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Hybrid Plasma-Sol-Gel Technologies for Flame Retardancy and NIR Camouflage of Military Textiles: Review

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***Abstract*— This review examines hybrid technologies combining dielectric barrier discharge (DBD) plasma treatment and sol-gel nanocomposite coatings to improve the performance of military textiles. The paper examines cotton/polyester (CO/PES) blended fabrics that exhibit good physicomechanical and comfort properties but limited thermal resistance. The reviewed literature identifies DBD plasma as an effective surface activation method that improves textile adhesion and chemical reactivity through the formation of active functional groups. The sol-gel silica matrix serves as a stable carrier for halogen-free phosphorus-nitrogen refractory systems and functional additives, contributing to improved limiting oxygen index (LOI) values and increased coating wash durability. In addition to fire protection, the reviewed studies demonstrate the potential for controlling spectral reflectance in the near-infrared (NIR) region by incorporating selected pigments, carbon-based materials, and metal oxide additives into the hybrid coating system. Such modifications can reduce the optical detectability of military textiles while maintaining the flexibility and comfort of the fabric. Based on the reviewed studies, the paper proposes a conceptual technological model for multifunctional military textiles with controlled spectral properties and improved thermomechanical performance. The review also outlines key performance indicators and future experimental directions for validating the proposed hybrid plasma-sol-gel concept on CO/PES military fabrics.**

Keywords*— *DBD plasma; flame retardancy; military textiles; NIR camouflage.

I. Introduction

The operational environment of military personnel exposes uniforms and protective textile systems to multiple thermal hazards, including open flames, incendiary devices, explosions, and high temperatures. Consequently, flame-retardant (FR) treatments have become a strategic requirement in military textile engineering. These treatments must provide effective resistance to ignition and flame propagation and maintain protective functionality throughout prolonged use. However, repeated laundering, mechanical abrasion, and environmental exposure can significantly alter the physicochemical properties, color stability, and overall performance of FR-treated fabrics, reducing their long-term protective efficiency [1]–[4]. Thus, washing durability and mechanical stability are critical design parameters for modern military protective textiles.

Furthermore, combining functional coatings, including nanostructured additives and metal oxide-based treatments, has shown potential to improve fire resistance and additional protective properties, such as antimicrobial activity or infrared (IR) camouflage, without damaging the mechanical integrity or comfort of textile layers [5], [6]. Chemically stabilized fire-resistant treatments, plasma or sol-gel surface alterations, and optimized fiber blends (e.g., cotton/polyester or high-performance aramids) represent a multi-faceted approach to achieving durable, operationally effective uniforms that withstand both thermal and mechanical stress. Overall, the evidence emphasizes that protective military textiles must be designed as integrated systems in which material selection, functional coatings, and durability converge under real-world stressors to maintain life-saving performance and mission readiness in extreme warfare settings.

This article does not present original experimental results. Instead, it provides a literature-based conceptual review. It presents a hybrid technological framework for the future development of multifunctional military textiles, combining plasma activation, sol-gel coatings, flame-retardant systems, and NIR signature management.

II. LITERATURE REVIEW, METHODOLOGY, AND TECHNOLOGICAL BACKGROUND

The present study is based on a qualitative literature review of scientific publications related to dielectric barrier discharge (DBD) plasma treatment, sol-gel textile coatings,

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halogen-free phosphorus–nitrogen flame-retardant systems, and near-infrared (NIR) camouflage technologies for military textiles. The analyzed sources include peer-reviewed journals, books, and conference proceedings in textile engineering, plasma processing, flame retardancy, and smart camouflage materials. The review focuses on identifying technological synergies, functional processes, and performance indicators relevant to multifunctional cotton/polyester military fabrics. The analysis focused on studies reporting working mechanisms, coating durability, flame-retardant performance, and spectral-related behavior in the NIR region.

A. Dielectric Barrier Discharge (DBD)

Dielectric Barrier Discharge (DBD) represents a form of cold atmospheric plasma generated between two electrodes separated by one or more dielectric layers, such as glass, ceramic, or quartz. This plasma can operate at atmospheric pressure, offering a versatile, energy-efficient, and environmentally friendly approach to surface modification of textile substrates [4], [5].

In textile engineering, DBD plasma treatment has been widely investigated as an effective approach to increase surface energy, improve wettability, and facilitate the deposition of functional compounds, including flame-retardant agents, hydrophobic layers, and antimicrobial finishes. Plasma-assisted activation has been shown to improve chemical uptake while preserving the mechanical integrity of textile substrates during conventional high-temperature pad–dry–cure processing [5].

Similarly, atmospheric DBD treatment has been successfully applied to cotton fabrics prior to the deposition of phosphorus-based flame-retardant systems, such as Pyrovatex CP New, in combination with the crosslinking agent Knittex FFRC. These studies show improved flame-retardant performance and higher residual tensile strength compared with conventional impregnation–drying–thermal fixation processes, thereby demonstrating the technological significance of plasma activation as a process-optimization strategy that reduces thermally induced fiber degradation [6].

DBD plasma treatment promotes the formation of reactive surface functionalities, including hydroxyl (–OH), carboxyl (–COOH), and carbonyl (–C=O) groups, which improve the interfacial adhesion, homogeneity, and durability of subsequently applied chemical and sol-gel coatings. Furthermore, plasma pre-treatment has been shown to improve capillary behavior and facilitate more efficient flame-retardant functionalization of polyester-based textile substrates [7].

It is important to emphasize that the role of DBD plasma in hybrid textile treatment systems is not to provide complete flame resistance on its own, but rather to generate a chemically active fiber surface that improves the effectiveness and durability of subsequent multifunctional coatings. Through increased surface energy and improved interfacial bonds, DBD treatment promotes uniform coating deposition and contributes to the formation of advanced textile systems with flame-retardant, ultraviolet-protective, hydrophobic, and antimicrobial properties [8].

B. Halogen-Free Phosphorus–Nitrogen Flame-Retardant Systems

Contemporary research on textile flame retardance increasingly focuses on halogen-free systems based on phosphorus (P) and nitrogen (N). These systems are favored for their success in retarding combustion through both condensed-phase and, in some formulations, gas-phase mechanisms. In the condensed phase, phosphorus compounds promote the formation of a protective char layer that limits the heat and mass transfer between the flame and the substrate [9]. Nitrogen-containing components can enhance this effect through intumescent expansion or by synergistically stabilizing the char structure. Consequently, P/N/Si combinations are considered particularly promising for developing thin, multifunctional coatings with durable flame-retardant performance [9], [10]. For cotton-polyester blends, untreated fabrics typically exhibit low limited oxygen index (LOI) values (17%), indicating high flammability. The application of phosphorus–nitrogen sol-gel coatings can substantially increase LOI values, e.g., to 27.3–31.8%, depending on the coating composition and application parameters. Integration of plasma surface activation before coating further enhances performance by generating reactive surface groups, improving chemical bonding between the flame retardant and the fiber, and increasing washing durability—a key limitation of conventional impregnation-based treatments [7].

C. Sol-Gel Technologies

Sol-Gel technologies for textile surface modification. The sol-gel process constitutes a transition from a liquid phase (sol) to a solid three-dimensional network (gel) through hydrolysis and condensation reactions:

$$Si(OR)_4+H_2O \rightarrow Si(OH)_4 \quad (1)$$

Condensation:

$$Si\text{-}OH+HO\text{-}Si \rightarrow Si\text{-}O\text{-}Si \quad (2)$$

In the textile field, sol-gel technology has become an established platform for depositing thin, multifunctional coatings that impart flame-retardant, hydrophobic, ultraviolet-protective, and other advanced functional properties to textile substrates [8]. During the sol-gel process, the formation of a silicate network creates a stable inorganic matrix that improves the fixation and distribution of refractory compounds and other active additives within the coating structure. Among the most widely used precursors in textile sol-gel processing is tetraethyl orthosilicate (TEOS), owing to its high chemical reactivity, compatibility with low-temperature processing, and ability to generate homogeneous silica-based networks on fiber surfaces [11].

A major advantage of sol-gel systems is their ability to serve as carrier matrices for additional functional components, including phosphorus–nitrogen flame-retardant agents and nanoscale or microscale particles that modify surface morphology and optical behavior. The final properties of sol-gel coatings, including thickness, uniformity, flexibility, vapor permeability, and surface appearance, are strongly influenced by precursor composition, additive concentration, deposition technique, and curing conditions. Therefore, careful optimization of these parameters is required to achieve an effective balance between protective performance and physiological comfort [12].

Recent developments in UV-curable sol-gel systems have additionally expanded the applicability of this technology to temperature-sensitive textile substrates. Unlike conventional thermal curing processes, ultraviolet-assisted crosslinking allows coating stabilization at near-ambient temperatures using UV-sensitive photoinitiators. Although localized outer temperatures may increase during irradiation, they remain below the thermal degradation thresholds for cotton and polyester fibres, thereby minimizing structural damage and reducing the overall energy consumption of the coating process [12].

In addition to their flame-retardant properties, sol-gel coatings can greatly improve the hydrophobicity of textile materials. Cotton fabrics treated with silica nanoparticles and water-repellent agents have been reported to exhibit superhydrophobic characteristics, with liquid contact angles exceeding 130°, indicating substantially reduced surface wettability [13]. Such functionality is particularly important in military textile systems, where moisture accumulation may alter thermal transport properties, reduce wearer comfort, and modify the infrared radiation emitted from the clothing surface, thus affecting the near-infrared (NIR) and thermal camouflage performance of military garments under service conditions [14], [15].

D. Near-Infrared Signature Management (NIR Signature Management)

Protective military textiles are not solely mechanical or thermal barriers; control of near-infrared (NIR) reflectance is essential for operational concealment [14], [15]. NIR camouflage focuses on modifying the reflective properties of textile surfaces in the 700–1200 nm range to reduce contrast with environmental backgrounds when observed with NIR-sensitive devices. The objective is not absolute invisibility, but the reduction of spectral detectability. Pigments, coatings, and functional additives can modulate the NIR reflectivity. Approaches in “smart textiles” include incorporating carbon-based materials, metal or metal-oxide nanoparticles, and conductive polymers to tune spectral characteristics. Carbon black dispersions, for example, have been shown to effectively adjust the NIR reflectance of camouflage fabrics [16]. Sol-gel matrices can serve as carriers and stabilizing environments for such additives, enabling the embedding of multifunctional properties—including flame retardance, water repellency, and NIR signature modulation—into a single coating system. Additionally, recent studies highlight that repeated laundering and environmental exposure can influence both the functional and aesthetic performance of treated textiles. Investigations into flame-resistant fabrics and antibacterial finishes show that appropriate sol-gel matrices, combined with plasma activation, can preserve physico-mechanical properties and maintain functional efficacy after multiple wash cycles [17], which is critical for operational dependability in military applications [18], [19].

III. STRUCTURE–PROPERTY RELATIONSHIPS IN HYBRID PLASMA–SOL–GEL COATINGS FOR MULTIFUNCTIONAL MILITARY TEXTILE APPLIC

The literature data analysed in the present study indicate that the development of multifunctional protective textiles for military applications requires the synergistic integration of surface activation technologies, inorganic/organic hybrid coatings, and halogen-free flame-retardant systems, while simultaneously preserving the near-infrared (NIR) camouflage performance and the physico-mechanical integrity of the textile substrate.

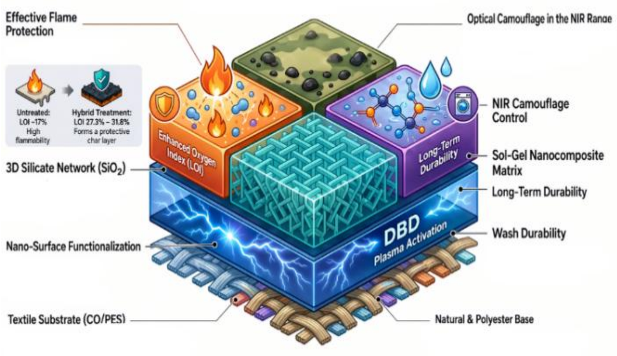

Fig. 1. Hybrid protection technologies for military textiles.

Based on the analysed literature, a conceptual hybrid technology system can be proposed to develop multifunctional military textiles that combine plasma-assisted surface activation, sol-gel nanocomposite coatings, flame-retardant additives, and NIR signature management components. The proposed system integrates complementary functional elements intended to improve thermal protection, coating durability, moisture resistance, and spectral camouflage performance, while preserving the mechanical flexibility and operational comfort of the textile substrate. Table 1 summarizes the principal components of the proposed hybrid system, their technological roles, and expected functional effects.

TABLE 1 PROPOSED HYBRID PLASMA–SOL-GEL SYSTEM FOR MULTIFUNCTIONAL MILITARY TEXTILES

Component	Function	Expected Effect
CO/PES fabric	Base textile substrate	Mechanical flexibility and wear comfort

DBD plasma treatment	Surface activation	Improved wettability and coating adhesion
Silica sol-gel matrix (TEOS)	Carrier network	Stabilization of functional additives
Phosphorus–nitrogen FR additives	Flame retardancy	Increased LOI and char formation
Carbon-based and metal-oxide additives	NIR modulation	Controlled reflectance in 700–1200 nm
Hydrophobic additives	Moisture control	Reduced water uptake
UV curing	Low-temperature crosslinking	Reduced thermal degradation

The data presented in Table 1 demonstrate that the proposed hybrid plasma-sol-gel system relies on the synergistic interaction of multiple functional components rather than on a single protective treatment. The CO/PES blended fabric serves as a mechanically flexible and operationally suitable substrate, while DBD plasma treatment serves as a surface-activation step that improves wettability and promotes stronger interfacial adhesion between the textile fibers and the subsequently deposited coating layers.

The silica-based sol-gel matrix, primarily derived from TEOS precursors, serves as a stabilizing carrier network that can incorporate multiple categories of functional additives into a unified coating architecture. In this system, phosphorus–nitrogen flame-retardant systems improve thermal stability and increase the limiting oxygen index (LOI) values by enhancing char-formation mechanisms. Simultaneously, carbon-based and metal-oxide additives enable modulation of near-infrared reflectance, which is necessary to reduce spectral detectability in NIR surveillance systems.

Hydrophobic agents further enhance operational performance by reducing water uptake and lessening moisture-related changes in thermal exchange and optical behavior. In addition, UV-curing technology provides an important processing advantage by enabling low-temperature crosslinking of the coating system, thereby reducing thermal stress and minimizing degradation of the textile substrate during finishing.

IV. Other Recommendations

A. *Programs Key Performance Indicators for Future Validation*

The reviewed literature indicates that future validation of hybrid plasma–sol-gel military textile systems should include both protective and operational performance criteria. The most important indicators include:

- Limiting Oxygen Index (LOI);
- Vertical flame test performance;
- Char length;
- Afterflame and afterglow time;
- Washingdurability;
- Tensile ad tear strength;
- Air permeability;
- Bending stiffness;
- Mass add-on;
- Color stability;
- Near-infrared reflectance in the 700–1200 nm range.

B. *Effect of Dielectric Barrier Discharge (DBD) Plasma on Textile Surface Reactivity*

One of the most significant findings from recent research is that dielectric barrier discharge (DBD) plasma treatment offers an effective, relatively mild means of tailoring the surface chemistry of textile materials without inducing bulk fiber degradation. DBD plasma, generated at atmospheric pressure between electrodes separated by dielectric barriers, produces a chemically active environment containing ions, radicals, metastable species, and UV photons, all of which can interact with the outermost molecular layers of the textile substrate [4], [5].

For both cellulosic and synthetic textile materials, plasma exposure forms oxygen-containing polar functional groups, such as hydroxyl (–OH), carbonyl (–C=O), and carboxyl (–COOH), while also partially cleaning and micro-roughening the fiber surface. These modifications increase surface free energy, improving wettability, capillary transport, and substrate affinity for subsequent chemical treatments [7]. Technologically, this is important because a persistent limitation in conventional textile finishing is incomplete penetration and weak fixation of functional agents on relatively inert or hydrophobic surfaces, especially in polyester-containing blends. For polyester and polyester-rich blended fabrics, plasma pre-treatment facilitates the uptake and distribution of flame-retardant formulations by enhancing fiber surface accessibility and improving the uniformity of coating deposition. This effect is valuable in systems that would otherwise require aggressive thermal fixation for acceptable bonding. DBD plasma acts not only as a surface-cleaning technique but also as a chemical activation step that partially compensates for polyester's intrinsic low reactivity. For cotton-based systems, plasma activation is equally important, though the rationale differs. Since cotton already has abundant hydroxyl groups, the benefit of DBD treatment lies less in creating new reactive chemistry and more in increasing accessibility and energetic state of the fiber surface, while improving homogeneity of subsequent deposition. Studies with phosphorus-based flame-retardant formulations, such as Pyrovatex CP New, show plasma-assisted pretreatment can improve finishing efficiency and may reduce the severity of post-application curing conditions needed for acceptable flame-retardant performance [7].

Therefore, within the framework of advanced military textile finishing, DBD plasma should not be regarded as a stand-alone flame-retardant treatment, but rather as a strategic enabling technology that improves the interfacial compatibility between the textile substrate and the functional coating. This role is particularly relevant in hybrid treatment concepts, where coating adhesion, wash resistance, and minimization of mechanical damage are decisive parameters for long-term field performance.

C. Sol-Gel Coatings as Hybrid Platforms for Functional Surface Engineering.

The reviewed literature strongly supports the conclusion that sol-gel technology is one of the most versatile and scientifically robust approaches for functionalizing textile surfaces. From a materials engineering perspective, the importance of sol-gel coatings does not lie in their ability to form thin films, but in the fact that these films can serve as multifunctional carrier matrices. In other words, the silica-based network is not only a protective shell but also a structurally tunable host phase that can immobilize flame-retardant molecules, nanoparticles, pigments, and other performance-enhancing additives. This gives sol-gel systems a clear advantage over conventional monofunctional finishes, which are often limited by poor durability or additive incompatibility when applied in a single bath [9], [20].

The effectiveness of sol-gel systems for textile applications depends on network architecture, crosslink density, and interfacial bonding with the substrate. When optimized, these coatings provide uniform coverage without excessively affecting textile flexibility or handle. However, sol-gel performance depends heavily on formulation. Excessively dense or brittle silica networks may reduce drapeability, increase stiffness, or cause cracks upon repeated deformation, especially in woven fabrics under flexural stress. Successful implementation requires balancing inorganic network formation with textile-specific requirements such as softness, breathability, and laundering resistance. An important finding from the reviewed studies is that sol-gel-derived coatings can simultaneously enhance flame retardancy, hydrophobicity, UV protection, and surface durability, making them particularly attractive for defence textiles exposed to complex environmental and operational stressors. This multifunctionality is highly relevant in military environments where separate finishing steps for each property would increase process complexity, weight, and cost [8].

The sol-gel process, based on the hydrolysis and condensation of alkoxide precursors such as tetraethyl orthosilicate (TEOS), enables the formation of three-dimensional inorganic or hybrid inorganic-organic networks at comparatively low processing temperatures [11].

Another important technological implication concerns UV-curable solgel systems. The use of photo-initiated curing, rather than conventional thermal curing, is particularly attractive for heat-sensitive or dimensionally unstable textile substrates. Rico et al. (2023) demonstrated that UV-induced sol-gel curing can proceed under relatively mild thermal conditions, thereby lowering thermal stress on the substrate while maintaining coating functionality [12]. This is of considerable industrial significance because it opens the possibility of lower energy, higher-throughput finishing processes compatible with blended and synthetic military fabrics.

Particularly noteworthy is the observation that silica-based sol-gel layers can significantly modify surface wetting behavior. Bae et al. (2009) demonstrated that cotton fabrics treated with silica nanoparticles and a water-repellent agent exhibited contact angles exceeding 130°, indicating strong hydrophobicity [13]. From a military perspective, this is not merely a comfort-related feature. Moisture accumulation in garments can alter thermal exchange, increase garment mass, compromise wearability, and potentially affect the optical and infrared behavior of the textile surface. Thus, hydrophobic sol-gel systems may indirectly contribute to both operational comfort and signature stability under field conditions.

Taken together, the literature suggests that sol-gel technology should be interpreted not simply as a coating method but as a materials design platform for engineering textile surfaces with customized multifunctionality.

D. Flame-Retardant Performance of Halogen-Free Phosphorus–Nitrogen Systems

The literature reports that untreated CO/PES blends typically have low oxygen index (LOI) values, often around 17%, confirming their pronounced flammability. In contrast, incorporating phosphorus–nitrogen flame-retardant systems via sol-gel or related hybrid deposition routes can substantially increase LOI values, in some cases reaching approximately 27.3–31.8%, depending on the exact formulation, add-on level, and processing conditions [6]. From a fire safety perspective, this increase is highly significant, as it indicates a transition from easily combustible behaviour toward markedly improved resistance to fire spread.

A major result emerging from the analysed literature is the clear shift towards halogen-free flame-retardant systems, particularly those based on phosphorus (P) and nitrogen (N) chemistry. This transition is driven not only by environmental and toxicological considerations, but also by growing evidence that P/N systems can provide effective fire protection in textiles through multiple, complementary mechanisms [10].

This mechanism is especially important in cotton/polyester (CO/PES) blends, which are widely used in military clothing but exhibit notably difficult fire behavior. Cotton contributes to rapid ignition and afterglow due to its cellulosic nature, whereas polyester tends to melt, shrink, and drip, which may exacerbate burn injuries. The combined flammability of these blended systems makes them highly relevant targets for advanced flame-resistant engineering. However, a critical point that repeatedly emerges in the literature is that initial flame-retardant efficacy alone is insufficient if the treatment lacks durability. A coating or finish that performs well only before washing has limited practical value for military uniforms intended for prolonged field use. In this context, the combination of plasma activation with phosphorus–nitrogen systems appears particularly promising. Plasma-generated reactive groups can enhance the chemical anchoring of flame-retardant formulations or sol-gel matrices to the fibre surface, thereby reducing wash-off and improving long-term functional retention [7]. This strength issue is reinforced by recent work on flame-resistant military fabrics, which reported that repeated washing can cause measurable changes in both physico-mechanical properties and color characteristics, underscoring the need to evaluate flame-retardant systems not just under ideal laboratory conditions but also under realistic maintenance scenarios. These conclusions are particularly relevant for military textiles, where performance retention after repeated laundering is not optional, but operationally mandatory.

The flame-retardant action of phosphorus-containing compounds is primarily attributed to the condensed phase, where they promote dehydration, cyclization, and carbonization, thereby facilitating the formation of a coherent char layer on the textile surface. This carbonaceous barrier acts as a thermally insulating, mass-transfer-limiting shield, reducing the release of flammable volatiles and slowing heat feedback from the flame to the substrate. Nitrogen-containing components can reinforce this effect through intumescent expansion, gas release, and synergistic stabilization of the developing char structure [8].

Accordingly, the most hopeful direction is not simply the application of an isolated flame-retardant chemistry, but the construction of durable hybrid protective systems in which phosphorus-nitrogen chemistry is structurally integrated into an inorganic or hybrid matrix and further stabilized by controlled surface activation.

E. Implications for Near-Infrared (NIR) Signature Management

A further important conclusion drawn from the reviewed literature is that the design of military protective textiles should not focus solely on reducing flammability. In contemporary operational environments, military uniforms must also provide effective spectral concealment, particularly in the near-infrared (NIR) region, where night vision devices and advanced surveillance systems operate [14], [15]. The NIR spectral region relevant to textile camouflage generally spans approximately 700-1200 nm. The main goal is not complete invisibility, but rather to adjust the textile's reflectance profile to more closely match the surrounding environment. This achievement requires accurate control not only of visible coloration but also of pigment composition, surface morphology, and optical effects arising from coatings and functional additives.

In this context, the literature emphasizes the key role of carbon-based materials and metal or metal-oxide additives in spectral-tuning applications. Carbon in particular is widely recognized as an efficient electromagnetic absorber and has been investigated for its influence on the reflective behavior of textile materials in the visible and near-infrared regions. Conductive or semiconductive particulate phases can greatly alter electromagnetic dynamics and may therefore contribute to NIR signature management when appropriately incorporated into textile-compatible matrices [16].

These findings provide a strong scientific rationale for using sol–gel matrices as multifunctional carriers for NIR-active additives. Within such systems, the inorganic network can improve the physical stabilization and homogeneous distribution of carbonaceous or oxide-based particles while simultaneously providing additional protective functionalities, including flame retardancy and water repellency. The scientific significance of this approach lies in its potential to integrate traditionally separate defense requirements—thermal protection and spectral camouflage—into a single multifunctional material platform. At the same time, the literature indicates that factors such as surface moisture, repeated laundering, and progressive coating degradation may significantly affect NIR performance over time [17]. Therefore, the development of military camouflage textiles for NIR applications must incorporate durability considerations alongside spectral optimization. This further stresses the relevance of combined plasma-sol-gel flame-retardant systems, whose performance should be evaluated not only under initial laboratory conditions but also under repeated environmental exposure and maintenance-related stress. Future optimization of NIR camouflage systems should focus on tailoring the spectral reflectance characteristics of treated fabrics to specific operational environments, including woodland, desert, and urban terrains. This requires careful adjustment of parameters such as pigment concentration, particle size distribution, and coating thickness. In addition, potential trade-offs between flame-retardant efficiency and NIR camouflage performance must be carefully considered, as certain phosphorus-containing or inorganic additives may alter optical reflectance across both the visible and near-infrared spectral regions.

F. Relationship Between Surface Functionalization and Mechanical Integrity.

An important scientific and practical issue in advanced textile finishing is the balance between functional enhancement and preservation of substrate integrity. High-performance coatings are of limited utility if they induce unacceptable deterioration in tensile strength, flexibility, abrasion resistance, or color stability. According to established fiber chemistry principles, the mechanical performance and functional response of textile substrates are strongly governed by fiber morphology, polymer composition, and intermolecular interactions. The reviewed studies show that the application of inorganic particles or metal-oxide-based functional systems can affect physical and mechanical performance, as well as ergonomics and comfort, in different ways, depending on particle chemistry and deposition uniformity. A study of antibacterial coatings for shoe lining materials reported that different metal oxide systems affect the substrate's physicochemical properties to varying degrees, indicating that functionality cannot be considered independently of structural characteristics [18], [21].

Studies involving the addition of silica or metal oxide-based coatings can improve fire resistance, antimicrobial resistance, or signature control, but can also modify flexural stiffness, tear resistance, and interfiber friction. Therefore, the formulation should be treated as a multifactorial optimization task in which protective properties, comfort, and mechanical resistance are optimized simultaneously. In this context, DBD plasma and sol–gel technologies offer a significant advantage, as they enable modifications confined primarily to the fiber surface without substantially altering the fiber's bulk structure. By localizing functionalization at or near the external fiber interface, these approaches minimize mechanical and chemical stress on the textile substrate. As a result, the likelihood of increased brittleness, deterioration of mechanical properties, or undesirable weight gain is reduced. This represents a substantial advantage over more invasive finishing methods, which typically rely on high add-on levels or repeated impregnation cycles.

IV. CONCLUSION

The reviewed literature demonstrates that advanced protective military textiles must be engineered using an integrated, multi-parameter design strategy that simultaneously targets flame retardancy, long-term durability, and spectral management. Dielectric barrier discharge (DBD) plasma has been shown to be an efficient surface activation technology that increases surface energy and reactivity by generating polar functional groups and microscale surface modifications, thereby significantly improving interfacial adhesion and the stability of subsequent functional coatings. In parallel, sol–gel processing provides a highly adaptable inorganic–organic hybrid platform that can structurally embed halogen-free phosphorus–nitrogen flame-retardant systems, as well as hydrophobic agents and near-infrared (NIR)-active additives, within a unified coating architecture.

For CO/PES military fabrics, the synergistic combination of plasma pre-treatment and phosphorus–nitrogen-based sol–gel systems enables a coordinated enhancement of critical performance metrics, including limiting oxygen index (LOI), laundering resistance, and mechanical integrity, while enabling controlled tuning of NIR reflectance in the 700–1200 nm spectral window. The proposed framework integrates substrate engineering, plasma activation, sol–gel formulation design, and standardized multifunctional performance metrics, establishing a coherent methodological basis for systematic optimization and experimental validation. Collectively, the hybrid plasma–sol–gel approach constitutes a robust materials engineering paradigm for next-generation multifunctional military textiles, enabling the concurrent realization of fire safety, environmental resilience, and adaptive near-infrared signature control within a single integrated functional system.

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