A Review of Low-Temperature Plasma Technology in Textile Engineering

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***Abstract*—In recent years, the textile industry has changed a lot due to growing environmental concerns and the need for sustainable processing methods. Traditional textile finishing uses a large amount of water, energy, and chemicals, which causes environmental pollution. To overcome this, low-temperature plasma technology has become a promising alternative for modifying textile surfaces. Unlike conventional methods, plasma treatment is a dry and eco-friendly process that changes only the surface of the fibers without affecting their inner structure. This review explains the basic principles, working mechanisms, and applications of plasma technology in textiles. It discusses different types of plasma systems, such as atmospheric and vacuum plasma, and their role in improving dyeability, wettability, antibacterial properties, and adhesion of fabrics. It also compares plasma treatment with traditional methods to highlight its environmental and practical benefits, while addressing its limitations and future possibilities in sustainable and smart textile development.**

***Index Terms*—Low-temperature plasma, Textile surface modification, Sustainable finishing, Plasma technology, Eco-friendly textiles, Functional finishes.**

I. INTRODUCTION

The textile industry is one of the largest and most important manufacturing sectors worldwide. However, it is also a major contributor to environmental pollution due to the extensive use of water, chemicals, and energy in textile processing. Traditional finishing methods involve chemical treatments that generate large amounts of wastewater and hazardous residues.

With increasing awareness of environmental sustainability and stricter regulations, there is a growing need for cleaner and more efficient processing technologies. Low-temperature plasma technology has gained attention as a promising solution for sustainable textile processing.

Plasma, often referred to as the fourth state of matter, consists of ionized gas containing electrons, ions, radicals, and neutral particles. When applied to textiles, plasma treatment modifies only the surface properties of fibers while preserving their internal structure. This makes it highly suitable for enhancing fabric performance without causing damage.

This review aims to provide a detailed understanding of low-temperature plasma technology, including its principles, mechanisms, applications, advantages, and future prospects in textile engineering.

II. PRINCIPLE OF PLASMA TREATMENT

When plasma interacts with textile materials, three main reactions occur:

Surface Cleaning: Organic contaminants, oil, waxes, and spin finishes are removed by electron bombardment and radical oxidation.

Surface Activation: Plasma introduces polar functional groups (–OH, –COOH, $-NH_2$) on the fiber surface, increasing: Wettability, Adhesion, Dyeability.

Surface Etching or Roughening: Energetic ion collisions cause microscopic surface roughening, which improves bonding with coatings, increases surface area, Enhances mechanical interlocking.

Cross-linking or Deposition (PECVD): Plasma polymerization deposits thin functional films (e.g., hydrophobic layer) on the surface.

III. PLASMA TREATMENT EFFECTS ON DIFFERENT FIBRES

In the case of cotton, which is a natural cellulose fiber, plasma treatment effectively removes surface impurities such as natural waxes and oils. This results in increased absorbency and improved wettability, making the fabric more receptive to subsequent processes like bleaching and dyeing. Additionally, plasma treatment enhances print quality and improves the adhesion of coatings, leading to better overall fabric performance.

For polyester (polyethylene terephthalate), which is inherently hydrophobic, plasma treatment plays a crucial role in increasing surface hydrophilicity. This modification improves the dyeability of polyester, particularly with disperse dyes, and results in better color uniformity. Moreover, plasma treatment helps reduce the tendency of polyester fabrics to pill and enhances adhesion properties, especially in applications involving laminates and coatings.

Polypropylene fibers, known for their highly hydrophobic nature and low surface energy, are generally difficult to dye or finish using conventional methods. Plasma treatment overcomes these limitations by introducing functional groups onto the fiber surface, which increases surface energy and enables better dye uptake, improved printability, and stronger bonding in nonwoven applications.

In the case of wool, plasma treatment modifies the outer scale structure of the fibers through a mild etching process. This reduces felting shrinkage, a common problem associated with wool fabrics, and improves wettability. Furthermore, plasma treatment reduces the need for traditional chlorine-based shrink-proofing treatments, making the process more environmentally friendly.

Similarly, for nylon fibers, plasma treatment enhances moisture absorption and improves dye fastness properties. It also increases the durability of functional finishes, such as flame-retardant treatments, by improving the bonding between the fiber surface and the applied chemicals. Overall, plasma treatment provides a versatile and effective method for enhancing the performance characteristics of a wide range of textile fibers.

Fibre	Effect of Plasma Treatment
Cotton	Removes wax, increases absorbency, improves bleaching, printing, and coating adhesion
Polyester (PET)	Increases hydrophilicity, improves dyeing, reduces pilling, improves adhesion
Polypropylene (PP)	Improves dyeing, printing, and bonding by adding functional groups
Wool	Reduces shrinkage, improves wettability, replaces chemical treatments
Nylon	Improves moisture absorption, dye fastness, and finish durability

TABLE I: Plasma treatment effects on different fibres

IV. FUNDAMENTALS OF LOW-TEMPERATURE PLASMA

Low-temperature plasma is generated by supplying energy to a gas through electrical discharge, radio frequency, or microwave sources. This process causes ionization of the gas molecules, resulting in a mixture of charged and neutral particles.

A key feature of low-temperature plasma is that the electrons have high energy, while the overall gas temperature remains relatively low. This allows chemical reactions to occur without damaging heat-sensitive textile materials.

Type	Conditions
Atmospheric Plasma	Normal pressure
Vacuum Plasma	Low pressure
DBD Plasma	Atmospheric

TABLE II: Types of Plasma Systems

IV. PROCESS OF LOW-TEMPERATURE PLASMA TREATMENT

Low-temperature plasma treatment involves the modification of textile surfaces through a controlled plasma environment. The process begins with the selection of a suitable gas, such as oxygen, nitrogen, or argon, depending on the desired surface effect. The textile material is then placed inside a plasma chamber (in vacuum systems) or passed through a plasma zone (in atmospheric systems).

An external energy source, such as electrical discharge or radio frequency, is applied to the gas, causing ionization and the formation of plasma. This plasma contains energetic electrons, ions, and reactive species that interact with the surface of the textile fibers. These interactions lead to surface activation, etching, or functionalization, depending on the treatment conditions.

During the treatment, only the outermost layer of the fiber is modified, while the internal structure remains unaffected. The duration of exposure, type of gas, and power input are carefully controlled to achieve the desired surface properties. After treatment, the textile material is removed and can undergo further processing such as dyeing, coating, or finishing.

V. LOW-TEMPERATURE PLASMA IN TEXTILE ENGINEERING

Low-temperature plasma technology is widely used to improve the functional properties of textiles. It enhances dyeability by increasing the surface energy of fibers, allowing better dye penetration and resulting in improved color strength and uniformity while reducing chemical usage. Plasma treatment also helps control wettability, making fabrics either water-absorbing or water-repellent depending on the treatment conditions, which is useful in sportswear, medical textiles, and protective clothing.

In addition, plasma technology improves antibacterial finishing by strengthening the bonding of antimicrobial agents to the fabric, ensuring durable antibacterial properties. It also enhances adhesion by increasing surface roughness and introducing reactive groups, which improves the bonding of coatings, prints, and laminates, leading to better durability and performance.

VI. COMPARATIVE ANALYSIS

The below table shows the comparative analysis of plasma treatment and conventional finishing:

Parameter	Plasma Treatment	Conventional Finishing
Water Usage	Very low	Very high
Chemical Usage	Minimal	High
Environmental Impact	Low	High
Energy Consumption	Moderate	High
Treatment Type	Surface modification	Bulk treatment
Waste Generation	Very low	Significant

TABLE II: Comparison of Plasma Treatment & Conventional Finishing

VII. BENEFITS AND CHALLENGES OF LOW-TEMPERATURE PLASMA TECHNOLOGY

Low-temperature plasma technology offers several important advantages in textile processing. It is an environmentally friendly method as it significantly reduces the use of water and chemicals, thereby minimizing pollution. The process enables precise surface modification without affecting the bulk properties of the textile material, resulting in improved fabric performance. Additionally, plasma treatment enhances functional properties such as dyeability, wettability, and adhesion, making it highly effective for advanced textile applications.

However, the technology also has certain limitations. The initial cost of plasma equipment is relatively high, which can be a barrier for small-scale industries. The process requires skilled operators and technical expertise to ensure proper control and effectiveness. Furthermore, large-scale industrial adoption is still limited due to challenges in scalability and process integration. Equipment complexity and maintenance requirements also add to the overall operational challenges.

VIII. EMERGING TRENDS AND FUTURE PROSPECTS

Low-temperature plasma technology has significant potential for future developments in textile engineering, particularly due to its compatibility with emerging technologies such as nanotechnology, smart textiles, and wearable systems. Its ability to precisely modify surface properties makes it highly suitable for the development of advanced functional materials. In the coming years, this technology is expected to contribute to the creation of intelligent fabrics with responsive properties, as well as advanced medical and protective textiles with enhanced performance. It also holds promise for enabling sustainable large-scale textile production by reducing resource consumption and environmental impact. Ongoing research is primarily focused on improving process efficiency, lowering operational costs, and enhancing industrial scalability, which will further support the widespread adoption of plasma technology in the textile industry.

IX. CONCLUSION

Low-temperature plasma technology provides a sustainable and efficient alternative to conventional textile finishing processes. It enables precise surface modification while reducing the use of water, chemicals, and energy, thereby minimizing environmental impact. The technology significantly enhances fabric properties such as dyeability, wettability, adhesion, and antibacterial performance, making it highly valuable for modern textile applications.

Although challenges such as high initial cost and limited industrial scalability remain, ongoing research and technological advancements are expected to address these issues. With its strong potential for improving both performance and sustainability, low-temperature plasma technology is likely to play an important role in the future of textile processing.

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