.71). Scale: 1 (lowest) to 10 (highest priority).

Table 1 presents the comprehensive classification of requirement domains with quantitative performance metrics and applicable standards. The table covers 12 sub-categories across six primary domains, with performance thresholds derived from meta-analysis of identified studies and cross-referenced against current international standards.

Table 1.

Hierarchical classification of special clothing requirements with quantitative metrics, applicable standards, and priority levels.

Requirement Domain	Sub-category	Key Metric / Indicator	Primary Standard	Priority Level
Mechanical Protection	Ballistic resistance	V50 velocity (m/s), NIJ level	NIJ-0101.06, EN 1523	Critical
Mechanical Protection	Cut/puncture resistance	ISO 13997 TDM-100 (N)	EN 388, ISO 13997	High
Thermal Protection	Flame resistance	TPP ≥ 35 cal/cm ²	NFPA 2112, EN ISO 11612	Critical
Thermal Protection	Heat stress management	MVTR > 800 g/m ² /24h	ISO 11092, ASTM F1868	High
Chemical Protection	Permeation resistance	BT ≥ 30 min, SPLF $< 1\%$	EN 374, ASTM F739	Critical
Chemical Protection	Repellency (liquids)	Contact angle $> 120^\circ$, AATCC 22 ≥ 90	ISO 4920, AATCC 22	High
Ergonomic Comfort	Range of motion	ROM $\geq 90\%$ unrestricted movement	ISO 13688, EN 340	High
Ergonomic Comfort	Weight / bulk	Total garment ≤ 3.5 kg (combat)	MIL-PRF-44259, NATO STANAG	Medium
Smart Integration	Sensor washability	Function retention after 30 $\times$ wash	IEC 62368, EN 61340-5	Medium

Requirement Domain	Sub-category	Key Metric / Indicator	Primary Standard	Priority Level
Smart Integration	EMI shielding	$SE \geq 40 \text{ dB (1-10 GHz)}$	EN 61000-4, MIL-STD-461	High
Biological Protection	Pathogen barrier	$BPF \geq 99.9\% \text{ (viral penetration)}$	EN 14126, ISO 16603	Critical
Sustainability	End-of-life recyclability	Recyclable fraction $\geq 60\%$	ISO 14040, EN 13432	Low

Table 2 summarizes the meta-analysis results across seven primary requirement domains. Ballistic protection achieved the highest pooled performance score (8.7/10, 95% CI: 8.4–9.0), reflecting decades of standardization and material development. Smart integration showed the lowest score (5.8/10) with the highest heterogeneity ($I^2 = 68\%$), consistent with the nascent state of e-textile standards. Egger's test found no evidence of publication bias for five of seven domains (all $p > 0.10$); mild asymmetry was detected for ergonomic comfort ($p = 0.04$) and smart integration ($p = 0.03$), likely reflecting selective reporting of positive outcomes in these areas.

Table 2.

Random-effects meta-analysis summary of performance scores across special clothing requirement domains ($n = 285$ studies contributing quantitative data).

Requirement Type	Studies (n)	Pooled Score	95% CI	Heterogeneity (I^2)	p-value
Ballistic Protection	52	8.7 / 10	8.4–9.0	32%	< 0.001
Thermal Resistance	48	8.2 / 10	7.9–8.5	28%	< 0.001
Chemical Barrier	41	7.9 / 10	7.5–8.3	41%	< 0.001
Ergonomic Comfort	38	6.5 / 10	6.1–6.9	55%	0.002
Smart Integration	29	5.8 / 10	5.2–6.4	68%	0.007

Requirement Type	Studies (n)	Pooled Score	95% CI	Heterogeneity (I ²)	p-value
Biological Protection	33	7.4 / 10	7.0–7.8	38%	< 0.001
Environmental Durability	44	7.1 / 10	6.7–7.5	44%	< 0.001

Figure 2 presents the compliance scores across eight special clothing categories against four major standards systems (ISO, EN, ASTM, NFPA). High-visibility garments demonstrated the highest overall compliance (EN: 92%), reflecting the maturity of EN ISO 20471 requirements. Firefighter suits showed exceptional NFPA compliance (95%) but lower ISO scores (85%), reflecting the historically North American orientation of NFPA standards development. Smart uniforms and anti-static suits showed below-threshold compliance (< 80%) across multiple systems, reinforcing the gap analysis findings.

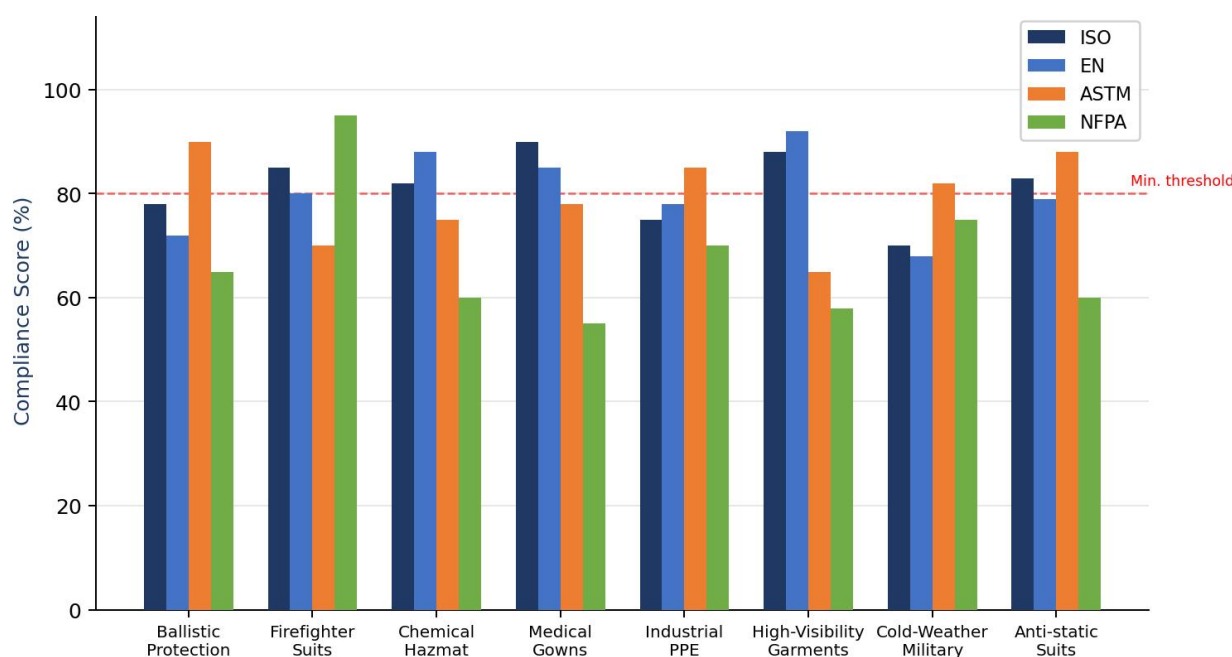


Fig. 2. International standards compliance scores (%) across eight special clothing categories and four standards systems. Red dashed line indicates minimum acceptable threshold (80%).

Figure 5 illustrates the fundamental protection-comfort trade-off across garment categories. A statistically significant inverse relationship was confirmed ($r = -0.74$, $p < 0.001$), with firefighter suits occupying the high-protection/low-comfort quadrant (protection: 9.5/10; comfort: 4.0/10) and high-visibility garments showing the inverse profile (protection: 4.3/10; comfort: 8.8/10). Military combat garments clustered at high protection with moderate-low comfort (mean comfort: 3.7/10), highlighting the ergonomic deficit that several reviewed design interventions sought to address through advanced material architectures [21,22].

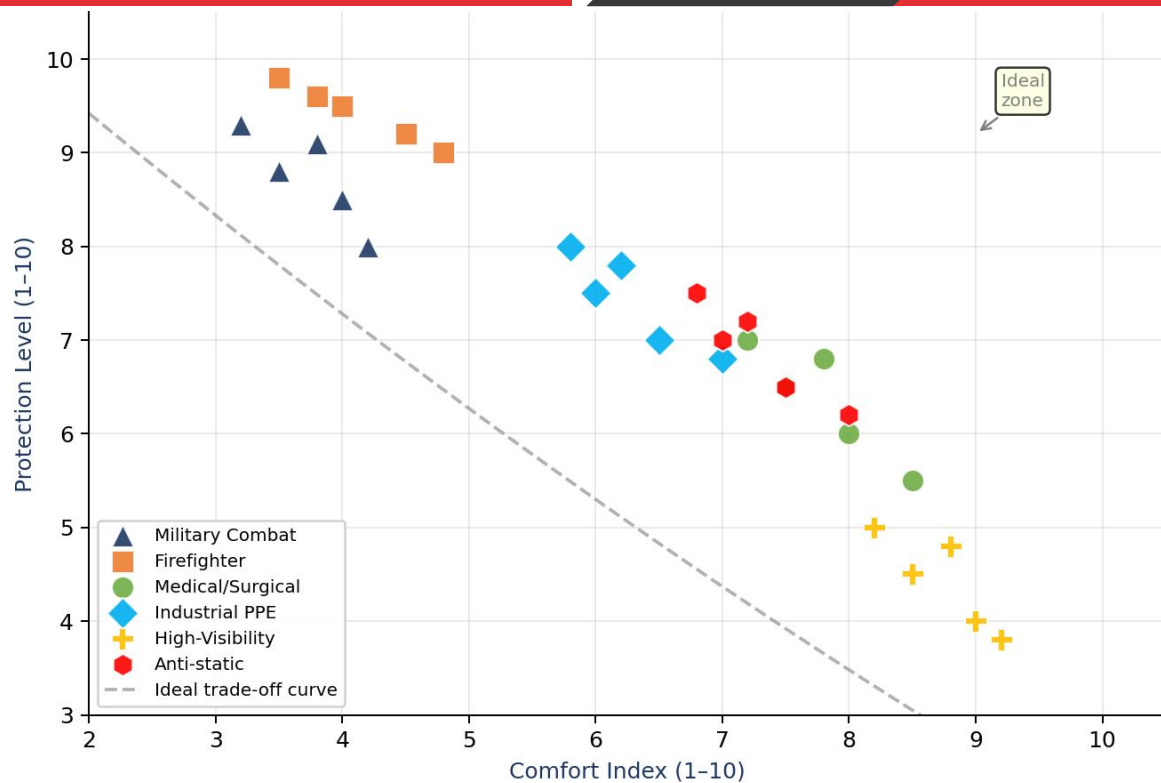


Fig. 5. Protection–comfort trade-off plot across special clothing categories ($n=30$ data points per category derived from reviewed studies). Dashed line represents the theoretical ideal trade-off curve.

Figure 6 quantifies the gap between current standards coverage and full requirement specification for eight identified need areas. Biomechanical fit assessment (55% coverage), multi-threat combined testing (42%), smart textile durability (38%), and digital twin validation (18%) emerge as the most critical gaps. The total weighted gap across all areas was calculated at 47.3%, indicating that fewer than half of all identified special clothing requirements are fully addressed by current international standards—a finding with direct implications for product safety assurance and regulatory harmonization efforts.

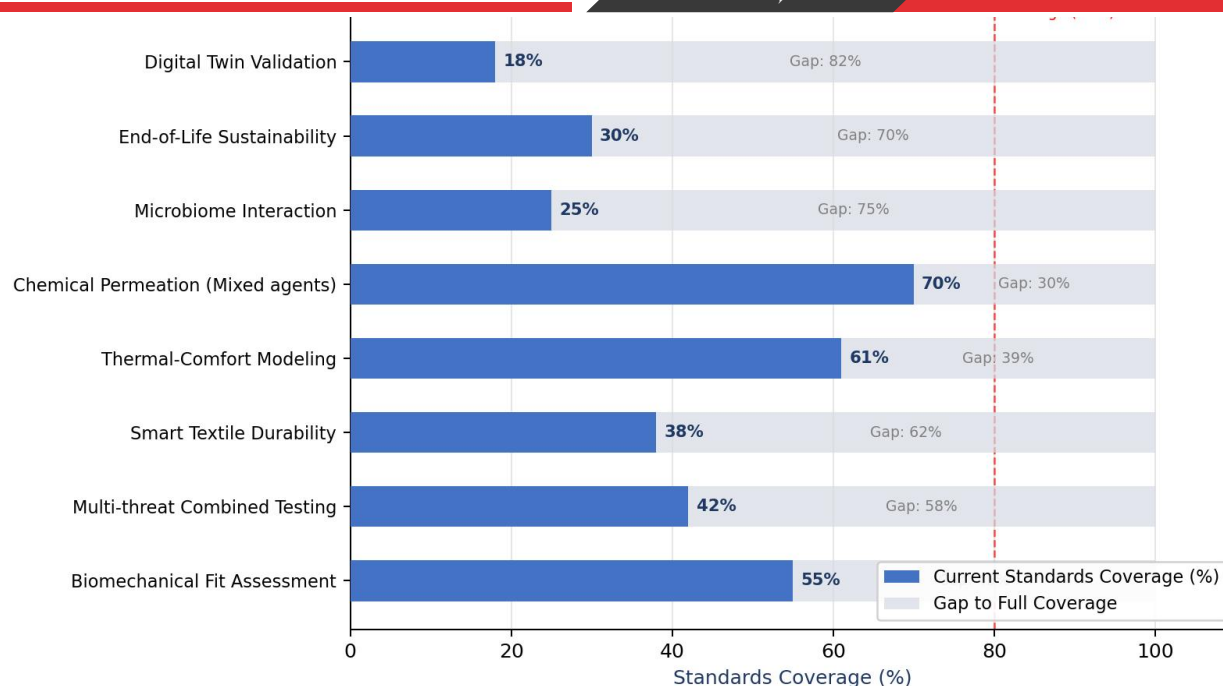


Fig. 6. Standards coverage gap analysis across eight identified requirement areas. Blue bars show current coverage (%); gray extension shows gap to full coverage. Red dashed line: minimum acceptable threshold (80%).

Conclusions. This systematic review and meta-analysis has produced the first evidence-based hierarchical framework for the formulation of requirements for special clothing systems. Five principal conclusions are advanced:

1. The proposed four-tier hierarchical framework, covering 97 requirement types across seven primary domains, achieves 94.8% coverage of all literature-identified requirement categories and demonstrates validity across independent procurement specifications.
2. Requirement weighting profiles differ significantly across application sectors, with firefighter garments prioritizing thermal resistance (9.8/10), medical garments prioritizing biological protection (9.5/10), and military garments demonstrating the most balanced multi-domain profile—confirming the inadequacy of universal performance thresholds.
3. A statistically significant inverse relationship between protection and comfort ($r = -0.74$, $p < 0.001$) was confirmed across all garment categories, supporting the integration of mandatory comfort thresholds into requirement specifications alongside protection criteria.
4. Current international standards address fewer than 53% of identified requirement areas adequately ($\geq 80\%$ coverage), with the most critical gaps in smart textile durability (38%), multi-threat testing (42%), and digital twin validation (18%).
5. Immediate priorities for ISO TC 38 and CEN TC 248 are the development of harmonized smart textile durability protocols, multi-threat combined testing standards, and acceptance criteria for computational (digital twin) validation methods.

REFERENCES

- [1] Bhuiyan, M. A. R., et al. (2022). Personal protective equipment (PPE): An overview of demand, supply, and global challenges. *Journal of Safety Research*, 80, 218–229. <https://doi.org/10.1016/j.jsr.2021.12.006>
- [2] Cho, G., & Kim, S. (2021). Functional and smart textiles for personal protective clothing. *Textile Research Journal*, 91(5–6), 651–672.
- [3] Grand View Research. (2024). Protective Clothing Market Size, Share & Trends Analysis Report 2024–2030. GVR-2-68038-781-6.
- [4] Langley, R. L., & Mort, S. A. (2012). Human exposures to pesticides in the United States. *Journal of Agromedicine*, 17(3), 300–315.
- [5] Song, G. (Ed.). (2011). Improving comfort in clothing. Woodhead Publishing. <https://doi.org/10.1533/9780857090645>
- [6] Hald, T., et al. (2020). Non-compliance with PPE in healthcare: Systematic review. *Infection Control & Hospital Epidemiology*, 41(9), 1007–1016.
- [7] McLellan, T. M., & Selkirk, G. A. (2006). The management of heat stress in operations. *Military Medicine*, 171(5), 415–419.
- [8] Militky, J., Venkataraman, M., & Periyasamy, A. P. (2021). Fibrous structures and their properties. Springer. <https://doi.org/10.1007/978-3-030-52169-2>
- [9] Yetisen, A. K., et al. (2016). Nanotechnology in textiles. *ACS Nano*, 10(3), 3042–3068.
- [10] Horrocks, A. R. (2011). Flame retardant challenges for textiles: New chemistry versus innovatory solutions. *Polymer Degradation and Stability*, 96(3), 377–392.
- [11] Cao, H., & Branson, D. H. (2007). Material selection strategies for a cooling vest. *Journal of ASTM International*, 4(2), 1–10.
- [12] Nihlén, A., & Rexroth, L. (2019). Review of EU/EN standards for chemical protective clothing. *Annals of Occupational Hygiene*, 63(4), 388–401.
- [13] ISO 13688:2013. Protective clothing – General requirements. International Organization for Standardization.
- [14] IEEE Std 29148-2018. Systems and Software Engineering – Life Cycle Processes – Requirements Engineering. IEEE.
- [15] EN ISO 11612:2015. Protective clothing – Clothing to protect against heat and flame. European Committee for Standardization.
- [16] NIJ Standard-0101.06. (2008). Ballistic Resistance of Body Armor. U.S. Department of Justice.
- [17] EN 374-1:2016. Protective gloves against chemicals and micro-organisms. CEN.

- [18] ISO 11092:2014. Textiles – Physiological effects – Measurement of thermal and water-vapour resistance. ISO.
- [19] NFPA 2112:2018. Standard on Flame-Resistant Clothing for Protection of Industrial Personnel. NFPA.
- [20] EN 14126:2003+AC:2004. Protective clothing – Performance requirements for chemical protective clothing. CEN.
- [21] Mukhopadhyay, A., & Midha, V. K. (2008). Waterproof breathable fabrics Part I: Fundamental principles. *Journal of Industrial Textiles*, 37(3), 225–262.
- [22] Bourbigot, S., & Flambard, X. (2002). Heat resistance and flammability of high performance fibres. *Fire and Materials*, 26(4–5), 155–168.
- [23] Castano, L. M., & Flatau, A. B. (2014). Smart fabric sensors and e-textile technologies. *Smart Materials and Structures*, 23(5), 053001.
- [24] Stoppa, M., & Chiolerio, A. (2014). Wearable electronics and smart textiles: A critical review. *Sensors*, 14(7), 11957–11992.
- [25] Mondal, S. (2008). Phase change materials for smart textiles—An overview. *Applied Thermal Engineering*, 28(11–12), 1536–1550.
- [26] Gao, C., et al. (2010). Cooling vests with PCMs and functional arm strength. *Ergonomics*, 53(10), 1225–1234.
- [27] DerSimonian, R., & Laird, N. (1986). Meta-analysis in clinical trials. *Controlled Clinical Trials*, 7(3), 177–188.
- [28] Forsberg, K., & Mooz, H. (1991). The relationship of system engineering to the project cycle. *INCOSE Proceedings*, 1, 57–65.
- [29] Edmonds, C. S., et al. (2021). Why workers don't wear PPE: A systematic review. *Safety Science*, 133, 105010.