Integrating Plasma Technology for Water Conservation in Textile Processing

A study on dyeability and colour fastness properties of plasma treated knitted modal fabrics

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Abstract- The multidisciplinary approach to sustainable development of future cities integrates innovative emerging technologies, fostering resilience, efficiency, and liveability. Science and technology play a pivotal role, particularly in industries like textiles and apparel, where innovations such as plasma treatment, a waterless technique, enhance dyeability, comfort, and functionality of advanced cellulosic fabrics like modal knitted fabrics. This dynamic field bridges chemistry, engineering, environmental science, and economics, addressing key challenges while promoting cleaner production methods, circular economy principles, and water conservation. Plasma technology not only reduces resource consumption and pollution but also ensures longer-lasting textiles, contributing to environmental and economic sustainability. Aligned with the objectives the paper presents the research data on the dyeability aspects of air plasma treated knitted modal fabrics and highlights key goals such as fostering multidisciplinary collaboration among geoinformatics, urban planning, and public health experts, and promoting geo-spatial solutions like GIS, AI/ML, and IoT for addressing urban challenges, including climate change, disaster resilience, and resource management. Knowledge exchange among stakeholders, including researchers, policymakers, and industry professionals, further enables sustainable water resource management, disaster preparedness, and net zero initiatives. Water, being a social, environmental, and economic issue, connects directly to the three pillars of sustainability. Multidisciplinary strategies are vital to achieving the Sustainable Development Goals, addressing global water resource challenges, and ensuring eco-wellbeing and ecological balance. Holistic research and actionable policy recommendations are essential for empowering town planners and fostering global partnerships among academia, governments, and industries. By incorporating innovative technologies like plasma treatment, future cities can achieve ecological and economic balance while enhancing the quality of life. This integrated approach paves the way for creating resilient and sustainable ecosystems, ensuring their alignment with global sustainability objectives through collaborative efforts and strategic innovation.

Index Terms- *Circular Economy, Multidisciplinary Approach, Plasma Technology, Sustainable Development, Water Conservation.*

I. INTRODUCTION

Water remains a critical environmental, social, and economic resource, it directly links to the core pillars of sustainability and determines the future resilience of the textile sector.[1]. Multidisciplinary strategies are therefore essential for achieving Sustainable Development Goals, mitigating global water-related challenges, and ensuring ecological balance across fibre-to-fashion systems [2]. Holistic research, technology adoption, and evidence-based policy recommendations are crucial for empowering industry leaders and accelerating global partnerships across academia, government, and the textile value chain. By integrating innovative technologies such as plasma treatment, the textile industry can advance towards environmentally conscious production while enhancing product quality, thereby shaping resilient, resource-efficient, and sustainable manufacturing ecosystems aligned with global sustainability commitments. [3, 4]

Sustainability and resource stewardship are converging imperatives in the Anthropocene: accelerating urbanization, climate-driven hydrological variability, and intensifying industrial demand make integrative, technology-enabled strategies essential for resilient futures [5, 6]. In this context, water conservation emerges as a cross-cutting priority because it directly constrains urban infrastructure, public health, industrial productivity, and ecosystem stability. Integrated approaches that combine geospatial intelligence (GIS, remote sensing), data- driven analytics (AI/ML), and pervasive sensing networks (IoT) enable temporally and spatially explicit decision support for water allocation, leak detection, pollution control, and climate-adaptive planning [7,8,9] .These tools also facilitate multi-scale coupling between urban and rural planners, public health authorities, and industrial stakeholders to operationalize sustainable development objectives.[10,11]

Figure 1: SDG Mapping Relevant to plasma treatment on textiles

The textile sector is both a major water consumer and a critical leverage point for reducing industrial water footprints. Conventional wet-processing operations (scouring, bleaching, dyeing, rinsing) generate substantial effluent volumes and chemical loads, which in turn impose treatment burdens on wastewater systems and local ecosystems [12,13,14] Consequently, technology-driven process re-design — shifting from high-water to waterless or low-water pathways — is a high-impact mitigation strategy for water stress.[15] Recent reviews emphasize scalable water-saving interventions including closed-loop rinsing, membrane recovery, supercritical CO_2 dyeing, and surface activation techniques such as plasma treatment that reduce dye bath residuals and effluent chemical oxygen demand (COD). However, industrial uptake depends on process compatibility, energy balance, and product quality parity. [16,17,18]

Plasma-based surface modification is a particularly promising technology for decarbonizing and dewatering textile finishing. Non-thermal atmospheric and low-pressure plasma processes modify polymer surface chemistry and topography—introducing oxygenated functional groups (–OH, –COOH), increasing wettability, and enhancing dye-fiber interaction—without bulk fiber degradation or water-intensive chemistry [19,20].Empirical studies report increased dye exhaustion, improved wet rubbing and washing fastness, and reduced need for chemical mordant following air- or oxygen-plasma pre-treatment for cellulosic substrates [21,22]. From a life-cycle perspective, adopting plasma pre-treatment can reduce effluent volumes and residual dye loads, thereby lowering downstream treatment energy and chemical demands — provided energy inputs for plasma generation are optimized and integrated into factory energy management. [23, 24].

Modal fiber, a regenerated cellulosic material with favourable mechanical and comfort properties, is increasingly used in apparel and home textiles because of its renewability and softness. Yet like other cellulosic fibers, modal's dye uptake and finishing performance are constrained by surface accessibility and crystallinity. Air plasma treatment effectively increases surface reactivity of modal by etching amorphous regions and creating polar sites, resulting in higher dye exhaustion and enhanced fastness metrics while avoiding wet-chemical pre-treatments that drive water consumption [25,26] Consequently, plasma-enabled modal processing aligns with circular-economy imperatives by reducing process inputs, extending product functional life, and improving recyclability potential when combined with responsible design and end-of-life systems.[27] .

Operationalizing plasma at industrial scale requires rigorous assessment of process windows (power, gas composition, exposure time, line speed), compatibility with downstream dye chemistries, and the trade-offs between surface activation and potential over-etching that can degrade mechanical integrity. Laboratory-to-pilot studies indicate an optimal treatment duration (often short exposures in the order of seconds to minutes) beyond which additional exposure yields diminishing returns or adverse surface oxidation [28]. Optimization must therefore integrate spectroscopic surface analysis (XPS/FTIR), morphological assessment (SEM/AFM), and standardized colourimetric and fastness testing to ensure both quality and sustainability gains. [29]

Linking textile process innovations to water governance amplifies impact: higher dye exhaustion means fewer dye molecules return to municipal effluent streams, lowering local pollutant loads and treatment costs. When textile clusters adopt water-saving technologies (plasma, closed-loop water recycling, membrane filtration), coupled with geospatial monitoring for industrial effluent and IoT-enabled plant telemetry, municipalities gain improved capacity for regulatory oversight, pollution hotspot identification, and infrastructure.[30,31,32] Moreover, AI-driven process control can minimize energy and chemical use while maintaining product quality, making the textile–urban nexus central to achieving several SDGs simultaneously (clean water, sustainable cities, responsible production).[33,34] This paper therefore adopts an interdisciplinary and technical framing: it evaluates air plasma treatment's effects on dyeability, exhaustion percentage, and colour fastness metrics in modal knitted fabrics while situating these process outcomes within water-conservation and sustainability frameworks.
The objectives are:
To quantify surface-chemistry and colourimetric changes induced by air-plasma under controlled exposure regimes.
To assess fastness performance (washing, rubbing, perspiration, light) against industrial standards.
To estimate downstream water- and chemical-use reductions attributable to improved dye exhaustion
To discuss integration pathways for plasma-enabled textile processing within smart, geographically-aware water-management systems.

Achieving these aims requires a combination of surface-analytical characterization, standardized textile testing (ISO/AATCC protocols), and scenario-based water-balance estimation to demonstrate both material- and system-level sustainability gains. In doing so, the study contributes to a growing evidence base that couples advanced materials processing with urban-environmental planning, offering a replicable methodology for evaluating how textile process modernization can deliver measurable water savings and reduced environmental externalities at city scales.[35,36]

II. MATERIALS AND METHOD

In the present study, knitted fabrics using 100% modal yarns in single jersey construction were used. Based on the review of literature and standard procedures, the research methodology was formulated. The modal knitted fabrics were treated using low pressure glow discharge plasma. The glow discharge was generated using an apparatus made by an industry. The DC glow discharge was operated at 0.5 mbar. The type of plasma treatment used air. Cathode was located in the centre of the chamber and the chamber walls acted as anode. Samples were placed hanging at a distance of about 18 cm from the cathode. The air flow was maintained at a constant rate. The duration of air plasma treatment was 5, 10 and 20 minutes for the plasma treatments. The size of samples during each run was 50x50 cm. The treated fabric samples were removed from the chamber and then conditioned under 65% RH and 25^0C standard conditions for 24 hours before testing.
The weight per square metre of the fabrics was determined using GSM cutter as per IS 1962-197. The number of wales and course per centimetre was recorded as per ASTM standard D 3775. Thickness was measured at different places in the pieces on different samples as per BS 2544-1954. The loop length measured at different places in the fabric samples as per BS 5441.
SEM topography: SEM studies were carried out on the samples after mounting them on specimen stubs and coating with AU-PD in a vacuum fine coat ion sputter. For each sample, two specimens were taken. The thickness of the coating and time were optimized before the samples were examined in JOELSEM model 84 OA.

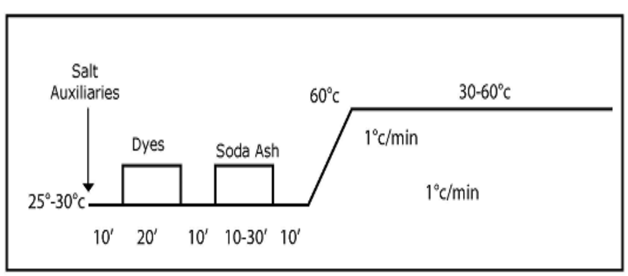

Figure 2: Dyeing profile of fabrics

The regenerated cellulosic fabrics were dyed using reactive dyes. The liquor ratio was maintained at 1:10. The untreated and plasma treated bamboo, modal and their 50/50% blends with cotton were separately dyed with 2% shade containing 40 g/L

Glauber's salt (electrolyte) and 12g/L of soda ash (alkali) at 60°C for 60 minutes. The pH was maintained at 10.3. The dyed samples were washed with 0.5 g/L of neutral soap at 95°C for 10 minutes. The extent of dye exhaustion for 2% concentration of dye, before and after dyeing was determined using spectroscopic analysis. The dyeing profile is given in Figure 1

Measurement of dye exhaustion

The dye bath exhaustion percentage (%E) was calculated using Equation 1.

$$\% E = \frac{(A_b - A_a)}{A_b} \times 100 \qquad (1)$$

Where, A_b and A_a are the absorbencies at maximum wavelength (λ max) of dye originally in the dye bath and of the residual dye after dyeing respectively.

Testing of colour strength of dyed samples

The testing of colour performance was measured in terms of reflectance values of the conditioned dyed samples at the maximum wavelength (λ max). Colour strength (K/S) of the dyed samples was calculated using Kubelka-Munk Equation 2.

$$K / S = \frac{(1-R)^2}{2R} \qquad (2)$$

III. RESULT AND DISCUSSION

Table 1: Geometrical properties of untreated and air plasma treated modal fabrics

Sample Code Description	Course/ Cm	Wale/ cm	Stitch density (cm^2)	Loop length (mm)	Tightness factor ($tex^{0.5}$ mm^{-1})	Loop shape factor	Thickness (mm)	Mass per unit area (g/m^2)
Untreated – control	21.0	16.0	336	2.20	2.02	1.31	0.45	158.67
5 min. air	21.0	16.0	336	1.86	2.38	1.31	0.33	134.70
10 min. air	20.0	17.0	264	2.07	2.14	1.18	0.35	151.11
20 min. air	17.0	15.0	255	2.63	1.68	1.13	0.32	144.43

The analysis of untreated and air plasma-treated modal knitted fabrics reveals significant changes in their geometrical properties depending on the treatment duration (5, 10, and 20 minutes). The effects of plasma treatment on key parameters are summarized as follows:

Course and Wale Density: Plasma treatment reduces course density (horizontal stitches/cm) significantly at longer treatment durations, from 21.0 courses/cm in untreated fabric to 20.0 and 17.0 courses/cm after 10 and 20 minutes, respectively. Wale density (vertical stitches/cm) shows a complex pattern, with a slight increase to 17.0 wales/cm at 10 minutes, followed by a reduction to 15.0 wales/cm at 20 minutes. These changes suggest structural relaxation and surface modification, particularly at extended treatment durations.

Stitch Density: Stitch density decreases progressively after plasma treatment, from 336 cm^2 in untreated fabric to 264 cm^2 and 255 cm^2 after 10 and 20 minutes, respectively. This indicates loosening of the fabric structure due to plasma-induced fiber changes, such as swelling or reduced interlocking.

Loop Length: Loop length initially decreases from 2.20 mm to 1.86 mm after 5 minutes, indicating increased fabric stiffness or compaction. However, at 20 minutes, loop length increases significantly to 2.63 mm, suggesting relaxation or elongation of the fibres under prolonged plasma exposure.

Tightness Factor: Tightness factor increases from 2.02 to 2.38 after 5 minutes, reflecting higher compactness. It then decreases to 2.14 and 1.68 at 10 and 20 minutes, respectively, indicating a loss of compactness as the fabric structure relaxes with extended treatment.

Loop Shape Factor: The loop shape factor decreases slightly with treatment, from 1.31 in untreated fabric to 1.18 and 1.13 after 10 and 20 minutes, respectively. This points to a transformation in loop geometry, potentially affecting the fabric's appearance and texture.

Thickness: Fabric thickness reduces significantly after 5 minutes (from 0.45 mm to 0.33 mm) and continues to decrease slightly with prolonged exposure, stabilizing at 0.32 mm by 20 minutes. This reduction is likely due to fiber surface etching and compaction induced by plasma treatment.

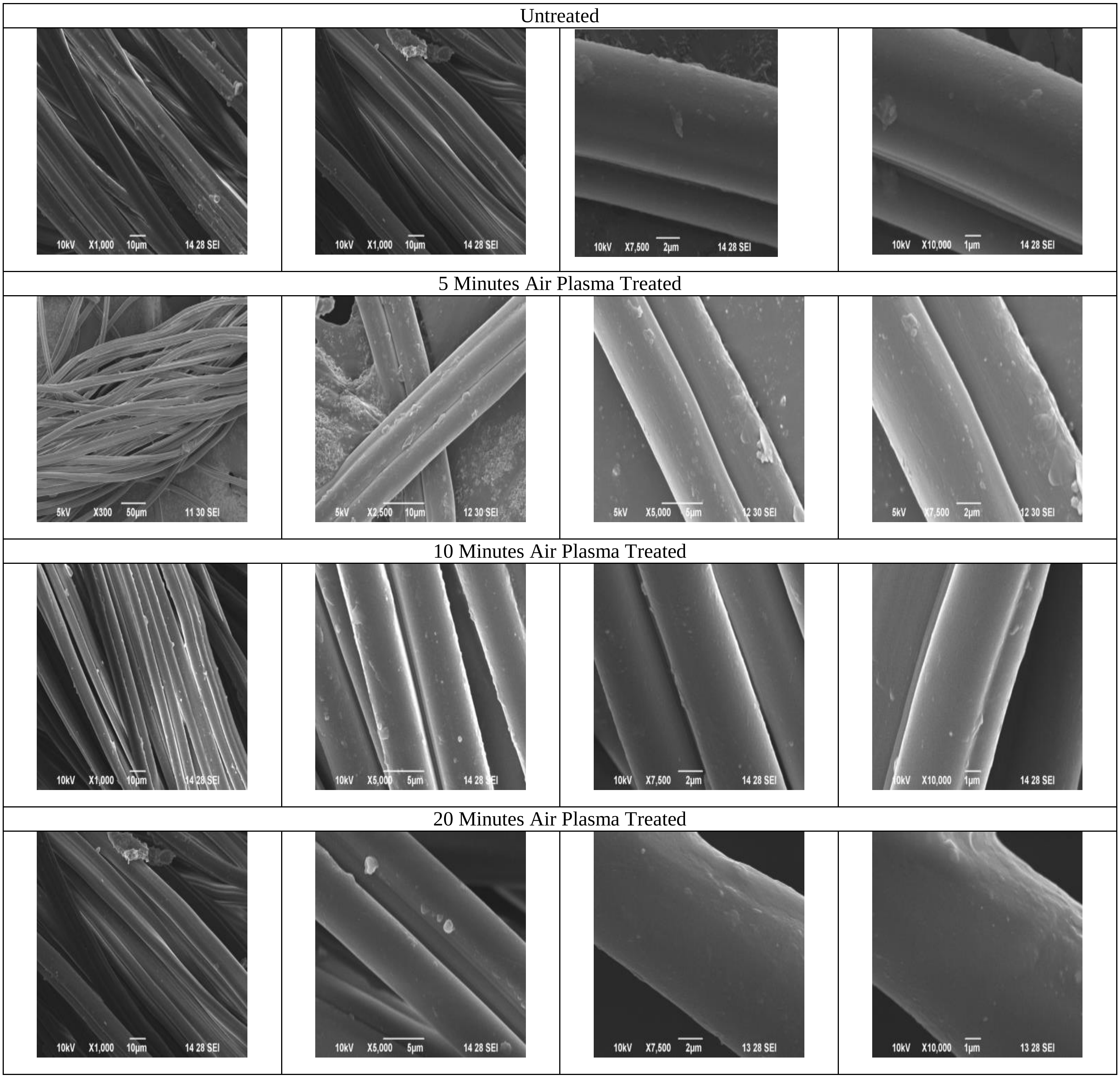

Figure 3: Scanning Electron Micrographs of Untreated and Air Plasma Treated Modal Fabric

Mass per Unit Area: Mass decreases significantly after 5 minutes (from 158.67 g/m² to 134.70 g/m²) due to the removal of surface material or moisture. It partially recovers at 10 minutes (151.11 g/m²) and reduces again to 144.43 g/m² at 20 minutes. These fluctuations reflect the dynamic balance of material removal and structural changes during plasma treatment.

Short-Term Effects (5 Minutes): Plasma treatment compacts the fabric, reduces thickness and mass, and tightens the loops, resulting in increased tightness factor. Longer-Term Effects (10–20 Minutes): Relaxation of the fabric structure occurs, with reduced stitch density, increased loop length, and decreased tightness factor. Thickness and mass also reduce overall, indicating surface activation and structural modification.

Air plasma treatment significantly alters the structural and geometrical properties of 100% modal knitted fabrics. The effects are time-dependent, with short treatments enhancing compactness and longer treatments inducing relaxation and surface changes. This highlights the need for precise optimization of treatment duration to achieve desired functional and aesthetic outcomes in modal fabrics.

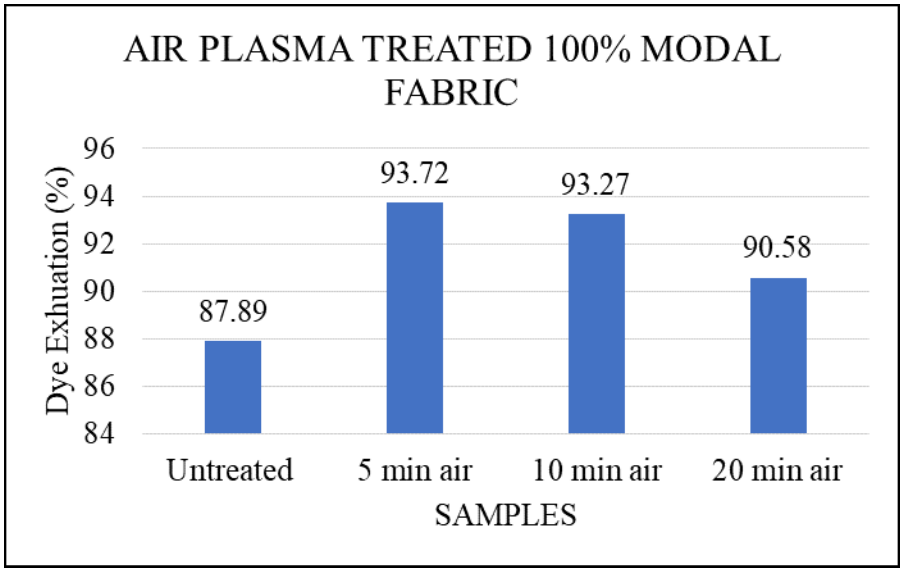

Figure 4: Dye Exhaustion (%) of plasma treated fabrics

Figure 4 presents the percentage exhaustion of dye on untreated and air plasma-treated 100% modal knitted fabrics. Dye exhaustion refers to the amount of dye taken up by the fabric from the dye bath, expressed as a percentage. Higher exhaustion values indicate better dye uptake, suggesting improved dyeability of the fabric.

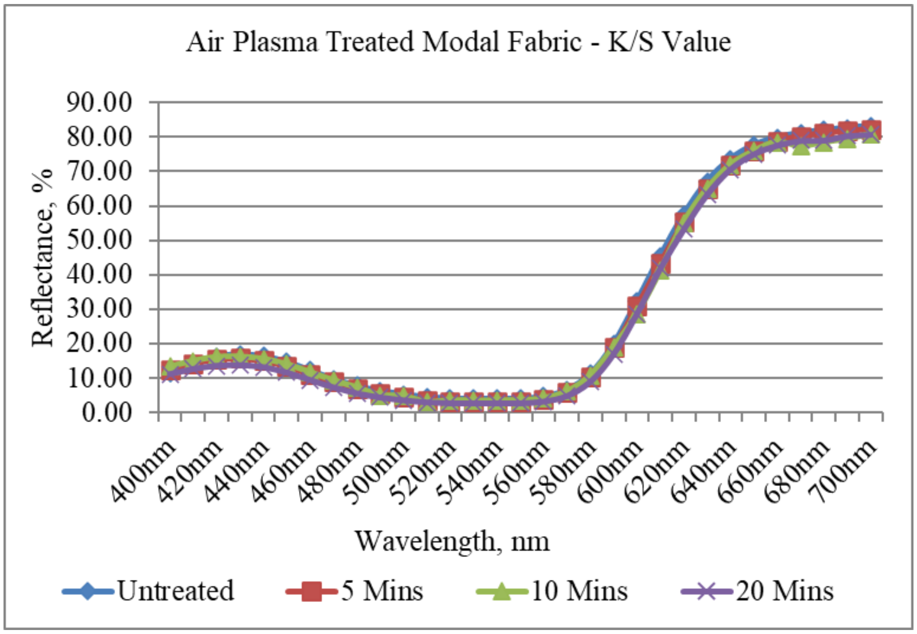

Figure 5 : K/S of air plasma treated modal fabric

The study shows that air plasma treatment significantly enhances the dyeability of knitted modal fabrics, with clear differences observed across treatment durations. The untreated fabric recorded the lowest dye exhaustion (87.89%), reflecting limited surface activity and weaker dye–fibre interaction. A 5-minute plasma treatment resulted in the highest dye exhaustion (93.72%), indicating optimal surface activation through the introduction of polar functional groups that improve wettability and bonding with dye molecules. At 10 minutes, dye exhaustion remained high (93.27%) but showed a slight decline, suggesting that surface activation begins to plateau. Prolonged exposure for 20 minutes led to a further reduction in exhaustion (90.58%), likely due to over-etching or excessive surface modification that reduces effective dye-binding sites.

Overall, the results indicate that shorter plasma treatment durations (5–10 minutes) are most effective for improving dye uptake while maintaining fabric integrity. From a sustainability perspective, higher dye exhaustion reduces residual dye in the bath, lowering water usage, chemical discharge, and effluent load. Thus, a 5-minute air plasma treatment offers an efficient and environmentally responsible approach to enhancing dyeability in modal fabrics without relying on chemical pre-treatments.

Table: 2: Calourimetric values of plasma treated modal fabric

Samples	**L***	**a***	**b***	**c***	**h**
Untreated Modal	45.88	57.90	3.62	58.11	3.57
5 min air	49.51	59.25	3.67	59.47	3.54
10 min air	43.85	58.55	3.87	58.63	3.00
20 min air	41.85	53.35	5.74	60.21	5.46

Air plasma treatment caused notable shifts in the colourimetric properties of single jersey modal knitted fabrics. Lightness (L*) increased at 5 minutes, indicating smoother surface activation and improved dye diffusion, but decreased at 10–20 minutes due to plasma-induced roughening that deepened the colour and slightly reduced uniformity. The a* values remained positive across all samples, confirming a consistent reddish hue, while the gradual increase in b* with longer treatment reflected the development of a mild yellow undertone; at 20 minutes, the combination of lower a* and higher b* indicated a shift toward an orange-tinted shade, likely due to chromophore changes or fibre oxidation. Chroma (c*) increased progressively, with the highest value at 20 minutes, suggesting enhanced colour vividness resulting from intensified surface activation. The hue angle (h) remained within 3–5°, placing all samples firmly in the red region, though the slight rise at 20 minutes supported the observed shift toward an orange hue. Overall, shorter plasma treatments enhanced brightness and maintained the intended red tone, whereas prolonged exposure darkened the fabric and altered its hue, attributable to oxidation and morphological modifications affecting light reflection and dye–fiber interaction.

Table 3: Sample-Wise Interpretation of air plasma treated modal fabric

Sample	Interpretation
Untreated Modal	Moderate lightness and high redness (a*). The untreated modal shows slightly dull red tone with low yellowness (b* = 3.62), indicating baseline dye uptake with limited colour intensity.
5 min Air Plasma	Increase in L* shows lighter shade, suggesting better dye diffusion and surface activation. a* and c* slightly increase, indicating improved red intensity and chroma due to enhanced dye-fiber interaction from plasma etching. Slight rise in b* (3.67) shows negligible yellow shift.
10 min Air Plasma	Decrease in L* shows deeper coloration (darker tone). Redness (a*) remains high, while b* increases marginally, leading to a warmer red hue. Optimum plasma exposure enhances surface energy and dye bonding, resulting in richer colour depth and higher colour yield.
20 min Air Plasma	Significant reduction in L* indicates darker tone. However, the a* value drops (less red) while b* increases (more yellow). High c* suggests high saturation but hue angle increase (5.46) implies a shift towards orange-yellow hue—possibly due to overexposure or surface degradation affecting uniform dye fixation.

Air plasma treatment demonstrates a noticeable impact on the colour fastness properties of modal knitted fabrics under various conditions, including washing, rubbing, perspiration, and light exposure. The observations across untreated and plasma-treated fabrics (5, 10, and 20 minutes) are summarized below: Washing Fastness: The washing fastness results, assessed for both colour change and colour staining, indicate that plasma treatment enhances or maintains excellent fastness ratings.

Colour Change: Untreated modal fabric exhibited a washing fastness rating of 4 (good). Plasma-treated fabrics at all durations (5, 10, and 20 minutes) improved slightly to 4-5, reflecting very good stability.

Table 4: Washing fastness of plasma treated modal

Modal Samples	WASHING FASTNESS						
	COLOUR CHANGE	COLOUR STAINING					
		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
Untreated	4	4-5	4	4-5	4-5	4-5	4-5
5 min air	4-5	4-5	4-5	4-5	4-5	4-5	4-5
10 min air	4-5	4-5	4-5	4-5	4-5	4-5	4-5
20 min air	4-5	4-5	4-5	4-5	4-5	4-5	4-5

Colour Staining: Across all substrates (acetate, cotton, nylon, polyester, acrylic, wool), untreated and treated fabrics showed consistent staining ratings of 4-5, indicating minimal transfer of dye.

Rubbing and Light Fastness: The plasma treatment also influences dry and wet rubbing fastness, as well as light fastness properties.
Rubbing Fastness (Dry and Wet): Untreated fabrics had a dry rubbing fastness of 4-5 (very good) and wet rubbing fastness of 3-4 (good). Plasma treatment improved wet rubbing fastness to 4, indicating reduced dye transfer during wet conditions. Dry rubbing fastness remained consistently excellent at 4-5.

Table 5: Rubbing and light fastness of air plasma treated modal fabrics

Samples	RUBBING		LIGHT
	Modal		
	COLOUR STAINING		COLOUR CHANGE
	Dry	Wet	
Untreated	4-5	3-4	4
5 min air	4-5	4	4
10 min air	4-5	4	4
20 min air	4-5	4	4

Light Fastness: Light fastness, rated at 4 (good) for untreated modal fabrics, remained unchanged for plasma-treated fabrics regardless of the treatment duration. This indicates that plasma exposure does not degrade the fabric's resistance to light-induced fading.

Perspiration Fastness (Acidic and Alkaline): Plasma-treated fabrics showed consistent ratings under acidic and alkaline perspiration conditions for both colour change and colour staining.

Acidic Perspiration: Untreated fabrics exhibited good fastness with colour change ratings of 4-5 and staining ratings ranging from 3-4 to 4-5 across all tested substrates. Plasma-treated fabrics (5, 10, and 20 minutes) maintained these high ratings, indicating no adverse effects of treatment.

Alkaline Perspiration: Untreated fabrics had a slightly lower staining rating of 3 (moderate) on nylon, with other substrates showing excellent fastness (4-5). Plasma-treated fabrics showed improvement, achieving consistent staining ratings of 4-5 across all substrates, even on nylon, after all treatment durations.

Plasma-treated fabrics demonstrated improved colour change and maintained excellent resistance to staining on various substrates, signifying enhanced washing durability. Air plasma treatment improved wet rubbing fastness, with dry rubbing fastness remaining stable and excellent. The light fastness of modal fabrics was unaffected by plasma treatment, maintaining good resistance to fading. Plasma treatment enhanced alkaline perspiration fastness on nylon, while maintaining high fastness ratings for all other substrates under acidic and alkaline conditions.

Table 6: Perspiration fastness of air plasma treated modal fabrics

Modal Samples	COLOUR CHANGE	ACIDIC PERSPIRATION					
		COLOUR STAINING					
		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
Untreated	4-5	4-5	3-4	4-5	4-5	4-5	4-5
5 min air	4-5	4-5	3-4	4-5	4-5	4-5	4-5
10 min air	4-5	4-5	3-4	4-5	4-5	4-5	4-5
20 min air	4-5	4-5	3-4	4-5	4-5	4-5	4-5
		ALKALINE PERSPIRATION					
Untreated	4-5	4-5	3	4-5	4-5	4-5	4-5
5 min air	4-5	4-5	4-5	4-5	4-5	4-5	4-5
10 min air	4-5	4-5	4-5	4-5	4-5	4-5	4-5
20 min air	4-5	4-5	4-5	4-5	4-5	4-5	4-5

IV. CONCLUSION

Air plasma treatment effectively modifies the geometrical properties of 100% modal knitted fabrics by altering their stitch structure, surface characteristics, and compactness. These changes depend on the treatment duration, with more pronounced effects at longer exposure times. This process can be beneficial for enhancing specific fabric properties like surface activation for dyeing or functional finishes, while also making the fabric lighter and potentially more flexible.

Air plasma treatment significantly improves dyeability by enhancing the surface properties of 100% modal knitted fabrics, primarily through the introduction of reactive functional groups (e.g., carbonyl, carboxyl, and hydroxyl) that strengthen the bonding between dye molecules and fibers. The optimal treatment duration is 5 minutes, achieving the highest dye exhaustion (93.72%), while longer exposures (10–20 minutes) show diminishing returns, possibly due to fiber surface degradation or saturation of functional groups. Overall, air plasma treatment is a sustainable, efficient alternative to chemical pre-treatments, with shorter durations (5–10 minutes) being most effective for improving dye uptake while maintaining fabric integrity. Additionally, the increased dye exhaustion reduces residual dye in the bath, minimizing water and chemical waste, thus offering an environmentally friendly enhancement to dyeing processes.

Table: 7: Overall Interpretation of air plasma treated modal fabrics

Observation	Air Plasma Treatment Impact on modal fabric
Improved Dyeability	Up to 10 min treatment enhances surface hydrophobicity and dye uptake, producing deeper shades.
Optimum Exposure Time	10 min found optimal—balance between lightness and chroma without undesirable hue shift.
Overexposure Effects	20 min leads to surface degradation, red tone loss, and hue shift toward yellow-orange.
Sustainability Advantage	Plasma activation improves colour yield without chemical mordents or high water use, supporting cleaner production goals.

L*, a*, b*, c*, and h values effectively describe the colour quality and surface interaction changes caused by plasma treatment. The major findings was that optimum plasma duration (≈10 min) results in maximum colour depth and vibrancy for modal fabrics. Excessive treatment (20 min), though increasing chroma, induces colour shift and potential fiber damage. The CIELAB analysis thus confirms plasma treatment as a sustainable, waterless method enhancing dyeability and surface functionality in advanced cellulosic fabrics.

Air plasma treatment positively influences the colour fastness properties of modal knitted fabrics, particularly by improving wet rubbing and alkaline perspiration fastness while maintaining high performance in washing and light fastness. The findings suggest that plasma treatment is a viable approach for enhancing the functional durability of modal fabrics without compromising their visual integrity.

The integration of multidisciplinary strategies for sustainability and achieving SDGs with advanced technological solutions like plasma treatment creates a robust framework for the sustainable development of future cities. Plasma treatment on advanced cellulosic fabrics, especially air plasma treatment on modal fabrics, exemplifies the potential of innovative technologies in promoting circular economies and reducing ecological footprints. By addressing environmental challenges through holistic research and actionable policies, this integrated approach fosters urban resilience and enhances quality of life. Future cities can achieve ecological balance and socioeconomic growth by adopting these forward-thinking strategies and technologies.
Incorporating multidisciplinary strategies to address water management challenges is critical to achieving the SDGs. By integrating technological innovations, community-based initiatives, and policy reforms, societies can mitigate water scarcity's adverse effects on economic, social, and environmental systems. Such approaches emphasize the interconnected nature of sustainability, ensuring that progress in one domain supports advancements in others.

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