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Plasma-Assisted Surface Engineering of Textiles and Polymers for Improved Flame Retardancy: A Comprehensive Review

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Abstract

Flame-retardant materials are increasingly critical across textiles, polymers, electronics, and construction, yet conventional chemical finishing often compromises fabric integrity, durability, and environmental safety. Plasma-assisted surface modification has emerged as a sustainable alternative, selectively functionalizing the outer nanolayers of substrates without altering bulk properties. This review highlights the principles and types of plasma, particularly non-thermal methods such as dielectric barrier discharge (DBD), corona, and glow discharge, and examines their role in enhancing adhesion, durability, and performance of flame-retardant coatings on cotton, polyester, polypropylene, and polyamide. Compared with traditional chemical, sol–gel, or inherently flame-resistant approaches, plasma treatment offers superior surface specificity, reduced chemical usage, and eco-friendliness. Despite challenges in cost and process optimization, plasma-assisted strategies represent a versatile route for next-generation, durable, and environmentally responsible flame-retardant materials.

Key words:
Plasma treatment, Flame retardancy, Surface modification, Dielectric barrier discharge (DBD).

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1. Introduction:

The increasing demand for materials exhibiting enhanced flame-retardant performance has significantly increased interest in the development of efficient, sustainable, and technologically advanced strategies for improving fire resistance across a broad spectrum of industrial sectors. In applicationslike electronics, textiles, transportation, and construction, fire safety is not only a regulatory requirement but also a critical factor influencing product performance, durability, and human safety. Conventionally, flame-retardant treatments have relied heavily on halogenated compounds and other chemically intensive systems. Although effective, these materials are associated with significant drawbacks, including the release of corrosive and toxic gases during combustion, which pose serious harm to living beings and the environment [1]. In response to these limitations, plasma-based surface modification techniques have emerged as promising alternatives, offering a viable route to meet both performance and sustainability requirements [2,3].

From a textile flame-retardancy perspective, plasma treatment functions primarily as a surface-engineering tool that enhances fibre–chemical interactions rather than as a bulk modification technique.In flame-retardant finishing applications, plasma is valued for its ability to generate highly reactive surface sites that promote wettability, adhesion, and chemical anchoring of flame-retardant systems.. These interactions can significantly alter surface energy, introduce reactive functional groups, and improve wettability, thereby facilitating improved adhesion or grafting of flame-retardant agents [3]. In contrast to conventional dip-coating or chemical soaking processes, plasma treatments are inherently dry, require minimal chemical consumption, and enable precise control over surface modification. As a result, they reduce chemical waste, improve process uniformity, and enhance reproducibility, making them attractive for advanced material processing.

Over the past decade, extensive research has developed the efficiency of plasma-assisted treatments in improving flame retardancy across a wide range of substrates, including polymers, textiles, foams, and composite materials. Notably,

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atmospheric pressure plasma treatments have been shown to enhance the uptake and retention of phosphorus-based flame-retardant systems in polyester and polyamide fabrics [4,5]. These surface-induced modifications contribute to measurable improvements in key fire-performance parameters such as Limiting Oxygen Index (LOI), thermal stability, and char formation, all of which are essential for passive fire protection assessment. Importantly, such enhancements are typically achieved without compromising critical end-use properties, including mechanical strength, flexibility, or wearer comfort, which is particularly relevant for consumer-oriented textile applications [6].

Beyond simple surface activation, plasma-treated substrates also provide a favorable platform for subsequent graft polymerization processes. In such systems, flame-retardant monomers can be covalently bonded directly onto the substrate surface, significantly improving the durability and permanence of the flame-retardant functionality. Several studies have reported that plasma-induced grafting leads to sustained flame-retardant performance even after repeated laundering cycles, representing a substantial advancement over traditional coating-based approaches. In this context, dielectric barrier discharge (DBD) plasma has been widely employed as a pretreatment technique to enhance surface capillarity and wettability, thereby promoting deeper penetration and stronger fixation of flame-retardant formulations applied in subsequent finishing steps [6,7].

In addition to performance benefits, plasma-assisted flame-retardant treatments are increasingly recognised for their environmental compatibility. Unlike conventional wet-chemical processes, plasma-based techniques operate with little to no solvent usage, leading to a significant reduction in wastewater generation and residual chemical discharge. This characteristic aligns plasma processing with the principles of green chemistry and sustainable manufacturing, making it particularly attractive for industries facing strict environmental regulations and increasing consumer urging for eco-friendly products [8].

Another notable advantage of plasma technology lies in its high degree of tunability. By carefully selecting process parameters such as plasma gas composition, input power, and treatment duration, it is possible to tailor surface chemistry to meet specific application requirements. For example, oxygen or nitrogen plasmas can introduce polar functional groups that enhance the interaction of substrates with phosphorus- or nitrogen-based flame-retardant systems, while inert gases such as argon are commonly used to activate surfaces without introducing additional chemical functionalities or by-products [9]. This level of control provides a versatile platform for designing material-specific and performance-driven flame-retardant strategies.

Furthermore, plasma treatments can be readily integrated with hybrid flame-retardant technologies, including sol–gel coatings and nanoparticle-assisted systems. Such combined approaches enable the development of multifunctional finishes that not only improve fire resistance but also impart additional properties such as water repellency, ultraviolet protection, or antimicrobial activity [10]. For instance, plasma activation of cotton fabrics has been shown to significantly enhance the adhesion and long-term durability of silica-based sol–gel flame-retardant coatings, thereby improving both functional performance and wash resistance [11].

From an industrial perspective, plasma-assisted processes offer substantial advantages in terms of scalability and compatibility with continuous manufacturing operations. Atmospheric pressure plasma systems, in particular, enable roll-to-roll processing of fabrics, polymer films, and foams, facilitating seamless integration into existing production lines. This scalability, combined with reduced resource consumption and enhanced durability of flame-retardant finishes, positions plasma technology as a strong candidate to replace conventional wet-finishing methods in next-generation material processing [12].

Overall, plasma-assisted surface modification emerges as a powerful and sustainable approach for imparting flame retardancy while simultaneously enabling multifunctionality and long-term performance. In light of these developments, this review focuses on the fundamental mechanisms, recent advancements, and future prospects of plasma-assisted flame-retardant enhancement across various material systems.This surface-confined modification strategy is particularly advantageous for textiles, where preservation of mechanical integrity, flexibility, and wearer comfort is essential.

2.0 Types of Plasma

Plasma is widely recognized as the fourth state of matter and is defined as a partially ionized gas comprising a complex ensemble of electrons, ions, excited atoms and molecules, free radicals, and photons [13]. Unlike solids, liquids, or gases, plasma exhibits collective behavior governed by electromagnetic interactions, which allows it to induce unique physical and chemical effects at material surfaces. From a materials engineering perspective, plasma processing is particularly attractive because it enables controlled surface modification without significantly affecting the bulk properties of the substratean advantage that is rarely achieved using conventional wet-chemical or thermal treatments [14].

The interaction of plasma with solid surfaces depends strongly on plasma characteristics such as temperature, electron density, degree of ionization, pressure, and energy distribution. Consequently, plasmas are commonly classified based on their thermal equilibrium and operating pressure, both of which play a decisive role in determining their suitability for different material systems. In general, plasmas are classified into thermal (equilibrium) and non-thermal (non-equilibrium) plasmas [15, 16].

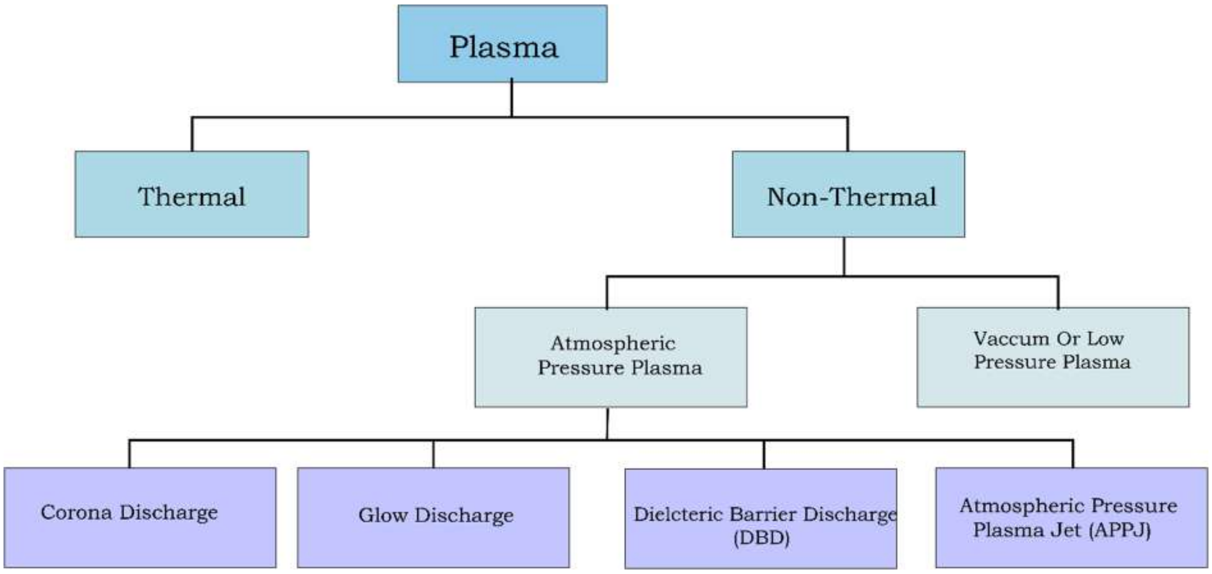

Fig 1. Types of Plasma

2.1. Thermal Plasma

Thermal plasma, also referred to as equilibrium plasma, is characterised by nearly equal temperatures of electrons, ions, and neutral species [17]. These plasmas operate at extremely high temperatures, often exceeding 1000–10,000 K, and are typically generated using arc discharges or plasma torches. Due to their high enthalpy and energy density, thermal plasmas are extensively used in applications such as metal cutting, welding, plasma spraying, and waste treatment.

However, the elevated temperatures associated with thermal plasmas render them unsuitable for heat-sensitive materials such as polymers and textiles. Exposure to thermal plasma would result in severe degradation, melting, or complete destruction of fibrous substrates. As a result, thermal plasma systems have very limited relevance in textile flame-retardant finishing and are not considered viable for surface engineering of organic materials.As a result, thermal plasma systems are not considered viable for textile flame-retardant finishing and are largely restricted to high-temperature industrial applications.

2.2 Types of Non-Thermal Plasma

Non-thermal plasma systems are of particular interest for flame-retardant textile processing because they enable highly reactive surface modification while maintaining the structural integrity of fibrous substrates. In these systems, electrons attain high kinetic energy, while the bulk gas temperature remains close to ambient conditions. This non-equilibrium state enables non-thermal plasmas to induce surface-confined chemical reactions, including bond scission and the formation of reactive functional groups, without causing thermal degradation or compromising the structural integrity of the underlying substrate.

Owing to their low thermal load combined with high surface reactivity, non-thermal plasma systems have attracted significant interest for the modification of polymeric and textile materials, particularly in flame-retardant surface engineering. Such treatments allow precise tailoring of surface chemistry and surface energy while preserving the intrinsic bulk properties of heat-sensitive textile substrates, including natural, synthetic, and blended fabrics. Based on operating pressure, non-thermal plasmas are generally classified into low-pressure (vacuum) plasma [18] and atmospheric-pressure plasma systems, each offering distinct advantages in terms of treatment uniformity, process controllability, scalability, and compatibility with textile manufacturing lines.

In addition to operating pressure, the discharge configuration strongly influences plasma–textile interactions and determines the suitability of a given plasma source for specific textile applications. Among the various non-thermal plasma technologies, dielectric barrier discharge (DBD), corona discharge, glow discharge, and plasma jet systems are the most widely adopted in the textile industry for surface modification and functional finishing. These plasma sources differ in discharge mechanism, energy distribution, penetration depth, and treatment homogeneity, which directly affect their effectiveness in activating fiber surfaces, improving wettability, enhancing coating adhesion, and increasing the durability of flame-retardant finishes.

Specifically, DBD plasma is extensively used in textile processing due to its ability to provide uniform, large-area treatment under atmospheric pressure and its compatibility with continuous roll-to-roll fabric production. Corona discharge plasma is commonly applied for rapid surface activation of textile and polymer films, particularly where improved wettability and coating spreadability are required. Glow discharge plasma, typically operated under low-

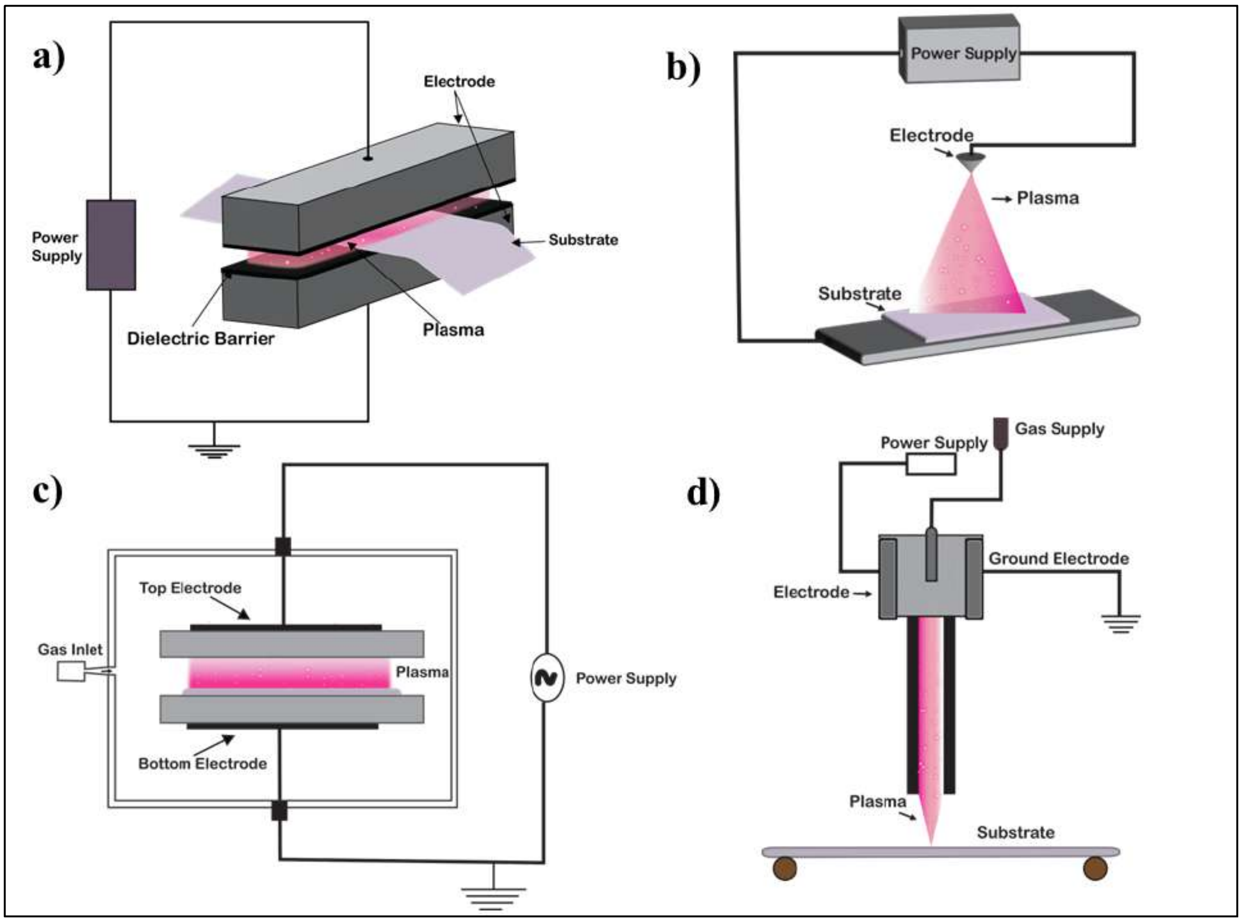

Fig 2.Types of Non-Thermal Plasma a) Dielectric Barrier Discharge b) Corona Discharge Plasma, c) Glow Discharge Plasma, d) Plasma Jet Technology

pressure conditions, offers precise and uniform surface functionalization and is well suited for research-scale studies and high-value textile applications requiring controlled modification. Plasma jet technology, on the other hand, enables localized and selective treatment of textiles and is increasingly explored for patterned functionalization and integration with hybrid flame-retardant finishing systems.

The following subsections therefore discuss DBD, corona discharge, glow discharge, and plasma jet technologies in detail, with particular emphasis on their operational principles, advantages, and relevance to flame-retardant treatments in textile applications.

2.2.1. Dielectric Barrier Discharge (DBD)

Among atmospheric-pressure plasma sources used for flame-retardant textile finishing, dielectric barrier discharge (DBD) plasma is particularly valued for its uniform treatment capability and compatibility with continuous fabric processing. The presence of the dielectric barrier plays a critical role in limiting the discharge current and distributing numerous short-lived micro-discharges uniformly across the electrode surface, thereby suppressing arc formation and preventing excessive thermal loading of the substrate [19]. Consequently, DBD plasma can be operated in a stable manner at atmospheric pressure while maintaining a low gas temperature, making it particularly applicable for the treatment of thermally responsive materials.

Owing to these characteristics, DBD plasma systems are widely employed for continuous surface modification of textiles, polymer films, and nonwoven substrates. In the context of flame-retardant finishing, DBD plasma treatment increases surface energy and promotes the formation of oxygen- and nitrogen-containing functional groups, which enhance wettability and interfacial adhesion. These surface modifications facilitate improved anchoring and long-term durability of flame-retardant coatings and additives on textile fibers. Furthermore, the commercial availability of roll-to-roll DBD plasma systems enables seamless integration into existing textile processing lines, underscoring their industrial relevance and scalability for large-area flame-retardant textile applications.

2.2.2. Corona Discharge

Corona discharge plasma is a form of non-thermal (cold) plasma generated by applying a high voltage across two asymmetrical electrodes, typically consisting of a sharply pointed wire or needle electrode and a grounded planar electrode, in a gaseous environment, most commonly air. This arrangement createsa non-uniform electric field, with intense field strength concentrated at the tip of the sharp electrode. As a result, gas molecules in the surrounding atmosphere become ionised, forming a localised plasma region identified by high electron density and relatively low gas temperature.

Corona discharge plasma is generally produced using sinusoidal voltages in the range of 10–15 kV at frequencies of several tens of kilohertz under atmospheric pressure (≈1 atm) [20]. The discharge current exhibits significant fluctuations and is primarily localised near regions of high electrode curvature, where the electric field intensity is greatest [21]. In polymer and textile surface modification, corona plasma is widely employed due to its ability to increase surface energy, enhance wettability, and introduce polar functional groups without changing the overallcharacteristics of the treated material. Key advantages of corona discharge include low power consumption, atmospheric-pressure operation, and straightforward integration into continuous industrial processing lines, making it particularly suitable for large-scale textile finishing applications.

2.2.3. Glow Discharge

Glow discharge plasma is typically generated under low-pressure conditions between two electrodes using direct current (DC) or radio-frequency (RF) power sources. Under these conditions, energetic species such as electrons, ions, and radicals are produced and interact with the surface of textile substrates, inducing both chemical and physical modifications. Glow discharge plasma is frequently applied for the surface treatment of natural fibres, such as cotton, where precise and uniform modification is required.

Low-pressure DC glow discharge treatment has been shown to significantly increase the flame-retardant performance of cotton fabrics through increased surface hydrophilicity and the introduction of oxygen-containing functional groups, including C–O, C=O, O–C–O, and O–C=O moieties. These functional groups improve surface wettability and capillary wicking behavior, which are critical for the effective uptake, dispersion, and fixation of flame-retardant formulations applied in subsequent finishing processes [22]. Although glow discharge plasma offers excellent control and treatment uniformity, its application is generally limited to batch processing due to the requirement for vacuum conditions.

2.2.4. Plasma Jet Technology

Plasma jet technology is a non-thermal plasma method in which plasma is generated between two concentric electrodes through which a continuous flow of process gassuch as helium, argon, oxygen, or their mixturesis introduced. The plasma is typically excited by radio-frequency or pulsed power sources, which energize free electrons. These electrons collide with the feed gas molecules, producing excited atoms, radicals, and additional ion–electron pairs, thereby sustaining the plasma state [23].

A major advantage of plasma jet systems is their ability to operate under atmospheric pressure without the need for a vacuum chamber, which significantly simplifies system design and enhances industrial applicability. Plasma jets enable localized and directional surface treatment, making them particularly suitable for selective functionalization, patterned modification, and treatment of complex or three-dimensional textile structures. In flame-retardant textile applications, plasma jet technology is increasingly explored as a pretreatment or activation step to enhance coating adhesion and to integrate hybrid flame-retardant systems, such as sol–gel or nanoparticle-based finishes.

3.0 Mechanism of Plasma

In flame-retardant surface engineering, the importance of plasma treatment lies less in plasma chemistry itself and more in the functional surface transformations induced on textile fibres. [24,25]. In plasma-assisted surface engineering, the interaction between these reactive species and the substrate is predominantly confined to the near-

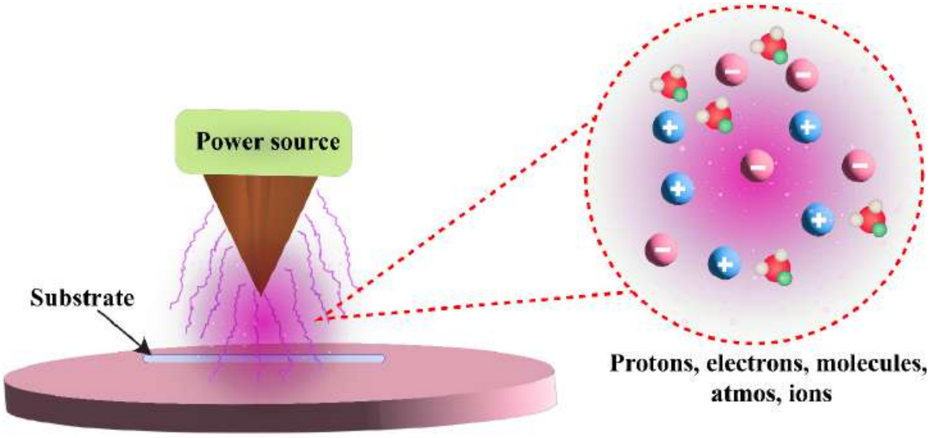

Fig 3.Graphical representation of plasma state

surface region, resulting in chemical and physical modifications without affecting the bulk structure of the material. This surface-selective nature distinguishes plasma treatment from conventional chemical methods, which may penetrate deeper into the substrate and compromise its structural integrity [24,25,26].

In the context of flame-retardant modification, plasma exposure creates reactive surface functionalities and nanoscale features that facilitate stronger interfacial bonding and more uniform distribution of flame-retardant formulations. [24,25]. These processes lead to the formation of new functional groups and increased surface roughness at the nanoscale, both of which enhance surface energy and chemical reactivity. As a result, the affinity of the substrate for flame-retardant agents is significantly improved, facilitating stronger interfacial bonding and more uniform distribution of the applied flame-retardant formulations [24,25,26,27].

Importantly, plasma treatment operates at low gas temperatures in non-thermal plasma systems, ensuring that the intrinsic mechanical and morphological properties of heat-sensitive substrates, such as textile fibers, remain unaffected. This makes plasma particularly suitable for fabrics and polymeric materials that are susceptible to degradation under aggressive chemical or thermal treatments. The plasma-modified surface either acts as an effective anchoring layer for flame-retardant coatings or promotes the formation of protective surface barriers that inhibit flame ignition and suppress flame propagation [24,26].

Furthermore, the effects of plasma treatment can be precisely controlled by adjusting process parameters such as gas composition, discharge power, and treatment duration. For instance, oxygen- or nitrogen-containing plasmas favor the introduction of polar functional groups, while inert gases primarily induce surface activation through physical etching. This high degree of tunability allows plasma treatments to be tailored to specific material systems and flame-retardant chemistries, establishing plasma technology as a versatile and effective tool for the development of advanced fire-resistant materials [24,25,26,28].By carefully controlling process parameters such as gas composition, discharge power, and treatment duration, plasma treatment can be tailored to maximize flame-retardant efficiency while minimizing fibre damage.

3.1. Pre- and Post-Plasma Treatment on Flame Retardancy

In plasma-assisted surface engineering, plasma treatment can be strategically applied either before or after the deposition of flame-retardant agents. The timing of plasma exposure plays a critical role in determining the effectiveness, durability, and interfacial bonding of flame-retardant systems with the substrate. Pre-plasma and post-plasma treatments serve distinct yet complementary functions, and the selection of either approach depends on the substrate chemistry, the nature of the flame-retardant formulation, and the targeted fire-performance requirements.

3.1.1. Pre-Plasma Treatment

Pre-plasma treatment is performed prior to the application of flame-retardant coatings or additives, with the primary objective of tailoring the surface chemistry and morphology of the substrate to enhance its receptivity toward subsequent finishing processes [2]. Plasma activation modifies the outermost surface layers of textile fibers by inducing bond cleavage and generating reactive functional groups, such as hydroxyl, carbonyl, carboxyl, amino, and amine moieties. The incorporation of these polar functionalities significantly increases surface energy and wettability, facilitating improved spreading, penetration, and uniform deposition of flame-retardant chemicals or nanostructured additives [18].

In addition to chemical activation, pre-plasma treatment may induce controlled surface roughening at the micro- or nanoscale, which further enhances mechanical interlocking between the substrate and the applied flame-retardant layer.

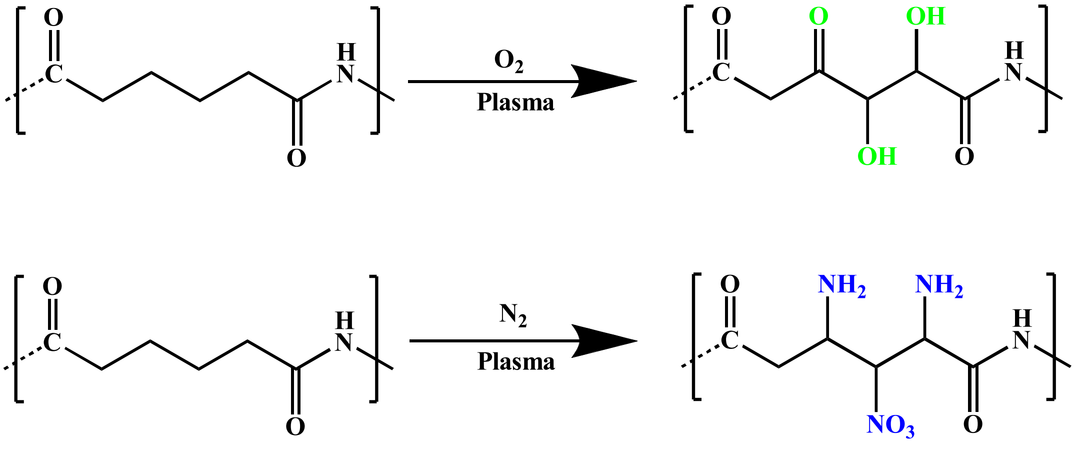

Fig 4. Surface functionalizationby Plasma treatment

Consequently, pre-plasma treatment improves coating adhesion, reduces leaching during laundering or use, and enhances the long-term durability of flame-retardant finishes, particularly for polymeric and textile substrates with inherently low surface reactivity.

3.1.2. Post-Plasma Treatment

Post-plasma treatment refers to plasma exposure applied after the flame-retardant agent or coating has been deposited onto the substrate. This approach is commonly employed to promote curing, crosslinking, and additional surface functionalization of the applied flame-retardant layer. The interaction of plasma-generated reactive species with the coated surface can induce surface crosslinking reactions, improve coating cohesion, and enhance film integrity.

Moreover, post-plasma treatment can activate residual monomers, binders, or reactive groups within the flame-retardant formulation, thereby strengthening interfacial bonding between the coating and the substrate. In some systems, plasma exposure facilitates deeper immobilization of flame-retardant elements or promotes the formation of protective surface barriers that improve resistance to thermal degradation and flame propagation. As a result, post-plasma treatment contributes to improved durability, reduced migration of active components, and enhanced flame-retardant performance without compromising the bulk properties of the underlying material.

To summarise, the principal differences between pre- and post-plasma treatment strategies are presented in Table 1.

The timing of plasma treatment, whether applied before or after flame-retardant deposition, has a substantial impact on the resulting fire-retardant performance. Pre-plasma treatment primarily ensures optimal surface activation, promoting uniform coating distribution and strong interfacial adhesion, particularly on hydrophobic or chemically inert substrates. In contrast, post-plasma treatment reinforces the applied coating, facilitates crosslinking and integration with the underlying substrate,

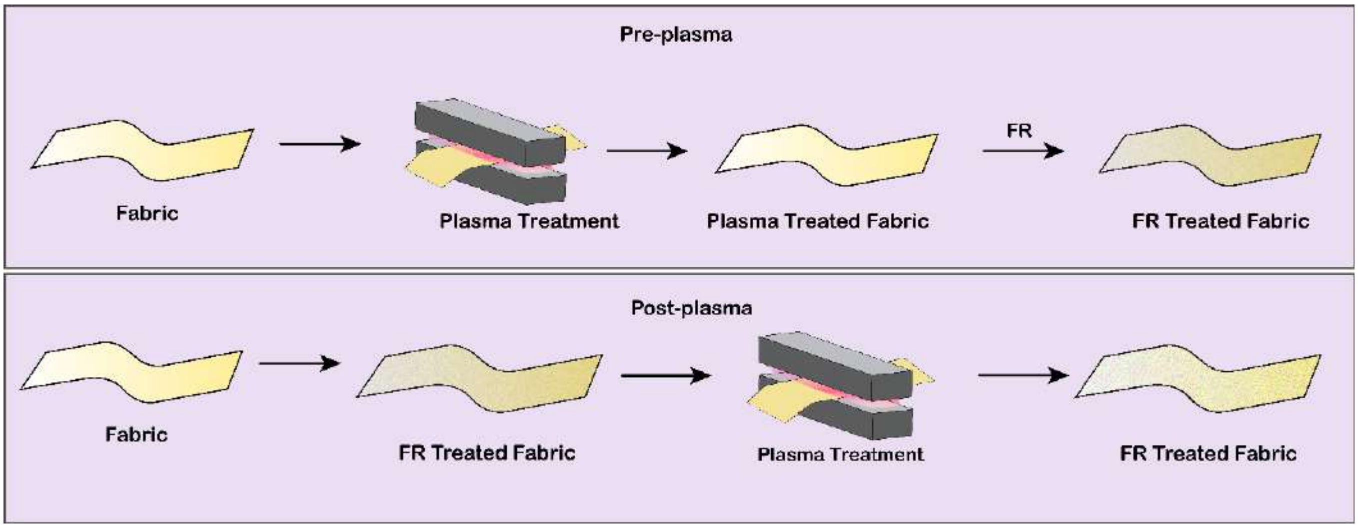

Fig 5. Graphical representation of Pre and Post-plasma treatment

Table 1.Comparison of pre- and post-plasma treatment on flame-retardant textiles

Aspect	Pre-Plasma Treatment	Post-Plasma Treatment
Treatment stage	Applied prior to flame-retardant deposition	Applied after flame-retardant application
Primary function	Surface activation and enhancement of interfacial adhesion	Coating fixation, crosslinking, and curing
Typical objective	Improve substrate wettability and bonding of flame-retardant systems	Enhance coating durability and flame-retardant performance
Suitable applications	Inert or low-surface-energy substrates	Biopolymer-based coatings and post-deposition enhancement
Processing gases	O2, Ar, N2	Air, N2, or mixed reactive gases
Representative systems	Polyester, polypropylene, nylon	Cotton–chitosan, epoxy–intumescent coatings
Resulting enhancement	Uniform coating, stronger interfacial bonding	Improved flame resistance, durability, and retention of active components

and improves the long-term durability of flame-retardant finishes.[24,25,26,29,30,31]

State-of-the-art plasma-assisted flame-retardant processes often combine both pre- and post-plasma treatments to maximize performance. This integrated approach leverages the advantages of surface activation and coating consolidation simultaneously, highlighting the versatility and effectiveness of plasma technology for advanced flame-retardant engineering.

4.0 Applications of Plasma Treatment in Flame Retardancy

Plasma treatment, once regarded largely as a laboratory-scale surface modification technique, has progressed into a mature and environmentally sustainable surface engineering approach with considerable relevance to textile flame retardancy. A key advantage of plasma technology is its ability to selectively alter only the outermost nanometric layers of textile fibres, thereby preserving the intrinsic bulk properties, including mechanical strength, flexibility, and aesthetic appearance. This highly surface-specific modification enables precise tailoring of interfacial chemistry, resulting in enhanced surface energy and the introduction of reactive functional groups that improve the adhesion, fixation, and durability of flame-retardant (FR) systems.

Owing to these characteristics, plasma treatment has emerged as an effective pre- or post-treatment strategy for functionalizing a broad range of textile substrates without excessive chemical consumption or harsh processing conditions. In the following sections, the contribution of plasma-assisted surface modification to improved flame retardancy is critically discussed with respect to four widely used textile materials: polyester, cotton, polypropylene, and polyamide.

4.1. Polyester

Polyester is widely used in apparel, home furnishings, and technical textiles owing to its high strength, dimensional stability, and chemical resistance. However, its inherent flammability, melt-dripping behavior, and chemically inert surface pose significant challenges for effective and durable flame-retardant finishing. Conventional flame-retardant treatments for polyester often rely on physically deposited coatings or additives, which frequently suffer from poor adhesion and limited durability. Consequently, plasma-assisted surface modification has been increasingly explored as a strategy to enhance fibre reactivity and improve the fixation of flame-retardant agents on polyester substrates.

Ayesh et al. [12] systematically investigated the role of atmospheric-pressure plasma treatment in enhancing the performance and durability of organophosphorus flame retardants on polyester fabrics. In their study, polyester fabrics were treated with commercially available flame retardants, including PE-CONC, PCO 900, and resorcinol diphenyl phosphate (RDP), followed by plasma exposure applied either before or after flame-retardant treatment. Plasma treatment, conducted with or without concurrent ultraviolet (UV, 308 nm) laser irradiation, generated reactive functional groups on the otherwise inert polyester surface, thereby enabling stronger chemical interactions between the flame-retardant molecules and the fibre. As a result, plasma-treated fabrics exhibited significantly improved retention of flame retardants, even after rigorous solvent resistance tests involving prolonged water and methanol soaking. Importantly, both plasma pre- and post-treatments markedly enhanced the durability of RDP-based finishes, demonstrating that plasma activationrather than UV irradiationwas the dominant factor governing improvement in the polyester–flame-retardant interfacial strength.

In a related but more integrated strategy, Zhou et al. [32] employed plasma technology not merely as a surface activation step, but as a key enabler for constructing a highly durable flame-retardant architecture on poly(ethylene terephthalate) (PET) fabrics. Owing to their smooth surface morphology and chemical inertness, PET textiles present considerable challenges for conventional finishing processes. To overcome this limitation, low-temperature oxygen plasma was used to induce surface etching, generate free radicals, and introduce polar functional groups on the PET surface, thereby enhancing its chemical reactivity. The plasma-activated PET was subsequently treated with maleic acid (MA), which covalently grafted onto the modified surface and acted as a reactive intermediary layer. This MA-functionalized interface then enabled the effective incorporation of pentaerythritol phosphate urea salt (PEPAS), a phosphorus–nitrogen-rich flame retardant. The resulting system formed a compact and chemically integrated polymer network that exhibited strong resistance to ignition and promoted the formation of a dense, intumescent char layer during combustion, effectively suppressing flame spread and melt dripping. The treated fabrics displayed excellent flame-retardant performance, achieving a limiting oxygen index (LOI) of 29.3 and retaining a V-0 rating in UL-94 vertical burning tests even after 20 laundering cycles, while maintaining tensile properties close to those of untreated PET. These findings clearly illustrate the potential of plasma technology to transcend conventional surface modification roles, functioning instead as a powerful platform for covalent flame-retardant engineering in advanced textile applications.

Further evidence of the effectiveness of plasma-assisted flame-retardant finishing of polyester has been reported by Nandy et al. employing 3-hydroxyphenyl phosphinyl propanoic acid (3HPP) as a phosphorus-based flame-retardant agent [5]. Atmospheric-pressure plasma was used to activate the polyester surface prior to flame-retardant application, resulting in a substantial increase in flame-retardant uptake and retention. Consequently, the limiting oxygen index (LOI) of untreated polyester, initially measured at 20.8 %, increased to approximately 30 % following treatment with a 4 % 3HPP formulation. Notably, the enhanced flame-retardant performance was highly durable, with the LOI remaining at ~28 % even after 20 laundering cycles, indicating strong fibre–flame-retardant interactions facilitated by plasma activation. In addition to improved fire resistance, the treated polyester fabrics retained their mechanical strength and visual appearance, underscoring the suitability of this approach for practical applications in protective clothing and industrial textiles.These findings, when viewed alongside related plasma-assisted studies, underscore a broader trend rather than an isolated material-specific outcome.

Overall, these studies demonstrate that plasma-assisted surface modification provides an effective route to overcome the inherent chemical inertness of polyester fibres. By enhancing surface reactivity and promoting durable bonding of phosphorus-based flame retardants, plasma treatment enables significant improvements in flame resistance and wash durability without compromising mechanical or aesthetic properties. As such, plasma technology represents a promising and scalable strategy for advanced flame-retardant finishing of polyester textiles.

4.2. Cotton

Chemical finishing has long been the dominant approach for imparting flame retardancy to cotton textiles, typically involving the application of phosphorus-, nitrogen-, or halogen-containing compounds through padding, coating, and curing processes. Although these treatments can provide effective fire resistance, they generally require high chemical add-on levels and elevated curing temperatures, resulting in increased energy consumption, wastewater generation, and residual chemical discharge. In addition, aggressive chemical processing may adversely affect fabric handle, tensile strength, and long-term durability. These drawbacks have stimulated growing interest in alternative surface-engineering strategies that can enhance flame retardancy while reducing chemical usage and preserving the intrinsic properties of cotton fabrics.

In this context, plasma-assisted surface modification has emerged as a promising, environmentally benign, and resource-efficient technique. Plasma treatment selectively alters only the outermost nanometric layers of cotton fibres, enabling targeted surface functionalization without disturbing the bulk cellulose structure. Such surface-specific modification is particularly advantageous for flame-retardant applications, as it enhances fibre surface energy and reactivity, thereby promoting stronger interfacial bonding between cotton and flame-retardant agents while avoiding the extensive fibre degradation often associated with conventional wet chemical treatments.

Edwards et al. [33] demonstrated the feasibility of plasma-assisted chemical grafting by successfully immobilizing phosphoramidate-based flame-retardant monomers onto cotton fabrics using post-treatment dielectric barrier discharge (DBD) plasma. Plasma exposure generated reactive oxygen-containing functional groups on the cotton surface, facilitating covalent bonding of the flame-retardant monomers and resulting in enhanced flame-retardant performance and durability. These findings highlighted the effectiveness of DBD plasma as a platform for chemical fixation of flame-retardant species.

Related studies by Tsafack et al. [34,35] investigated vacuum plasma-enabled grafting of phosphorus-based flame-retardant monomers onto cotton. While low-pressure plasma effectively activated cellulose surfaces and promoted stable fibre–flame-retardant interfaces, limitations related to scalability and processing cost constrained its industrial applicability. To overcome these challenges, atmospheric-pressure plasma was subsequently explored as a pre-treatment prior to conventional flame-retardant finishing. This surface activation allowed a reduction in curing temperature from 180 °C to 160 °C and shorter processing times while still achieving satisfactory flame retardancy, with limiting oxygen index (LOI) values ≥ 25.

However, these studies also revealed important trade-offs associated with plasma exposure. Excessive plasma treatment resulted in surface etching and partial fibre degradation, leading to measurable reductions in tensile strength, as confirmed by scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS). Despite this, plasma-treated cotton surfaces exhibited increased concentrations of oxygen-rich functional groups, including hydroxyl, carbonyl, and carboxyl moieties, which significantly enhanced the adhesion and retention of flame-retardant chemicals. These findings emphasize the critical need for careful optimization of plasma parameterssuch as power, treatment duration, and gas compositionto balance surface activation with mechanical integrity [2].

Beyond plasma-only strategies, hybrid approaches combining plasma treatment with photochemical activation have also been reported. The integration of atmospheric-pressure plasma with ultraviolet (UV) laser irradiation has been shown to improve the durability of non-durable flame-retardant finishes on cotton fabrics. Using nitrogen-, phosphorus-, and silicon-based systems, including diammonium phosphate (DAP), urea, and 3-aminopropyltriethoxysilane (APTS), plasma/UV-treated cotton fabrics exhibited enhanced flame resistance even after

30 min water soaking at 40 °C, simulating practical laundering conditions. Surface chemical analyses indicated an increased density of reactive groups, particularly carboxylic acid functionalities, which promoted stronger covalent bonding between flame-retardant species and cellulose chains. Among the tested formulations, the DAP–urea–APTS system demonstrated superior durability, retaining approximately 12 % of the flame-retardant load after soaking and exhibiting reduced burning rates and increased char formation [36].

A notable advancement in durable cotton flame retardancy was reported by Nandy et al.[37] who developed a chemically crosslinked phosphorus-based system reinforced by atmospheric plasma treatment. Cotton fabrics were treated with 3-hydroxyphenyl phosphinyl propanoic acid (3HPP) as the flame-retardant agent, 1,2,3,4-butanetetracarboxylic acid (BTCA) as a crosslinking agent, and dicyandiamide (DCDA) as a catalyst. FTIR and XPS analyses confirmed successful covalent incorporation of the phosphorus moiety into the cellulose matrix. Optimization of processing conditions increased the LOI from 17.4 % for untreated cotton to 29.5 %, which was further enhanced to 31.5 % following atmospheric plasma treatment, clearly demonstrating the role of plasma activation in strengthening fibre–flame-retardant interactions. Thermal analysis revealed improved thermal stability and enhanced char formation, while cone calorimetry showed reduced heat release and delayed ignition. Importantly, excellent wash durability was achieved, with an LOI of 28.1 % retained after 20 laundering cycles, effectively addressing a key limitation of conventional cotton flame-retardant finishes.

Overall, the literature clearly indicates that plasma-assisted approacheswhether applied as pre-treatment, post-treatment, or in combination with chemically crosslinked systemsoffer a viable pathway for enhancing flame retardancy, durability, and sustainability of cotton textiles. When appropriately optimized, plasma technology enables reduced chemical consumption, improved fixation efficiency, and preservation of fabric properties, making it a highly attractive strategy for next-generation flame-retardant cotton applications.

4.3. Polypropylene

Polypropylene (PP) is one of the most widely utilized thermoplastic polymers in technical textiles, automotive interiors, geotextiles, filtration media, packaging materials, and protective applications due to its advantageous combination of low density, high chemical resistance, good mechanical strength, and cost efficiency. However, from a fire safety perspective, PP presents significant challenges. It is intrinsically flammable, exhibits a low melting temperature during combustion, and tends to undergo severe melt dripping, which not only accelerates flame spread but also contributes to secondary ignition hazards. These characteristics render conventional flame-retardant treatments less effective and often necessitate high additive loadings, which can negatively affect mechanical performance, processability, and recyclability.

In recent years, plasma-based surface modification has emerged as a promising alternative strategy to address the inherent flammability of PP without compromising its bulk properties. As comprehensively reviewed by Horrocks [38], plasma treatments offer a non-thermal, solvent-free, and environmentally compatible route for enhancing flame retardancy in polymeric textiles. Rather than relying solely on bulk incorporation of flame-retardant additives, plasma technology enables targeted modification of the polymer surface, creating active sites that promote stronger interaction with flame-retardant agents. This approach is particularly attractive for PP, which is chemically inert and lacks polar functional groups, making it poorly receptive to conventional aqueous or solvent-based finishing formulations.

The effectiveness of plasma-assisted treatments for PP and related polymers has been further elucidated by Morent et al. [39], who systematically investigated the influence of medium-pressure dielectric barrier discharge (DBD) plasma treatments using different working gases, including air, helium, and argon, on nonwoven polyester (PET) and polypropylene (PP) textiles. Their findings revealed that plasma exposure significantly enhanced surface wettability for both polymer systems, although the extent of modification was more pronounced for PET than for PP. This difference was attributed to the aromatic ester structure of PET, which is more susceptible to plasma-induced oxidation and functionalization. Nevertheless, even for PP, plasma treatment introduced oxygen-containing functional groups and increased surface roughness, thereby improving liquid spreading and absorption behavior. Such enhancements in wettability are critical for flame-retardant finishing, as they facilitate uniform deposition, improved penetration, and stronger adhesion of flame-retardant formulations onto the textile surface.

The importance of plasma-induced wettability and surface activation has also been highlighted in the broader literature on plasma-enhanced fire performance. Jama et al. [40] reviewed several alternative plasma-based strategies aimed at improving the fire response of polymeric materials, emphasizing that plasma treatments can act either as a standalone surface modification technique or as a pre-treatment step that significantly boosts the efficiency of subsequent flame-retardant coatings. These studies collectively demonstrate that plasma activation can reduce the reliance on high chemical loadings by maximizing the effectiveness of flame-retardant agents at the material interface.

4.4. Polyamide

Beyond polyolefins, plasma-assisted flame retardancy has also been successfully demonstrated for polyamide-based textiles, which are widely used in protective clothing, upholstery, and industrial fabrics. A particularly illustrative case study involves the surface modification of polyamide 66 (PA66) fabrics using microwave vacuum plasma technology. In this approach, the fabrics were treated with a helium/oxygen (He/O_2) gas mixture under carefully optimized plasma conditions to generate a highly reactive surface enriched with polar functional groups. The plasma treatment significantly increased surface hydrophilicity and created reactive sites capable of forming stronger interactions with thiourea, a nitrogen-based flame-retardant compound.

Quantitative analysis revealed that plasma-treated PA66 fabrics exhibited approximately 38% higher thiourea uptake compared to untreated samples, confirming the role of plasma activation in enhancing chemical affinity and adsorption efficiency. This increased uptake directly translated into improved flame-retardant performance, as evidenced by a measurable increase in the limiting oxygen index (LOI) from 40.9% to 42.7% when the same thiourea concentration was applied. More importantly, the study demonstrated that plasma-treated fabrics achieved comparable flame-retardant performance using only half the thiourea concentration required for untreated fabrics. This reduction in chemical loading not only minimizes potential adverse effects on fabric handle and mechanical properties but also aligns with current sustainability goals by reducing chemical consumption and environmental impact [4].

From an industrial and environmental standpoint, these findings collectively underscore the transformative role of plasma technology in flame-retardant textile engineering. Plasma-assisted treatments enable precise control over surface chemistry, enhance the durability and effectiveness of flame-retardant finishes, and offer a viable pathway toward reducing additive usage. For polymers such as PP and PA66, which are traditionally challenging to functionalize, plasma activation provides a powerful tool to overcome interfacial limitations and achieve high-performance fire protection while preserving the intrinsic advantages of the base material. As a result, plasma-based surface engineering is increasingly regarded as a key enabling technology for the next generation of sustainable, high-performance flame-retardant textiles.

5.0 Comparison of Flame-Retardant Strategies for Textile Materials

Several approaches have been reported in the literature to impart flame retardancy to textile materials, including conventional chemical treatments, sol–gel coatings, layer-by-layer (LbL) assemblies, and inherently flame-retardant fibres. These techniques differ significantly in their working mechanisms, chemical requirements, environmental impact, processing conditions, and influence on fabric properties [41,42,43,44,45,46]. In recent years, plasma-assisted surface modification has emerged as an effective and environmentally favourable alternative due to its dry processing nature and minimal alteration of textile characteristics. A comparative summary of these flame-retardant strategies is presented in Table 2.When evaluated specifically for textile applications, plasma-assisted strategies provide a balanced combination of durability, environmental compatibility, and processing flexibility that is difficult to achieve using conventional flame-retardant approaches alone.

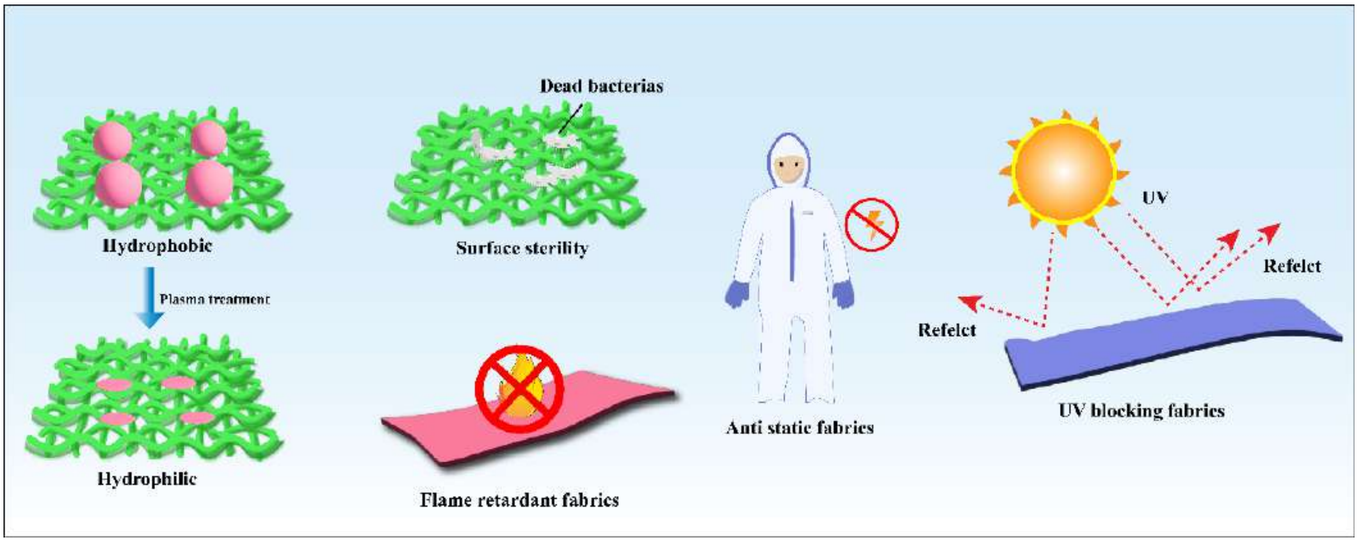

Fig 6. Other application areas of plasma technology

Table 2. Comparative Overview of Plasma-Assisted and Conventional Flame-Retardant Strategies for Textile Materials

Aspect	Plasma-Assisted Treatment	Conventional Chemical Treatment	Sol–Gel Technique	Layer-by-Layer (LbL) Assembly	Inherently Flame-Retardant Fibres
Flame-Retardant Mechanism	Activation of the textile surface by energetic species (ions, radicals, electrons, and UV photons), promoting surface functionalization and enhanced adhesion of flame-retardant moieties.	Flame retardancy achieved through bulk or surface application of halogenated, phosphorus-, or nitrogen-containing additives or finishes.	Formation of an inorganic or organic–inorganic hybrid protective barrier via hydrolysis and condensation of metal alkoxide precursors.	Fabrication of nanostructured multilayer assemblies through alternate adsorption of oppositely charged polyelectrolytes or nanoparticles.	Flame-retardant groups are chemically incorporated into the polymer backbone during fibre synthesis, resulting in intrinsic flame resistance.
Chemical Requirement	Enables a substantial reduction in flame-retardant chemical usage due to surface-specific modification.	Requires comparatively high add-on levels to achieve effective flame retardancy.	Involves tailored sol–gel precursors and controlled processing chemistry.	Requires multiple deposition cycles using aqueous solutions.	No post-processing flame-retardant chemicals are required.
Environmental Impact	Considered environmentally favourable as a dry, solvent-free process with minimal waste generation.	Often associated with solvent usage and chemical effluents, leading to environmental and regulatory concerns.	Environmental impact depends on precursor selection; some alkoxides and solvents may pose environmental risks.	Generally regarded as eco-friendly due to water-based processing and low solvent consumption.	Fibre production is energy-intensive, and recycling or disposal at end-of-life can be challenging.
Effect on Fabric Properties	Preserves fabric mechanical integrity, handle, and breathability, as modification is limited to the fibre surface.	May adversely affect tensile strength, flexibility, and fabric hand.	Can increase fabric stiffness; hybrid coatings may partially alleviate this drawback.	Minimal impact on fabric feel and flexibility; breathability is typically maintained.	Retains intrinsic fibre properties but is largely limited to synthetic fibres.
Processing Conditions	Operates at near-ambient temperature and pressure, offering reduced energy consumption and short treatment times.	Commonly requires high-temperature curing and longer processing durations.	Typically conducted at ambient conditions, followed by thermal or UV curing.	Performed at room temperature; however, the multi-step nature can be time-consuming.	Requires specialised polymerisation and spinning equipment and is not applicable to finished textiles.

6.0 Advantages and Limitations of Plasma-Assisted Flame-Retardant Surface Modification

Plasma-assisted surface modification offers several advantages for the development of flame-retardant textile coatings, particularly due to its ability to tailor surface chemistry without altering the bulk characteristics of the substrate. Since the plasma interaction is confined to the outermost fibre layers, the intrinsic mechanical properties of the textile are largely preserved [24,26]. Exposure to plasma generates polar functional groups on the fibre surface, such as hydroxyl (–OH), carbonyl (–C=O), and carboxyl (–COOH) functionalities, which increase surface energy and significantly improve the adhesion and durability of subsequently applied flame-retardant coatings or finishes [29,30,31]. From an environmental standpoint, plasma processing is widely regarded as a sustainable surface-engineering technique, as it is typically solvent-free, operates as a dry process, and substantially reduces chemical consumption compared with conventional wet-chemical methods [25,26]. Furthermore, plasma treatment induces minimal fibre damage and is applicable to a wide range of textile substrates, including cotton, polyester, and blended fabrics [24,30].

Despite these advantages, several limitations associated with plasma-assisted flame-retardant treatment must also be considered. The capital investment and operating costs of plasma equipment can be relatively high, particularly for vacuum-based systems or configurations integrating ultraviolet radiation, which may limit large-scale industrial adoption [24,28]. In addition, textiles composed of thermally sensitive or low-melting-point polymers may be prone to surface degradation if plasma parameters are not carefully controlled [29,47]. The range of flame-retardant chemistries that can be effectively immobilised on plasma-activated surfaces is also restricted, as plasma treatment primarily induces surface functionalisation rather than bulk modification [25,30]. Consequently, plasma treatment alone may be insufficient for applications requiring deep or long-term flame-retardant performance. Moreover, achieving reproducible and application-specific outcomes requires precise optimisation of multiple processing parameters, including gas composition, treatment time, applied power, and the distance between the electrode and the substrate, which increases process complexity [24,28].

7.0 Conclusion

Plasma-assisted surface treatment has emerged as a highly promising and sustainable strategy for imparting flame retardancy to textile and polymeric materials. Unlike conventional chemical finishing approaches, which often rely on large quantities of flame-retardant chemicals and energy-intensive curing processes, plasma treatment operates as a dry, solvent-free technique that selectively modifies only the outermost nanometric layers of the substrate. This highly controlled surface functionalization preserves the intrinsic mechanical strength, morphology, and aesthetic qualities of the material while avoiding bulk degradation or loss of performance.

One of the key advantages of plasma treatment lies in its ability to introduce reactive surface functionalities, such as hydroxyl, carbonyl, and carboxyl groups, which significantly enhance the interfacial bonding and fixation of flame-retardant agents. Improved chemical anchoring at the fibre surface leads to enhanced durability of flame retardancy, reduced migration or leaching of additives, and the possibility of lowering overall chemical loading. As a result, plasma-assisted approaches offer a viable pathway toward environmentally responsible fire-protection systems that align with current regulatory and sustainability demands.

This review critically examines the role of plasma treatments applied either as a pre-treatment or post-treatment step to improve flame-retardant efficacy across a variety of textile substrates, including both natural and synthetic fibres. The discussion encompasses recent advances reported in the literature, highlighting how plasma activation improves flame-retardant uptake, performance, and wash durability under practical conditions relevant to both laboratory studies and industrial applications. Despite these advantages, several challenges remain, such as the high initial investment required for plasma equipment, the limited depth of surface modification, and the sensitivity of treatment outcomes to process parameters including gas composition, power input, and exposure time.

Nevertheless, the collective evidence suggests that these limitations are primarily engineering and optimization challenges rather than fundamental barriers. With continued advances in plasma reactor design and process control, plasma-assisted surface treatments have strong potential to be scaled for industrial textile finishing. In the context of increasing emphasis on sustainability, regulatory compliance, and fire safetyparticularly within the apparel, protective clothing, and technical textile sectorsplasma technology represents a compelling route toward the development of efficient, durable, and environmentally responsible flame-retardant systems.

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Installation Damage of Geosynthetics

The geosynthetics are prone to some amount of damage during their installation. To assess the quantity of the installation damage, a standard method was initially developed by Watts and Brady of the Transport Research Laboratory in the United Kingdom. The procedure has also discussed in the ASTM D 5818 with similar requirements. We are at BTRA doing the test following same ASTM D 5818 method followed by respective tensile strength. For the time being we are using the construction site for the sample preparation. If customer will agree, BTRA will collect the sample from site after standard procedure and provide the report.

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