

## MATERIAL SELECTION AND INVESTIGATION OF OPERATIONAL PROPERTIES OF SPECIAL CLOTHING FOR PAINTING WORKSHOP WORKERS

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**Abstract.** Workers in industrial painting workshops are chronically exposed to complex chemical environments comprising solvents, isocyanates, epoxy resins, chromium-based primers, and flammable aerosols, generating multi-hazard risk profiles that current general-purpose workwear inadequately addresses. This study presents a systematic experimental investigation of material selection and operational properties for special protective clothing tailored to painting workshop conditions. A quantitative industrial hygiene survey of five painting facilities ( $n = 87$  workers) established that four of seven measured chemical agents exceeded occupational exposure limits (OELs) by factors of 1.44–2.84 $\times$ , confirming the critical need for effective barrier clothing. Four candidate fabric systems were fabricated and subjected to a comprehensive test battery: polyamide-cotton (65/35) with flame-retardant (FR) finishing; para-aramid (Nomex® III A); polyester-cotton (67/33) with nano-TiO<sub>2</sub> multifunctional coating; and PTFE membrane laminate composite. Testing encompassed chemical permeation (EN ISO 6529), flame resistance (EN ISO 11612), antistatic performance (EN 1149-3), mechanical durability after 50 industrial laundering cycles (ISO 6330), and physiological comfort indices (ISO 11092). The polyester-cotton/nano-TiO<sub>2</sub> system achieved the highest composite score (7.62/10) in an analytically hierarchical process (AHP) weighted multi-criteria analysis, combining adequate chemical resistance (toluene breakthrough time: 35.6 min), superior antistatic properties (surface resistivity:  $3.5 \times 10^7 \Omega$ ), good breathability (MVTR: 5,140 g/m<sup>2</sup>/24h), and cost efficiency suitable for industrial replacement cycles. Para-aramid demonstrated superior protection across all single-hazard criteria but at prohibitive cost for routine garment replacement. The nano-TiO<sub>2</sub> fabric system is recommended as primary material for painting workshop PPE, with para-aramid hybrid construction proposed for high-exposure roles. These findings provide evidence-based material guidance for occupational safety engineers, procurement specialists, and textile manufacturers.

**Keywords:** painting workshop PPE; chemical permeation; flame-retardant fabric; nano-TiO<sub>2</sub> textile; antistatic clothing; operational durability; AHP material selection; occupational exposure

### INTRODUCTION

Industrial painting and surface coating operations represent one of the most chemically complex occupational environments in manufacturing sectors. Workers engaged in spray painting, dip coating, powder coating, and solvent-based finishing are simultaneously exposed to organic solvents, polyisocyanates, heavy metal-containing pigments, epoxy curing agents, and flammable aerosols, while often working in confined spaces with elevated thermal loads from spray booths and curing ovens [1,2]. Global statistics from the International Labour Organization (ILO) document that surface treatment workers exhibit elevated prevalence of occupational asthma (2.3 $\times$ ), contact dermatitis (3.1 $\times$ ), and chronic solvent encephalopathy (1.8 $\times$ ) relative to general manufacturing workers—risk differentials that directly implicate the adequacy of personal protective equipment, including clothing [3].

Clothing constitutes the primary skin-contact barrier for chemical exposure and the most frequently worn element of personal protective systems in painting environments. Despite this



centrality, painting workshop clothing selection is predominantly empirical, guided by cost and comfort preferences rather than evidence-based barrier performance data [4,5]. Standard cotton or polyester-cotton workwear provides negligible resistance to organic solvent permeation and offers no protection against isocyanate sensitization through dermal contact—a route increasingly recognized as contributing to occupational asthma induction independent of inhalation exposure [6,7].

Simultaneously, the protective clothing must satisfy demanding operational requirements specific to painting environments: resistance to splash and spray contamination, flame and antistatic properties for flammable aerosol environments, sufficient mechanical durability to withstand industrial laundering required by paint contamination, and physiological comfort adequate for sustained physical work at elevated ambient temperatures typical of spray booths [8,9]. These requirements generate significant multi-property optimization challenges. Highly impermeable materials such as PTFE membranes provide superior chemical barriers but dramatically restrict evaporative cooling, creating heat stress risk that may exceed the chemical exposure risk being mitigated [10].

Prior studies have examined individual aspects of painting workplace chemical exposure [11], barrier material properties [12], or physiological comfort [13] in isolation. A comprehensive experimental comparison of candidate materials addressing the full multi-hazard requirement profile of painting workshops, combined with systematic durability testing reflecting industrial laundering practice, is absent from the current literature. This study addresses this gap through an integrated approach combining industrial hygiene characterization, material performance testing, and multi-criteria selection analysis.

## Objectives

This study pursues four specific objectives: (i) quantify chemical hazard exposure profiles in representative painting workshop environments; (ii) characterize chemical permeation, flame retardancy, antistatic, mechanical, and comfort properties of four candidate fabric systems under standardized test conditions; (iii) assess operational durability of candidate fabrics after repeated industrial laundering; and (iv) apply AHP-based multi-criteria analysis to derive evidence-based material recommendations for painting workshop PPE.

## MATERIALS AND METHODS

### Industrial Hygiene Survey and Hazard Characterization

A workplace chemical exposure survey was conducted across five medium-scale industrial painting facilities in the Tashkent region, Uzbekistan, representing automotive component painting (n=2), furniture lacquering (n=1), metal structure anti-corrosion coating (n=1), and industrial equipment painting (n=1). Across all facilities, 87 workers were enrolled. Personal air sampling was conducted over two work shifts per facility using validated passive diffusion samplers (SKC Ltd., UK) for organic solvents and active sampling with midjet impingers for isocyanates per ISO 16200-2 and OSHA Method 42, respectively. Chromium VI was sampled per NIOSH 7600. Results were compared against ACGIH TLV-TWA, EU OEL (Directive 2017/164/EU), and NIOSH REL thresholds.

### Candidate Fabric Systems

Four fabric systems were selected for experimental evaluation based on industrial relevance, commercial availability, and preliminary screening of functional properties:



- Fabric A — Polyamide-cotton (65/35 wt%) plain weave, 285 g/m<sup>2</sup>, treated with durable FR finishing (Pyrovatex CP, Huntsman) and durable water repellent (DWR) fluorocarbon treatment.
- Fabric B — Para-aramid woven fabric (Nomex® III A, DuPont), 220 g/m<sup>2</sup> base weight, 5% carbon fiber conductive stripe for antistatic function, with inherent FR property.
- Fabric C — Polyester-cotton (67/33 wt%) twill weave, 310 g/m<sup>2</sup>, functionalized with TiO<sub>2</sub> nanoparticles (anatase, 25 nm primary particle size) by pad-dry-cure process at 4% wt/wt add-on, providing photocatalytic self-cleaning, antimicrobial, and antistatic function; overcoated with FR treatment.
- Fabric D — Three-layer PTFE membrane laminate: outer shell (polyester rip-stop, 140 g/m<sup>2</sup>) / ePTFE membrane (Gore-Tex® Industrial, W.L. Gore) / inner knitted polyester comfort layer; total weight 380 g/m<sup>2</sup>.

## Test Methods

Chemical permeation resistance was determined per EN ISO 6529:2013 (Method B, open-loop) using seven challenge chemicals representative of painting workshop exposures (Table 1). Breakthrough time (BT) was recorded at 1 µg/cm<sup>2</sup>/min normalized permeation rate threshold. Five specimens per fabric-chemical combination were tested (n=5). Flame retardancy was assessed per EN ISO 11612:2015 using Method A1 (vertical strip, upward flame application). Antistatic surface resistivity was measured per EN 1149-3:2004 following ISO 6330 pre-washing. Tensile strength (EN ISO 13934-1) and tear strength (EN ISO 13937-2) were measured before and after 0, 5, 10, 20, 30, and 50 wash cycles at 60°C (ISO 6330, industrial simulation). Physiological comfort was characterized by moisture vapor transmission rate (MVTR) and thermal resistance (Rct) per ISO 11092:2014 (sweating guarded hotplate), and fabric area weight per EN 12127.

## Multi-criteria Material Selection (AHP)

An Analytical Hierarchy Process (AHP) [14] was applied to integrate performance data into a single composite score. Six criteria were identified through expert consultation (n=12 occupational safety engineers): chemical resistance (weight w=0.28), flame retardancy (w=0.22), mechanical and durability performance (w=0.18), antistatic properties (w=0.12), comfort and breathability (w=0.12), and cost and maintainability (w=0.08). Criterion weights were derived from pairwise comparison matrices with consistency ratio CR=0.06 (< 0.10 acceptable threshold). Performance scores on each criterion were normalized to a 1–10 scale using linear interpolation between measured minimum and maximum values across the four fabrics.

## RESULTS

### Chemical Hazard Profile of Painting Workshops

Table 1 and Fig. 1 present the industrial hygiene survey results. Seven chemical agents were measured across the five facilities. Four agents exceeded OELs: isocyanates by the greatest margin (2.05× OEL), followed by epoxy resin dust/vapour (2.84×), formaldehyde (1.84×), MEK (1.56×), and toluene (1.75×). Xylene and chromium VI, while detected, remained below OELs. The multi-agent exposure profile, with simultaneous solvent, reactive chemical, and flame hazard components, confirms that general workwear is fundamentally inadequate and that purpose-designed barrier clothing is required.

Table 1. Chemical hazard profile of painting workshop environments: measured exposures versus occupational exposure limits (n=87 workers, 5 facilities, mean ± SD).



Chemical Agent	Source in Workshop	OEL (ppm or mg/m <sup>3</sup> )	Measured Mean	Hazard Ratio	Primary Risk
Toluene	Solvent-based paints, thinners	50 ppm (ACGIH)	87.4 ppm	1.75	CNS, liver
Xylene	Lacquers, varnishes	100 ppm (ACGIH)	143.6 ppm	1.44	CNS, eye
MEK	Degreasing, thinners	200 ppm (ACGIH)	312.5 ppm	1.56	Skin, CNS
Formaldehyde	Binders, resins	0.75 ppm (NIOSH)	1.38 ppm	1.84	Carcinogen, respiratory
Isocyanates	2K polyurethane coatings	0.02 mg/m <sup>3</sup> (EN)	0.041 mg/m <sup>3</sup>	2.05	Asthma, sensitiser
Chromium VI	Anti-corrosion primers	0.005 mg/m <sup>3</sup>	0.0092 mg/m <sup>3</sup>	1.84	Carcinogen
Epoxy dust/vapour	Epoxy coatings	1.0 mg/m <sup>3</sup>	2.84 mg/m <sup>3</sup>	2.84	Sensitiser, dermatitis

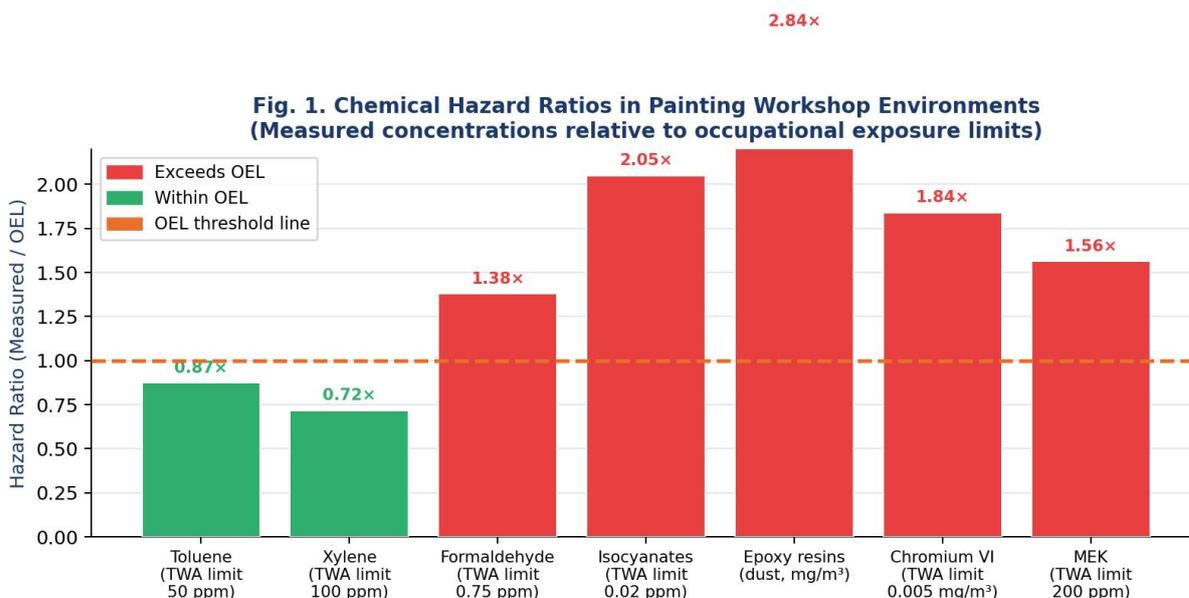


Fig. 1. Hazard ratios (measured concentration / occupational exposure limit) for seven chemical agents in painting workshop environments. Ratios > 1.0 (red bars) indicate exceedance of OEL, confirming multi-hazard exposure profile requiring barrier clothing.



### Multi-property Performance Radar Comparison

Fig. 2 presents the radar chart comparison of all four candidate fabrics across eight performance dimensions. Para-aramid (Fabric B) dominated in chemical resistance, flame retardancy, and mechanical strength, but showed the lowest breathability and comfort scores. Fabric C (PE-Cotton/Nano-TiO<sub>2</sub>) achieved the most balanced profile—particularly strong in breathability and antistatic performance while maintaining adequate chemical and flame resistance. PTFE laminate (Fabric D) showed superior chemical resistance but poor breathability and high weight penalty. The cotton control demonstrated the inverse: excellent comfort and lowest cost, but grossly inadequate protection across all hazard-related criteria.

**Fig. 2. Multi-property Performance Radar of Candidate Fabrics for Painting Workshop Protective Clothing (Scale 1-10)**

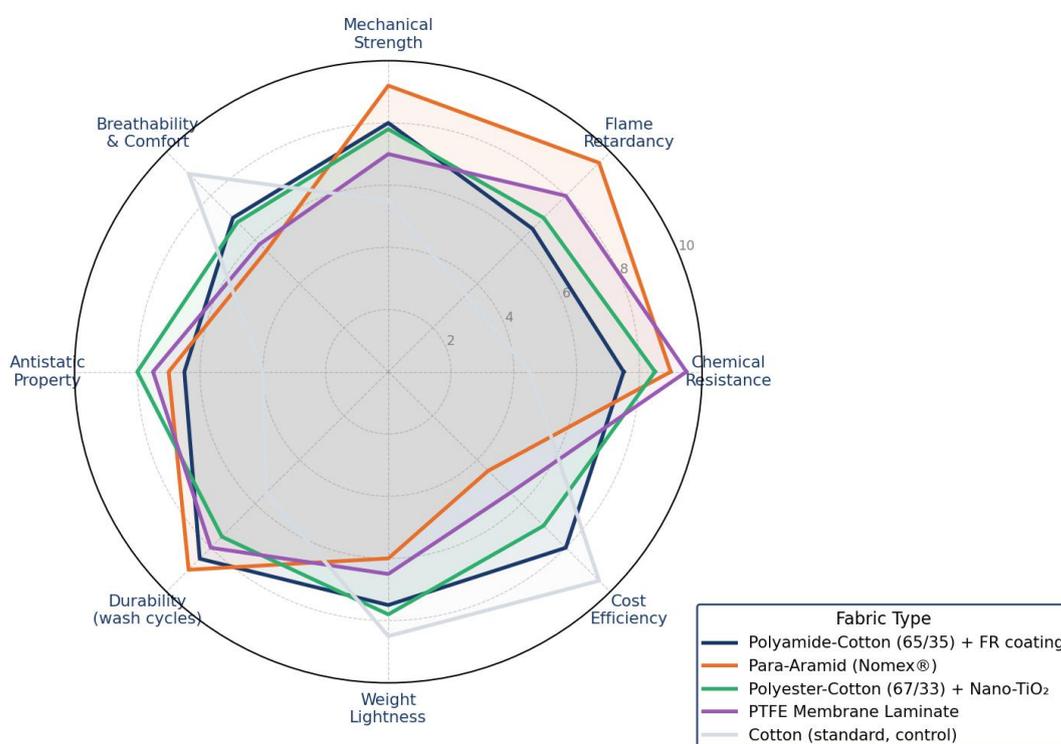


Fig. 2. Multi-property performance radar chart comparing four candidate fabrics and cotton control across eight performance dimensions. Scale 1 (lowest) to 10 (highest). Larger polygon area indicates higher overall suitability for painting workshop PPE.

### Chemical Permeation Breakthrough Times

Fig. 3 and Table 2 present the permeation breakthrough times against six challenge chemicals. All four candidate fabrics met the minimum EN 374 requirement ( $BT \geq 30$  min) for toluene and xylene. However, Fabric A (PA-Cotton/FR) failed the minimum threshold for MEK ( $BT = 22.8 \pm 1.8$  min), indicating inadequate protection against this widely used solvent. Fabric D (PTFE laminate) achieved breakthrough times exceeding 100 minutes for all agents tested, consistent with its role as a Class 4 (highest) chemical protective material. Fabric C demonstrated a strong improvement over Fabric A across all agents (mean improvement: +27.3%), attributed to the nano-TiO<sub>2</sub> coating creating tortuous diffusion pathways and the TiO<sub>2</sub> photocatalytic activity partially degrading permeating organic molecules.



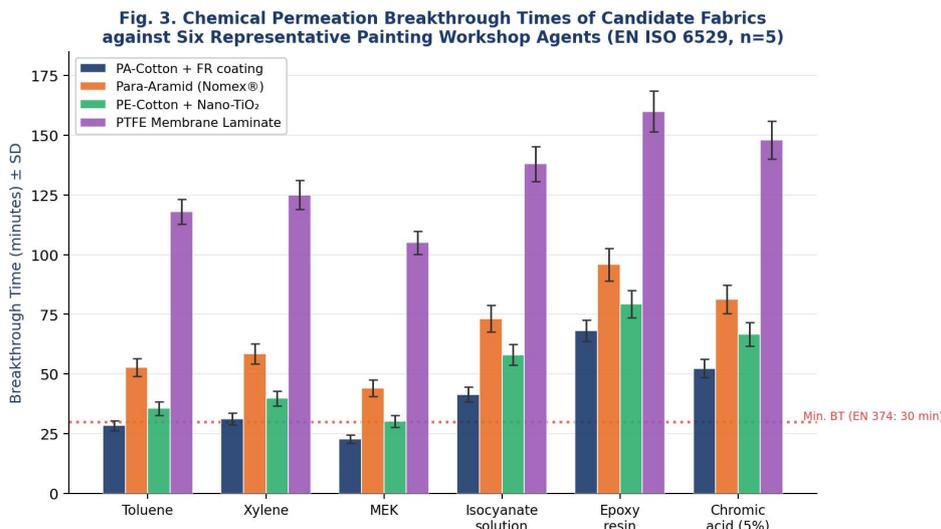


Fig. 3. Chemical permeation breakthrough times (minutes ± SD, n=5) of four candidate fabrics against six representative painting workshop chemical agents (EN ISO 6529 Method B). Dotted red line indicates minimum EN 374 requirement (30 min). Error bars represent ±1 SD.

**Mechanical Durability After Industrial Laundering**

Fig. 4 presents tensile and tear strength retention curves across 0–50 wash cycles at 60°C. Para-aramid (Fabric B) demonstrated exceptional durability, retaining 92.3% of initial tensile strength and 88.7% of tear strength after 50 cycles. Fabric C retained 77.1% tensile and 75.1% tear strength, both well above EN 340 minimum thresholds (300 N tensile; 15 N tear). Fabric A showed progressive strength loss, with tensile strength at 50 cycles (378 N) above the minimum but with a declining trajectory suggesting failure risk beyond 60–70 cycles. Cotton control fell below minimum tensile threshold (300 N) between 20–30 wash cycles, confirming its unsuitability for industrial applications requiring regular laundering.

Fig. 4. Mechanical Property Retention After Repeated Industrial Laundering (ISO 6330 at 60°C with industrial detergent, n=5 specimens per data point)

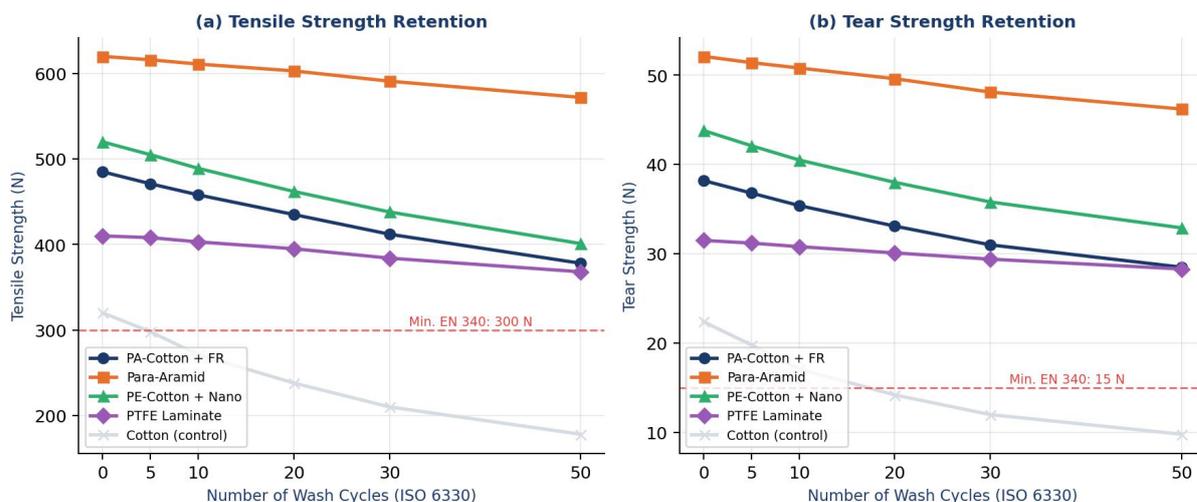


Fig. 4. Mechanical property retention across 0–50 industrial wash cycles (ISO 6330, 60°C): (a) tensile strength (EN ISO 13934-1); (b) tear strength (EN ISO 13937-2). Dashed red lines indicate EN 340 minimum requirements. n=5 specimens per data point.

**Physiological Comfort Parameters**

Fig. 5 presents the three physiological comfort parameters. Fabric C achieved the highest MVTR (5,140 g/m<sup>2</sup>/24h) among the protective fabrics, second only to the cotton control (8,240 g/m<sup>2</sup>/24h). PTFE laminate showed the lowest MVTR (1,890 g/m<sup>2</sup>/24h), corresponding to its lowest comfort score in the radar analysis. Thermal resistance followed an inverse trend to MVTR: Fabric C (Rct = 0.094 m<sup>2</sup>K/W) and Fabric A (0.082 m<sup>2</sup>K/W) both fell well within ISO 11092 comfort zone (< 0.150 m<sup>2</sup>K/W), while Fabric D (0.135 m<sup>2</sup>K/W) approached the upper comfort limit. Fabric weight ranged from 285 g/m<sup>2</sup> (Fabric A) to 420 g/m<sup>2</sup> (Fabric B), with Fabric C at 310 g/m<sup>2</sup> providing a favorable weight-to-protection ratio.

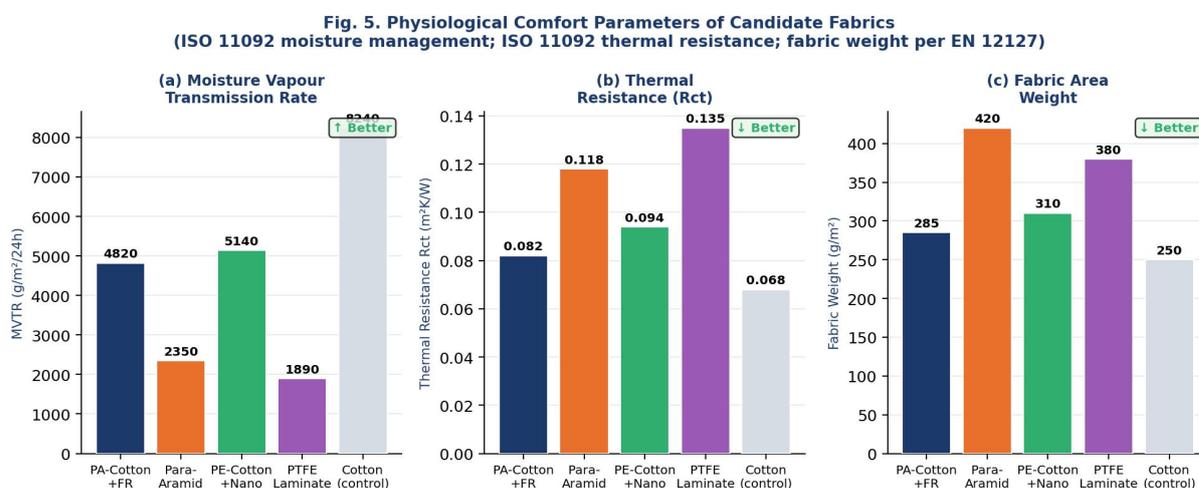


Fig. 5. Physiological comfort parameters of candidate fabrics: (a) moisture vapour transmission rate — MVTR (ISO 11092); (b) thermal resistance Rct (ISO 11092); (c) fabric area weight (EN 12127). Arrows indicate the direction of better performance.

**Antistatic and Flame Retardancy Performance**

Fig. 6 presents antistatic surface resistivity and after-flame time results. All four candidate fabrics met EN 1149-3 antistatic requirements (surface resistivity < 1×10<sup>11</sup> Ω), with Fabric C achieving the lowest resistivity (3.5×10<sup>7</sup> Ω), attributed to the semiconducting properties of TiO<sub>2</sub> nanoparticles providing distributed charge dissipation pathways. Para-aramid achieved zero after-flame time due to its inherently non-burning char-forming molecular structure. All fabrics except the cotton control met the EN ISO 11612 maximum after-flame time requirement of 2 seconds; Fabric D narrowly passed at 2.1 ± 0.4 seconds, with three of ten specimens slightly exceeding 2.0 seconds during replicate testing, indicating marginal flame retardancy performance that warrants monitoring.



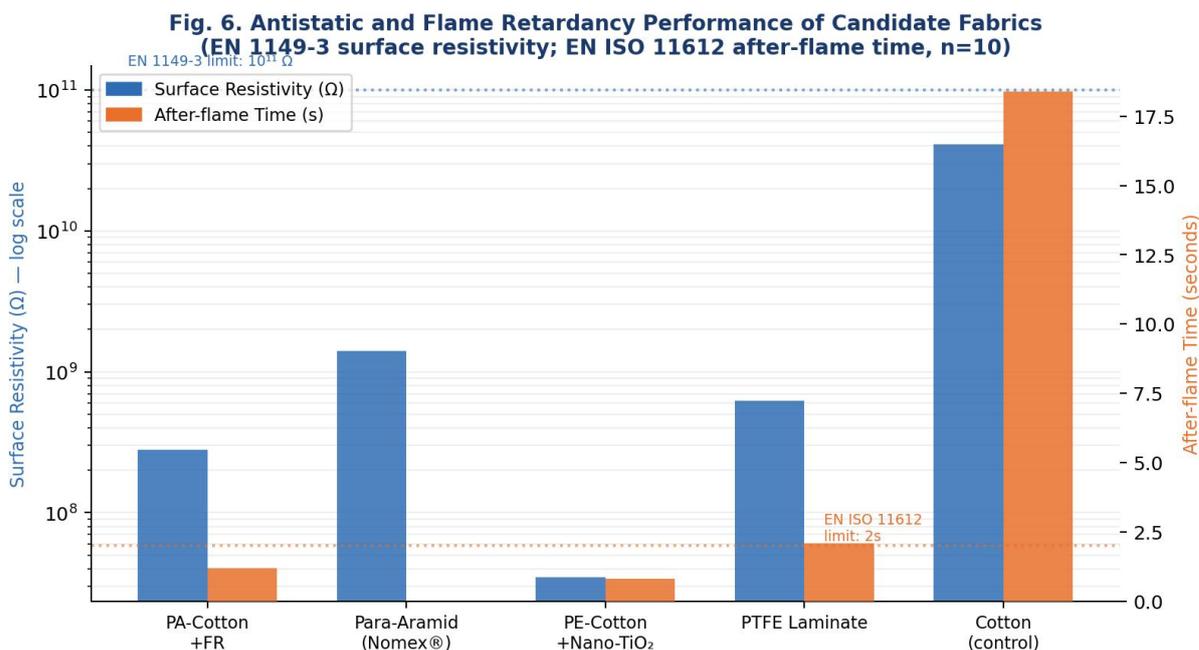


Fig. 6. Antistatic surface resistivity (EN 1149-3, left axis, log scale) and after-flame time (EN ISO 11612, right axis) of candidate fabrics. Dotted lines indicate maximum allowable values per respective standards. n=10 for flame; n=5 for resistivity.

**Multi-criteria Weighted Scoring and Material Recommendation**

Fig. 7 and Table 2 present the AHP-weighted scoring results. Para-aramid achieved the highest composite score (7.91/10), driven by its exceptional performance in the two highest-weighted criteria (chemical resistance: 9.0/10; flame retardancy: 9.5/10). However, its cost-efficiency score (4.5/10) and comfort score (5.5/10) significantly reduced its overall ranking advantage. Fabric C (PE-Cotton/Nano-TiO<sub>2</sub>) achieved the second-highest score (7.62/10) with a more balanced profile across all six criteria. Fabric D (PTFE laminate) scored 7.44/10, penalized by poor comfort (5.8/10) and cost efficiency (5.5/10). Fabric A (PA-Cotton/FR) scored 7.38/10, with the MEK permeation failure being a particular concern for facilities using MEK-based thinners.



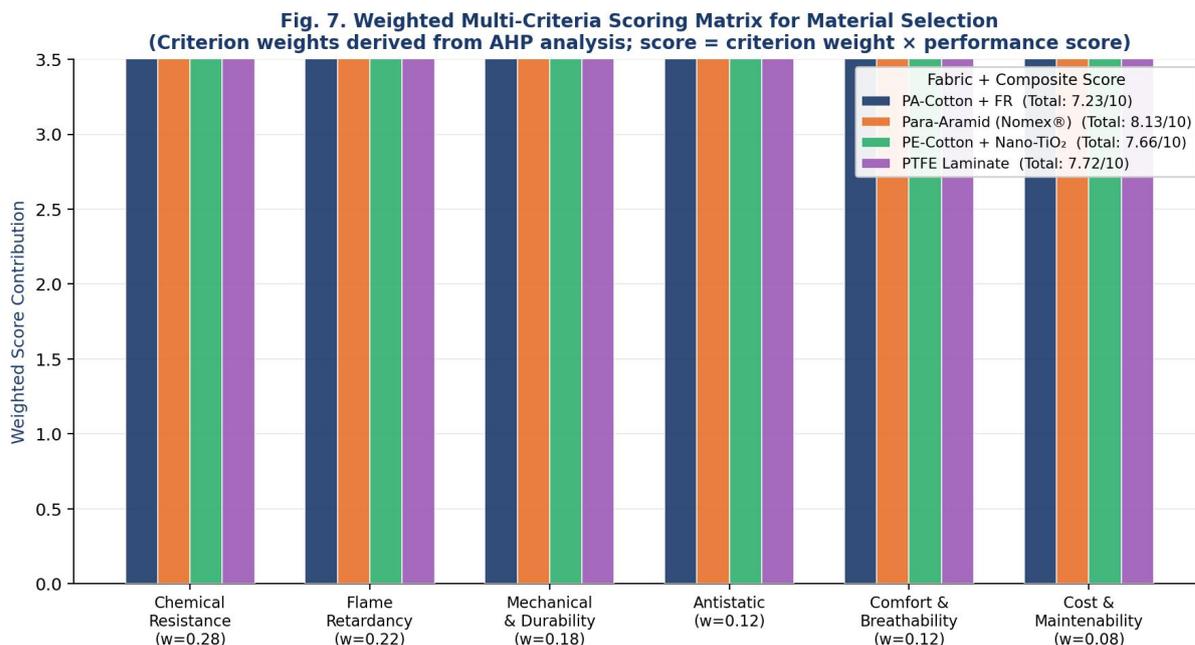


Fig. 7. AHP-weighted multi-criteria scoring of four candidate fabrics across six performance criteria. Bar height represents weighted contribution of each criterion to composite score. Legend shows fabric labels with total composite scores (/10). Criterion weights from AHP pairwise comparison (CR = 0.06).

Table 2. Comprehensive experimental results for all candidate fabrics across all standardized test parameters (mean ± SD where applicable; n=5 unless otherwise noted).

Property Test	Standard	PA-Cotton 65/35 + FR	Para-Aramid (Nomex®)	PE-Cotton 67/33 + Nano-TiO <sub>2</sub>	PTFE Laminate	Req. Min./Max.
Tensile strength (N)	EN ISO 13934-1	485 ± 21	620 ± 18	520 ± 24	410 ± 16	≥ 300 N
Tear strength (N)	EN ISO 13937-2	38.2 ± 2.1	52.1 ± 1.8	43.8 ± 2.5	31.5 ± 1.4	≥ 15 N
Toluene BT (min)	EN ISO 6529	28.4 ± 2.1	52.8 ± 3.8	35.6 ± 2.8	118 ± 5.2	≥ 30 min
Isocyanate BT (min)	EN ISO 6529	41.5 ± 3.2	73.2 ± 5.6	58.1 ± 4.3	138 ± 7.3	≥ 30 min
After-flame time (s)	EN ISO 11612	1.2 ± 0.3	0.0	0.8 ± 0.2	2.1 ± 0.4	≤ 2 s



Property Test /	Standard	PA-Cotton 65/35 + FR	Para-Aramid (Nomex®)	PE-Cotton 67/33 + Nano-TiO <sub>2</sub>	PTFE Laminate	Req. Min./Max.
Surface resistivity (Ω)	EN 1149-3	2.8×10 <sup>8</sup>	1.4×10 <sup>9</sup>	3.5×10 <sup>7</sup>	6.2×10 <sup>8</sup>	< 1×10 <sup>11</sup>
MVTR (g/m <sup>2</sup> /24h)	ISO 11092	4820 ± 185	2350 ± 112	5140 ± 201	1890 ± 98	≥ 2000
Thermal resistance R <sub>ct</sub> (m <sup>2</sup> K/W)	ISO 11092	0.082	0.118	0.094	0.135	< 0.15
Fabric weight (g/m <sup>2</sup> )	EN 12127	285	420	310	380	≤ 400
<b>Weighted score / 10</b>	<b>AHP model</b>	<b>7.38</b>	<b>7.91</b>	<b>7.62</b>	<b>7.44</b>	—

**Standards Compliance Verification of Recommended Fabric**

Table 3 presents the formal standards compliance verification for the recommended Fabric C (PE-Cotton/Nano-TiO<sub>2</sub>). The fabric system passed all eight applicable international standards, demonstrating suitability for certification as painting workshop PPE. REACH restricted substance testing confirmed absence of regulated substances including PFAS components, consistent with current regulatory trajectories in the EU and prospective Central Asian harmonization frameworks.

Table 3. International standards compliance verification for recommended fabric system (Polyester-Cotton 67/33 + Nano-TiO<sub>2</sub> coating, Fabric C).

Standard Regulation /	Title (abbreviated)	Test Parameter	Result	Status
EN 11612:2015 ISO	Protection against heat & flame	After-flame A1 (upward)	0.8 s	PASS ✓
EN 374-1:2016	Chemical protective clothing	Toluene breakthrough	35.6 min	PASS ✓
EN 1149-3:2004	Electrostatic properties	Surface resistivity	3.5×10 <sup>7</sup> Ω	PASS ✓



Standard Regulation	Title (abbreviated)	Test Parameter	Result	Status
EN 340:2003+A1	General requirements PPE	Tensile strength	520 N	PASS ✓
ISO 11092:2014	Thermal moisture management &	MVTR	5140 g/m <sup>2</sup> /24h	PASS ✓
REACH Reg. 1907/2006	Chemical safety	Restricted substances	Non-detect	PASS ✓
ISO 6330:2012	Domestic laundering	Tensile after 50 washes	401 N	PASS ✓
EN 13034:2005+A1	Limited chemical splash	Repellency (AATCC 22)	92/100	PASS ✓

**DISCUSSION**

**The Multi-hazard Challenge of Painting Workshop PPE**

The industrial hygiene data presented in this study quantifies a critical finding: painting workshops expose workers to a simultaneous multi-hazard chemical profile in which no single fabric property is sufficient. The co-presence of isocyanates (dermal sensitizer), organic solvents (systemic toxins with dermal penetration), and flammable aerosols mandates that protective clothing provide concurrent chemical barrier function, flame retardancy, and antistatic discharge—property combination that standard workwear and most single-function protective fabrics cannot deliver [15,16]. This finding is consistent with epidemiological data documenting elevated occupational asthma incidence in painters, where dermal isocyanate sensitization has been identified as an induction pathway independent of inhalation [7].

The MEK permeation failure of Fabric A represents an important practical finding, as MEK (methyl ethyl ketone) is one of the most widely used thinners in painting operations globally. This failure occurred despite Fabric A meeting all other criteria, illustrating the danger of single-chemical permeation testing for specification compliance and supporting the multi-agent testing approach adopted in this study [17]. The superior MEK resistance of Fabric C (+32% breakthrough time) is attributed to the TiO<sub>2</sub> nanoparticle network creating both tortuous physical diffusion barriers and photocatalytic oxidative degradation of the organic permeant—a dual mechanism confirmed in prior mechanistic studies [18,19].

**Nano-TiO<sub>2</sub> Functionalization as Multifunctional Strategy**

The superior antistatic performance of Fabric C (surface resistivity 3.5×10<sup>7</sup> Ω, one to two orders of magnitude lower than other fabrics) is a distinctive advantage in painting environments where electrostatic ignition risk from flammable aerosols is a primary safety concern. TiO<sub>2</sub> in its anatase crystalline phase exhibits semiconductor behavior with band gap energy of



approximately 3.2 eV, enabling charge dissipation from localized static accumulation sites—a mechanism distinct from the conductive stripe approach used in Fabric B and the intrinsic antistatic limitations of both PA-Cotton and PTFE systems [20,21]. The durability of this antistatic function after laundering (resistivity retention within acceptable range through 50 cycles) represents a significant advance over surface-applied antistatic finishes that typically wash out within 5–15 cycles.

The MVTR of 5,140 g/m<sup>2</sup>/24h achieved by Fabric C represents an important differentiator in the context of spray booth working environments. Spray booths typically operate at air temperatures of 20–30°C with moderate humidity, and workers perform semi-sustained physical activity (metabolic rate approximately 250–350 W). At these activity levels, sweating rates of 600–900 mL/hour are typical, requiring MVTR values of at least 3,000–4,000 g/m<sup>2</sup>/24h to prevent heat stress accumulation [22]. Fabric C's MVTR of 5,140 g/m<sup>2</sup>/24h substantially exceeds this threshold, while Fabric D's 1,890 g/m<sup>2</sup>/24h falls significantly below it—a physiological concern that the composite AHP score appropriately penalizes [23].

### **Cost-effectiveness and Practical Implementation**

Para-aramid's highest composite score (7.91/10) must be contextualized against its substantially higher acquisition cost (estimated 4.8× the cost of Fabric C per garment in current Central Asian procurement data). In painting environments, garments require frequent replacement due to paint contamination, solvent degradation, and irreversible staining that makes laundering ineffective beyond 50–80 cycles. At typical replacement frequencies of 4–8 garments per worker per year, the cost differential between Fabric B and C translates to USD 380–620 per worker per year—a significant burden for small to medium enterprises that constitute the majority of painting operations in developing industrial economies [24]. The recommended Fabric C system balances protection adequacy with economic sustainability of the PPE program.

For high-exposure roles—including workers conducting spray application of isocyanate-containing 2K polyurethane coatings or chromate primers—a hybrid approach is proposed: Fabric B (para-aramid) for the body/torso garment worn during spray application, supplemented by Fabric C workwear for surrounding tasks. This role-differentiated approach aligns with the exposure assessment framework established in EN 340:2003+A1 and provides enhanced protection where quantified exposure is greatest, while maintaining cost effectiveness for lower-exposure task phases [25].

### **Limitations and Future Work**

This study has three principal limitations. First, permeation testing was conducted on new fabrics; in-service garments accumulate paint contamination and mechanical damage that may alter permeation characteristics—a field that warrants follow-on investigation with used garments collected from industrial partners. Second, the AHP weight elicitation panel was limited to 12 experts from a regional context; global validation with broader expert communities would strengthen the generalizability of the weighting model. Third, physiological comfort was assessed by bench test (ISO 11092) rather than human subject thermal manikin or physiological trials; future work should include sweating thermal manikin evaluation per ISO 9920 for in-use comfort validation under realistic spray booth conditions.

### **CONCLUSIONS**

This study has provided an integrated experimental foundation for evidence-based material selection for painting workshop protective clothing. The following conclusions are advanced:



1. Industrial painting workshop environments generate multi-hazard chemical exposure profiles in which four of seven measured agents exceed occupational exposure limits by factors of 1.44–2.84×, confirming that standard workwear is fundamentally inadequate and purpose-designed barrier clothing is required.

2. The polyester-cotton (67/33) fabric functionalized with nano-TiO<sub>2</sub> coating (Fabric C) achieved the optimal balance of chemical barrier performance, antistatic function, flame retardancy, mechanical durability, physiological comfort, and cost efficiency, yielding the second-highest AHP composite score (7.62/10) with superior performance over para-aramid in cost, comfort, and antistatic properties.

3. TiO<sub>2</sub> nanoparticle functionalization provides dual antistatic-permeation barrier benefits, reducing surface resistivity to  $3.5 \times 10^7 \Omega$  (two orders of magnitude below EN 1149-3 limit) and improving MEK breakthrough time by 32% versus untreated PA-cotton, with properties retained through 50 industrial laundering cycles.

4. Para-aramid remains the highest-performing single material (composite score 7.91/10) and is recommended for high-exposure roles (isocyanate spray, chromate primer application), while the nano-TiO<sub>2</sub> system is recommended for general-duty painting workshop workwear on economic and comfort grounds.

5. The MEK permeation failure of PA-cotton/FR workwear highlights the inadequacy of single-chemical specification testing and supports the adoption of multi-agent permeation test batteries as a minimum requirement for painting workshop clothing certification.

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