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Atmospheric Pressure Plasma Surface Modification for Sustainable Textile Dyeing and Digital Textile Printing: A Mini-Review

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Abstract

This mini-review critically examines the mechanisms underlying atmospheric pressure plasma (APP)-assisted dyeability enhancement in cotton and biodegradable synthetic fibers, particularly polylactic acid (PLA), with emphasis on plasma-induced surface activation, dye-fiber interactions, and mass transport within porous textile architectures. Particular attention is given to the applicability of APP to continuous roll-to-roll processing and its potential integration into existing textile manufacturing lines. Key challenges toward industrial implementation, including treatment non-uniformity, hydrophobic recovery and aging of plasma-activated surfaces, limited penetration through multilayer textile structures, and the lack of validated process windows for large-scale operation, are critically discussed. Finally, emerging hybrid strategies combining APP pretreatment with bio-based coatings are highlighted as a promising route toward resource efficient and sustainable textile coloration and printing with reduced chemical consumption.

Keywords: Atmospheric pressure plasma; Digital textile printing; Polylactic acid; Dye

Introduction

Textile wet processing including dyeing, printing, and finishing is among the most water- and energy-intensive stages of textile manufacturing and generates substantial volumes of wastewater containing dyes, salts, surfactants, and other processing chemicals [1]. These environmental burdens have driven increasing interest in alternative surface-treatment technologies capable of reducing water, chemical, and energy consumption. Conventional dyeing

and digital textile printing (DTP) typically involve chemical pretreatment to improve fiber wettability, dye-fiber interactions, and colorant uptake, followed by fixation and washing steps to remove unfixed dyes and residual auxiliaries [2]. These processes contribute substantially to the overall water and energy demand of textile coloration. Atmospheric-pressure plasma (APP) has therefore emerged as a promising dry and low-temperature surface-modification technology for enhancing fiber surface reactivity prior



to dyeing and printing [3-5]. Through plasma-induced surface activation, APP can modify surface chemistry and morphology while minimizing changes to the bulk properties of the textile substrate. Moreover, operation at atmospheric pressure eliminates the need for vacuum systems, facilitating continuous roll-to-roll processing and in-line integration with existing textile manufacturing lines [6-8]. These characteristics make APP particularly attractive for the development of more resource-efficient textile coloration processes.

Despite these advantages, the mechanisms by which APP enhances dyeability vary considerably among fiber classes, reflecting differences in their surface chemistry, morphology, and interactions with plasma-generated reactive species. Following a brief overview of the environmental and technological drivers for APP adoption, the fundamental mechanisms governing plasma-induced improvements in dyeability, including surface functionalization together with the associated changes in wettability and surface energy, as well as plasma interactions with porous textile structures governing penetration depth, are discussed with reference to cotton, polyester, and biodegradable synthetic fibers. Recent progress toward continuous roll-to-roll processing and in-line integration of APP with dyeing and DTP systems is then reviewed, followed by a critical assessment of key challenges, including treatment uniformity, aging and hydrophobic recovery of plasma-modified surfaces, process scalability, and the lack of

standardized industrial processing windows. Finally, combination approaches integrating APP pretreatment with complementary dyeing chemistries are highlighted as a promising route toward low-chemical, resource-efficient, and sustainable textile coloration.

Mechanism of Plasma Treatments

Surface functionalization

Plasma treatment modifies fiber surface chemistry through the introduction or enrichment of polar functional groups, including carbonyl (C=O), carboxyl (-COOH), hydroxyl (-OH), and, depending on the plasma chemistry, amine (-NH₂) groups [9-12]. These surface modifications increase surface energy and wettability, thereby promoting liquid spreading, capillary wicking, and dye-fiber interactions that can facilitate subsequent dye uptake and penetration. Kan and Man [13] systematically investigated the effects of four Atmospheric Pressure Plasma Jet (APPJ) operating parameters: discharge power (130-170 W), oxygen flow rate (0.2-0.6 L/min), jet traverse speed (1-9 mm/s), and jet-to-substrate distance (3-9mm) on the wettability of cotton fabric, as evaluated by wicking height and wetting area. Their results demonstrated significant interactions among the operating parameters, indicating that plasma-induced wettability is governed by their combined effects rather than by any single parameter independently (Figure 1).

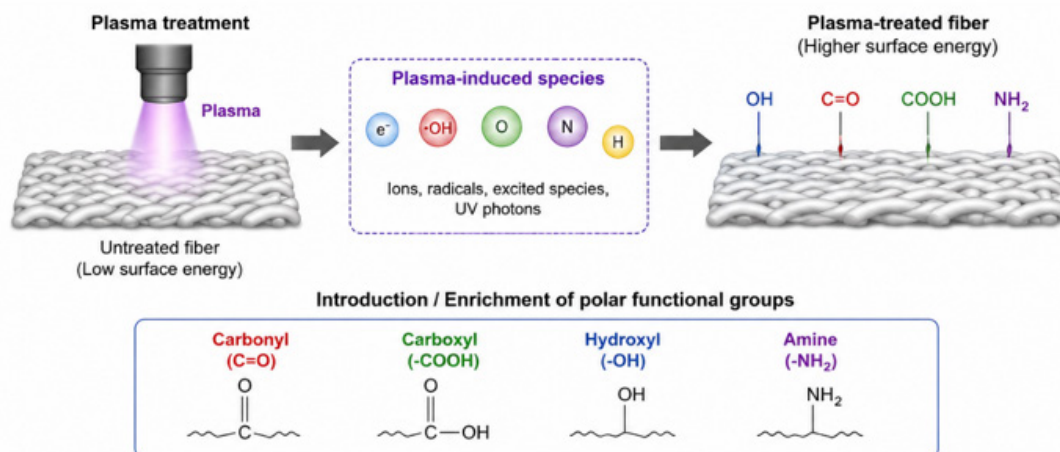


Figure 1: Schematic illustration of plasma-induced surface modification and enhanced dyeability of textile fibers.

Penetration depth and porosity effects

In porous textile structures, the interaction of atmospheric-pressure plasma with the substrate is strongly influenced by discharge characteristics, gas flow, and fabric architecture. In filamentary APP systems, numerous transient micro discharges and plasma-generated reactive species can interact with accessible fiber surfaces within the porous structure, potentially extending surface activation beyond the outermost fabric layer. By comparison,

plasma-surface interactions under low-pressure conditions are governed by different transport mechanisms, and the effective modification depth depends on the diffusion and accessibility of reactive species within the textile structure [14]. Jorda-Vilaplana, et al. [15] investigated the chemical and physical modifications induced on PLA by atmospheric-pressure air plasma using X-ray photoelectron spectroscopy (XPS) and Fourier-transform infrared spectroscopy (FTIR). The treatment increased the surface free energy and wettability of PLA, accompanied by changes in oxygen-

containing surface functionalities, demonstrating that APP can effectively modify the near-surface chemistry of PLA. From an industrial perspective, the ability of APP to activate complex textile surfaces under atmospheric conditions is particularly relevant to continuous in-line systems, including dual-sided treatment configurations, where uniform treatment across the fabric width and accessible fiber surfaces is essential for achieving consistent wettability and subsequent dye uptake.

Applications to Sustainable Dyeing and Digital Textile Printing

In addition to conventional dyeing, plasma pretreatment has also been explored as a means of reducing the use of chemical auxiliaries in digital textile printing (DTP). Because high-quality DTP requires controlled ink wetting, spreading, and fixation while minimizing lateral diffusion and color bleeding, plasma-induced changes in surface chemistry, wettability, and surface energy can contribute to improved print definition and color yield, while potentially reducing the demand for conventional pretreatment chemicals and wetting agents [16]. Wang, et al. [17] demonstrated that combining plasma pretreatment with a bio-based chitosan/siloxane polyester coating improved dyeing uniformity and simultaneously imparted antimicrobial functionality, confirming the feasibility of plasma-assisted hybrid treatments for reducing reliance on conventional chemical auxiliaries in PLA coloration. Such configurations could reduce pretreatment chemical consumption and associated wet-processing requirements while maintaining or improving color yield, print definition, and colorfastness. Nevertheless, the extent of these environmental and processing benefits depends strongly on the plasma configuration, substrate, printing chemistry, and downstream washing and fixation requirements.

Limitations

Several technical challenges continue to hinder the broader industrial adoption of APP pretreatment for textile dyeing and DTP. First, plasma-induced surface activation can be transient, particularly in polymeric fibers, because of hydrophobic recovery during storage. This aging behavior is generally associated with the reorientation of polar functional groups toward the polymer bulk and the migration or rearrangement of low-molecular-weight species at the surface, leading to a gradual decrease in surface energy and wettability [18, 19]. Consequently, minimizing the time interval between plasma treatment and subsequent dyeing or printing may be necessary to ensure consistent coloration performance. Second, achieving uniform treatment across the full width and both sides of a continuously moving fabric web remains challenging at industrial line speeds. Key operating parameters, including discharge power, gas flow rate, electrode-to-substrate distance, and line speed, must therefore be carefully coordinated because their combined effects govern plasma exposure and the resulting surface wettability [20]. Third, beyond these process-dependent factors, the intrinsic characteristics of atmospheric-pressure discharges can also contribute to treatment non-uniformity. Primc, et al. [21] noted that the stochastic spatial distribution of filamentary streamers can produce localized variations in plasma exposure, making completely uniform surface activation difficult to achieve even under carefully

controlled operating conditions. Fourth, plasma exposure must be maintained within an appropriate treatment window, as excessive treatment can cause pronounced surface etching and potentially compromise the mechanical integrity of textile fibers. For PLA fabrics, prolonged dielectric barrier discharge (DBD) treatment has been reported to reduce tensile strength, illustrating the trade-off between surface activation and preservation of bulk mechanical properties. Finally, although numerous studies have demonstrated the effectiveness of APP at laboratory and pilot scales, robust and reproducible process windows for continuous industrial-scale integration with dyeing and DTP lines remain insufficiently established. Further work is therefore needed to establish scalable and reproducible APP processes that provide uniform surface modification without compromising textile properties under industrial operating conditions.

Future Perspectives

Future research should extend beyond the optimization of plasma treatment in isolation toward integrated coloration processes in which APP is coupled with environmentally benign dyeing and printing chemistries. In particular, coupling plasma-activated surfaces with natural dyes, biopolymer coatings, or other low-toxicity auxiliaries may augment dye-fiber interactions while curtailing the quantity of conventional chemicals required for pretreatment and coloration [22]. This approach is particularly pertinent to PLA and other biodegradable fibers, for which surface activation can enhance dyeability without necessitating modification of the bulk polymer. Further investigations should elucidate how plasma-induced alterations in surface chemistry govern the adsorption, diffusion, and fixation of distinct dye and ink classes, thereby enabling plasma parameters to be rationally tailored to specific fiber-colorant systems. At the manufacturing level, future efforts should focus on integrating APP directly into continuous dyeing and DTP lines rather than treating plasma as a discrete pretreatment step. Compact, dual-sided plasma systems capable of operating at industrial web speeds, coupled with real-time monitoring of discharge behavior and surface response, could enhance process consistency and minimize the decay of surface activation prior to coloration. Establishing correlations among plasma operating conditions, line speed, surface properties, and coloration performance will also be essential for defining practical operating windows for scale-up. Ultimately, industrial validation should quantify not only improvements in color yield and colorfastness but also reductions in water, energy, and chemical consumption relative to conventional pretreatment processes. Such comparative data will be indispensable for determining whether APP constitutes a technically and environmentally viable alternative for large-scale textile coloration.

Conclusion

Atmospheric-pressure plasma treatment provides a dry and continuous approach to enhancing the dyeability of natural and biodegradable synthetic fibers through surface functionalization, increased wettability and surface energy, and improved accessibility of plasma-generated species within porous textile structures. Its compatibility with in-line processing offers opportunities to reduce

the use of conventional chemical pretreatments and associated water and energy consumption in textile dyeing and digital textile printing, including processes involving biodegradable substrates such as PLA. Realizing its full sustainability potential will require further work on treatment uniformity, the stability of plasma-induced surface effects over time, and validated process windows at industrial production scale.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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