

Enhancement of Transfer Printability of Polyester and Polyester/Cotton Fabrics via Clove Oil-Based Surface Modification

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ABSTRACT: This study examines the role of clove oil as a bio-based surface modification agent in improving the transfer printability of polyester (PET) and polyester/cotton blended fabrics. An oil-in-ethanol/water emulsion containing clove oil, predominantly composed of eugenol, was applied to the fabric substrates prior to sublimation transfer printing. The treatment is hypothesized to modify fibre surface characteristics and influence dye-fibre interactions during thermo-fixation, thereby affecting dye diffusion, sorption, and fixation behavior. The impact of clove oil concentration and fabric composition on printing performance was systematically evaluated through measurements of color strength (K/S), wettability, and color fastness to washing, rubbing and light. The results reveal that the treated fabrics exhibit enhanced dye uptake, which can be attributed to increased interfacial affinity between disperse dye molecules and the modified fibre surface, as well as improved dye mobility under thermal conditions. In polyester/cotton blends, the treatment promotes more uniform color distribution, likely due to partial modulation of the hydrophilic-hydrophobic contrast between fibre components. Furthermore, clove oil treatment induces measurable changes in wettability. Enhanced color fastness properties indicate better dye fixation and reduced surface dye migration. Overall, the findings demonstrate that clove oil-based surface modification provides a sustainable strategy for optimizing sublimation transfer printing performance.

KEYWORDS - Clove oil, Color fastness, Polyester fabrics, Polyester/Cotton blends, Surface modification, Sustainable textile processing, Transfer printing, Wettability.

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I. INTRODUCTION

The continuous evolution of the textile industry is increasingly driven by the demand for high-performance materials that combine aesthetic quality with enhanced functional characteristics. In parallel, environmental considerations have imposed strict constraints on conventional wet processing techniques, encouraging the development of sustainable coloration and finishing technologies with reduced water, chemical, and energy consumption [1, 2]. Within this context, dry processing methods, particularly sublimation transfer printing, have attracted significant attention as environmentally responsible alternatives to traditional dyeing and printing processes.

Sublimation transfer printing is a thermally driven coloration technique in which disperse dyes are transferred from a printed carrier substrate onto textile materials through a vapor-phase mechanism. Under elevated temperature conditions, dye molecules sublime, diffuse into the fibre structure, and become physically entrapped within the polymer matrix. This process eliminates the need for aqueous media and extensive post-treatment steps, resulting in reduced effluent generation and improved process efficiency [3, 4]. Additionally, the technique enables the production of high-resolution patterns with good reproducibility and satisfactory color fastness properties [5, 6].

Despite these advantages, the applicability of sublimation transfer printing is largely restricted to hydrophobic synthetic fibres, particularly polyester (polyethylene terephthalate, PET), due to the favourable interaction between disperse dyes and non-ionic polymer chains. In contrast, cellulosic fibres such as cotton exhibit low affinity toward disperse dyes because of their polar structure and limited dye solubility within the fibre matrix. This disparity becomes more pronounced in polyester/cotton blended fabrics, where differential dye uptake between fibre components leads to poor colour uniformity, reduced colour strength, and suboptimal print definition [6]. Given the widespread use of such blends in textile applications, overcoming this limitation remains a significant challenge.

One promising strategy to address this issue involves surface modification of textile substrates to regulate interfacial interactions during the transfer printing process. Modifying the fibre surface can influence key parameters such as surface energy, wettability, and dye sorption behaviour, which in turn affect dye transfer efficiency, diffusion kinetics, and fixation during thermo-fixation. Altering the balance between hydrophilic and hydrophobic characteristics in blended systems may improve dye distribution and enhance overall print performance.

In recent years, increasing attention has been directed toward the use of bio-based and environmentally benign materials for textile surface modification. Natural essential oils have emerged as attractive candidates due to their complex chemical composition and functional properties. These oils typically contain phenolic and aromatic compounds capable of interacting with textile substrates and modifying their surface characteristics without the environmental drawbacks associated with synthetic finishing agents [7–10]. Among these materials, clove oil—derived from the dried flower buds of *Syzygium aromaticum*—is of particular interest due to its high content of eugenol, a phenolic compound with amphiphilic characteristics. The presence of both hydrophobic aromatic rings and polar functional groups enables eugenol to interact with different fibre types, potentially acting as an interfacial mediator in blended textile systems. Such interactions may contribute to improved dye affinity, enhanced molecular mobility of disperse dyes during sublimation, and more uniform dye distribution across heterogeneous fibre structures [11–21].

Based on these considerations, the present study investigates the application of clove oil as a bio-based surface modification agent to enhance the transfer printability of polyester and polyester/cotton blended fabrics. Emphasis is placed on understanding its effect on color strength, print uniformity, wettability, and color fastness properties. By correlating surface modification with dye–fibre interaction mechanisms during thermo-fixation, this work aims to provide insight into the role of natural additives in optimizing sublimation transfer printing, particularly for blended textile systems where conventional approaches remain limited.

II. Experimental

2.1 Materials

Fabric

Polyester (PET) fabric and polyester/cotton (PET/CO) blended fabric were used as the textile substrates in this study. Polyester fabrics 100% (150 g/m²) produced by Misr Rayon and Polyester Fiber Company- Kafr El-Dawar, Egypt was used throughout the present work. Polyester/cotton blend fabrics (35/65%) (120 g/m²) produced by Misr Spinning, Weaving and Beida Dyers Company -Kafr El-Dawar, Egypt was also used.

Chemicals

Chemicals and reagents of pure grade were used in this study. All chemicals were used without further purification. These can be categorized as:

- Clove oil is extracted from the clove plant manufactured by (Harraz for Food Industry and Natural Products-Egypt). Clove oil was selected as an active treatment agent.
- Ethyl alcohol 95% was manufactured by (Egyptian Starch & Glucose Company). Ethanol served as the solvent for preparing treatment solutions.
- Non-ionic detergent was purchased from (Egptol PLM). Cairo, Egypt.
- Disperse inks code Sb411 (cyan, magenta, yellow and black) were supplied by (Thebes International-Egypt), manufactured by (Mimaki Engineering Co., LTD-Japan).

Key Ingredients and Composition:

- Water: 55-65% (Main solvent)
- 1,2-Propylene glycol (CAS 57-55-6): 10-20% (Humectant/solvent)
- Glycerin (CAS 56-81-5): 5-15% (Humectant/moisturizing agent)
- Disperse Dyes: 1-10% (Colorants, trade secret)
- 1,2-benzisothiazol-3(2H)-one: <0.5% (Biocide/preservative)
- Other chemicals: <10% (trade secret)

2.2 Treatments and Methods

2.2.1 Preparation of Clove Oil Treatment Solutions

Oil solutions were prepared by dissolving the clove oil in ethanol/ water mixture (50:50) to obtain concentrations of 5%, 10%, and 15% (v/v). To improve dispersion and ensure the formation of a homogeneous mixture, each solution was subjected to ultrasonic agitation. Sonication was carried out for different time intervals, namely 1, 5, 7, and 10 minutes. This step facilitated the uniform distribution of clove oil within the solvent and enhanced the stability of the prepared solutions prior to fabric treatment.

2.2.2 Fabric Treatment Procedure

The PET and PET/CO fabric samples were cut into appropriate dimensions prior to treatment. Fabric samples (polyester [PET] and polyester/cotton [PET/CO]) were subjected to various treatment methods to evaluate the effectiveness of oil application. Clove oil solutions were prepared in ethanol/ water (50:50). Fabric specimens were immersed in the oil solution for 30 minutes, then padded to achieve approximately 100% wet pickup and dried to remove excess solvent. The treated samples were subsequently cured using two methods. After curing, all samples were subjected to heat transfer printing at 160- 205 °C for 5-30 seconds.

2.2.3 Curing Methods

To fix the clove oil treatment onto the fabric surface, two different curing techniques were investigated.

Thermal Curing (Thermo-fixation): In this method, the treated fabric samples were placed in a laboratory oven and heated at 105 °C for 30 minutes. This process promoted the fixation of the treatment onto the fibers through thermal activation.

Microwave Curing: Alternatively, microwave irradiation was used as a rapid curing technique. The treated samples were exposed to microwave energy for different durations of 30, 45, and 60 seconds. Microwave curing was employed to evaluate its effectiveness in reducing processing time while maintaining adequate fixation of the treatment.

Heat Transfer Printing

After the curing step, all treated fabric samples were subjected to heat transfer printing using Mimaki sublimation printing machine (model no. TS330-1800) with two colour shades:

- Hue values of colour no.1 (orange): cyan 0% - magenta 87% - yellow 91% - black 1%.
- Hue values of colour no.2 (red): cyan 28% - magenta 99% - yellow 95% - black 30%.

Heat transfer printing was carried out using a heat press at a temperature of 160-205 °C. The printing process was performed for 5-30 seconds under controlled pressure conditions to ensure proper transfer of the design onto the fabric surface.

2.3 Analysis and Measurements

2.3.1 Wettability

The wettability of the fabric samples was evaluated by measuring the wetting time according to the AATCC Test Method 39 [14]. In this procedure, a distilled water droplet was allowed to fall from a fixed height onto the surface of the tested fabric. The time required for the droplet to completely penetrate or disappear from the fabric surface was recorded as the wetting time. For each sample, five measurements were performed, and the reported value represents the average of these readings.

2.3.2 Color Assessment (K/S)

The color strength of the printed samples was evaluated using a spectrophotometric method. Reflectance measurements were carried out using a Hunter Lab Ultra Scan PRO spectrophotometer. The color strength values (K/S) were calculated using a Data Color SF600 Plus colorimeter, which determines the optical properties of the printed fabrics based on the Kubelka–Munk theory.

2.3.3 Fastness Properties

2.3.3.1 Color Fastness to Washing

Color fastness to washing was evaluated according to the AATCC Test Method 36–1972 [22]. Printed fabric specimens measuring 5 × 10 cm were stitched between two pieces of bleached cotton and wool fabrics to form a composite specimen. The prepared specimen was immersed in an aqueous washing solution containing 5 g/L soap and 2 g/L sodium carbonate, with a liquor ratio of 50:1. The washing bath temperature was maintained at 45 °C using a thermostatically controlled system, and the test was conducted for 30 minutes. After completion of the washing process, the samples were thoroughly rinsed with water while gently squeezing by hand to remove excess solutions, followed by drying at room temperature. The degree of color change was assessed using the Gray Scale for color change.

2.3.3.2 Color Fastness to Rubbing

Color fastness to rubbing was determined according to AATCC Test Method 8–1977 [22]. This test measures the extent to which color may be transferred from the surface of a dyed or printed fabric to another surface through rubbing action. In this method, the test specimen was securely fixed on the base of a crock-meter and rubbed against a standard white crocking cloth under controlled conditions.

Dry Rubbing Test: The test specimen was placed flat on the crock-meter base, and a standard dry white test cloth was mounted on the rubbing finger. The rubbing finger was lowered onto the specimen and moved back and forth across the surface for 20 rubbing cycles, achieved by performing ten complete turns at a speed of one turn per second. After completion of the test, the white test cloth was removed and evaluated for staining using the Gray Scale.

Wet Rubbing Test: For the wet rubbing test, the white crocking cloth was first wetted with distilled water to achieve approximately 65% wet pickup. The same rubbing procedure described for the dry test was then applied. After the test, the wet cloth was air-dried prior to assessment using the Gray Scale for staining.

2.3.3.3 Color Fastness to Perspiration

Color fastness to perspiration was assessed using both acidic and alkaline artificial perspiration solutions.

Acidic Perspiration Solution: The acidic solution was prepared by dissolving 0.5 g L-histidine monohydrochloride monohydrate, 5.0 g sodium chloride, and 2.2 g sodium dihydrogen orthophosphate in one liter of distilled water. The pH was adjusted to 5.5 using 0.1 N sodium hydroxide solution.

Alkaline Perspiration Solution: The alkaline solution was prepared by dissolving 0.5 g L-histidine monohydrochloride monohydrate, 5.0 g sodium chloride, and 2.5 g disodium hydrogen orthophosphate in one liter of distilled water. The pH was then adjusted to 8 using 0.2 N sodium hydroxide solution. For the test, a colored specimen measuring 5 × 4 cm was sewn between two undyed fabric pieces to form a composite specimen, ensuring that a portion of the colored sample (approximately 5 × 1 cm) remained exposed. The composite specimen was immersed in the prepared perspiration solution for 15–30 minutes with occasional agitation to ensure complete wetting. After immersion, the specimen was placed between two glass plates under a load of approximately 4.5 kg. The assembly was then positioned vertically in an oven maintained at 37 °C for 4 hours [22]. Following treatment, the degree of color change was evaluated using the Gray Scale.

2.3.3.4 Light Fastness

Color fastness to light was determined according to AATCC Test Method 16A–1989 [22]. The evaluation was performed using the Blue Wool Scale as the reference standard for assessing color change. Light exposure was carried out using a Fade-meter 18-F equipped with a UV lamp. The specimens were exposed to light for a duration of 35 hours, after which the color change was assessed in comparison with the Blue Scale standards.

III. Result and Discussions

The results of untreated and treated fabrics were evaluated by measuring the wettability, colour strength, and fastness properties [24–68].

3.1 Wettability

The wettability behavior of polyester and cotton/polyester blended fabrics treated with clove oil under microwave irradiation was evaluated through wetting time measurements, as summarized in Tables (1 and 2). The results demonstrate that both microwave exposure time and curing methods significantly influence the surface hydrophobicity of the treated fabrics.

Table 1: Influence of microwave irradiation time on the wettability of polyester and cotton/polyester blend fabrics treated with clove oil

Time of Exposure (sec)	Wetting Time (sec)	
	Polyester	Cotton/Polyester
0	5.0	12.5
30	15	17.0
45	7.4	13.0
60	6.2	11.6

Treatment conditions: clove oil concentration 15% (owf), pickup 100%, microwave power 100%

Table 1 shows that microwave exposure produced a non-linear change in the wetting behavior of both fabric types. In the case of polyester, the wetting time increased from 5.0 s for the untreated fabric to 15.0 s after 30 s of microwave irradiation, indicating an initial enhancement in hydrophobicity. However, with prolonged exposure, the wetting time gradually decreased to 7.4 s at 45 s and 6.2 s at 60 s. This trend suggests that short microwave treatment promotes the fixation of clove oil components onto the polyester surface, whereas excessive irradiation may partially destabilize the deposited layer [27–34].

A more pronounced effect was observed in the cotton/polyester blend. The wetting time increased dramatically from 12.5 s in the untreated sample to 17.0 s after 30 s of microwave treatment. Although the wetting time decreased slightly with further irradiation (13.0 s at 45 s and 11.6 s at 60 s), the treated samples remained considerably more hydrophobic than the untreated fabric. This substantial increase indicates that microwave irradiation plays a critical role in facilitating the interaction between clove oil constituents and the textile substrate [27-34].

Enhanced hydrophobicity can be attributed to the chemical composition of clove oil, which is rich in eugenol and other phenolic compounds possessing hydrophobic aromatic structures. These molecules can adsorb onto the fiber surface and form a low-surface-energy coating that reduces water affinity. Microwave irradiation generates rapid dielectric heating within the textile material, increasing molecular mobility and promoting stronger physical adsorption or partial chemical interaction between the oil molecules and the fiber surface [33-40].

The significantly higher wetting time observed for the cotton/polyester blend compared with pure polyester can be explained by the structural characteristics of the fibers. Cotton fibers possess a highly porous morphology and contain abundant hydroxyl groups, which enable greater absorption and retention of the finishing agent. During microwave irradiation, the absorbed oil can become effectively entrapped within the cotton microstructure, leading to the formation of a more stable hydrophobic layer. In contrast, polyester fibers have a relatively smooth and compact surface, which limits the amount of finishing agent that can be retained. The gradual reduction in wetting time observed at longer microwave exposure times may be related to partial degradation or redistribution of the finishing layer. Excessive microwave irradiation can produce localized overheating, which may cause partial desorption of the oil molecules or slight modification of the fiber surface morphology. Such effects can increase the surface free energy of the material and consequently improve water spreading [38, 40].

The results presented in Table 2 demonstrate the influence of clove oil concentration and curing technique on the wettability behavior of polyester and polyester/cotton blend fabrics. Wettability was evaluated through the measurement of wetting time, where higher values indicate a reduction in surface hydrophilicity and improved water repellency resulting from the hydrophobic characteristics of the applied finish.

Table 2: Effect of clove oil concentration and curing technique on wetting time of polyester and polyester/cotton blend fabrics

Type of Sample	Concentration of Clove Oil (g/100g fibre)	Wetting Time (s)	
		Thermal	Microwave
Polyester / Cotton Blend	0	12.5	12.5
	5	30	7
	10	35	11
	12	35	13
	15	43	17
Polyester	0	5.0	5.0
	5	6.5	5.5
	10	11	11
	12	15	13
	15	25.5	15.0

Treatment conditions: 100% pickup, 7 min sonication, Thermal curing: 105 °C in a hot-air oven, 30 min., Microwave curing: 30 s, 100% microwave power.

For the polyester/cotton blend fabric, the untreated sample exhibited an identical wetting time of 12.5 s under both curing conditions, reflecting the inherent wettability of the untreated fabric. Upon application of 5 g/100 g fiber of clove oil, a pronounced difference between curing methods was observed. Thermal curing resulted in a substantial increase in wetting time to 30 s, indicating a significant reduction in wettability due to the formation of a hydrophobic coating on the fiber surface. In contrast, microwave curing produced a markedly lower wetting time of 7 s, suggesting a different interaction mechanism between the finishing agent and the fiber matrix. As the concentration of clove oil increased from 10 to 15 g/100 g fiber, the wetting time under thermal curing gradually increased from 35 s to 43 s, indicating progressive enhancement of hydrophobicity because of higher finish loading. Under microwave curing, the wetting time also increased with concentration, although the values remained significantly lower, rising from 11 s to 17 s within the same concentration range.

The differences between curing techniques can be attributed to their distinct heat transfer mechanisms. Conventional thermal curing relies primarily on conductive heat transfer from the external environment toward the fabric surface, which tends to promote the migration and accumulation of finishing agents on the outer fiber layers. This surface enrichment facilitates the formation of a more continuous hydrophobic film, thereby increasing wetting time. Microwave irradiation induces volumetric heating, where electromagnetic

energy is absorbed directly by polar molecules within the material. This process enhances internal heating and may facilitate deeper penetration of clove oil molecules into the fiber structure rather than concentrating them on the surface. Consequently, microwave-treated samples may exhibit a more homogeneous distribution of the finishing agent with a comparatively thinner surface layer, which explains the lower wetting times observed relative to thermally cured fabrics [27-34].

A similar behavior was observed for polyester fabrics, although the magnitude of the change was less pronounced. The untreated polyester sample exhibited a wetting time of 5.0 s under both curing methods. Following treatment, the wetting time increased progressively with increasing clove oil concentration. Under thermal curing, the wetting time increased from 6.5 s at 5 g/100 g fiber to 25.5 s at 15 g/100 g fiber, reflecting a significant reduction in wettability due to the deposition of hydrophobic compounds on the polyester surface. Microwave curing again resulted in lower wetting times, increasing from 5.5 s to 15.0 s across the same concentration range. These findings further confirm that thermal curing promotes greater surface accumulation of clove oil compared with microwave processing.

Comparatively, the polyester/cotton blend exhibited higher wetting times than pure polyester after treatment, particularly under thermal curing conditions. This difference can be attributed to the structural and chemical characteristics of the blend. Cotton fibers possess a higher moisture regain and contain abundant hydroxyl groups, which increase their affinity for finishing agents and enhance the retention of clove oil within the fabric structure. In addition, the presence of cotton introduces greater internal porosity and surface area, enabling higher loading of the hydrophobic finish and consequently leading to a greater reduction in wettability.

From a physicochemical perspective, the increase in wetting time observed after treatment reflects a decrease in the surface free energy of the fabrics. Clove oil contains hydrophobic aromatic and aliphatic components that can orient toward the air-fabric interface, partially shielding the polar functional groups present in cotton and polyester fibers. This modification reduces the ability of water to spread and penetrate the fabric structure, thereby increasing wetting time and enhancing water-repellent behavior.

Overall, the results indicate a clear concentration-dependent relationship between clove oil loading and wettability performance. While thermal curing produced higher wetting times and therefore stronger hydrophobic effects, microwave curing still imparted measurable water repellency while offering advantages such as significantly shorter processing time and potentially lower energy consumption. These characteristics highlight the potential of microwave-assisted finishing as a sustainable alternative to conventional textile curing processes, particularly when combined with natural bio-based finishing agents such as clove oil [41-47].

3.2 Colour Strength (K/S)

The primary objective of this research was to investigate the potential of clove oil, a natural and eco-friendly product, as a treatment agent for the transfer printing of polyester (PET) and polyester/cotton blend fabrics using disperse dyes. The study systematically evaluated the effects of various treatment parameters, including clove oil concentration, sonication time, fixation method (thermal vs. microwave), and printing conditions, on the resulting color strength (K/S) of the printed fabrics. The results, presented in Tables (3 – 10), demonstrate that clove oil treatment can significantly enhance the dye uptake and color strength, offering a more sustainable alternative to conventional synthetic carriers.

3.2.1 Effect of Clove Oil Concentration on Printability of PET

The data in Table 3 clearly indicates that the presence of clove oil substantially improves the color strength of transfer-printed PET fabric. For the control sample (0 g clove oil/100g fiber), a K/S value of 20.2 was obtained, which is attributed to the standard transfer printing mechanism where dye sublimates and diffuses into the fiber surface at high temperature (205°C). Upon treatment with clove oil, a notable increase in K/S was observed, even without a separate oven fixation step. For instance, at a 5 g/100g fiber concentration and 5 minutes of sonication, the K/S increased to 22.32. This initial enhancement can be explained by the carrier action of clove oil. The phenolic compounds in clove oil (primarily eugenol) act as a swelling agent for the polyester fibers [48-50]. A noticeable enhancement in colour strength was observed, particularly when the ethanolic-aqueous dispersion was sonicated for 5 minutes, where K/S increased to approximately 26.4. This represents a substantial improvement compared to the untreated fabric. This enhancement can be attributed to:

- Partial diffusion of clove oil (mainly eugenol) into the amorphous regions of polyester during curing at 105°C.
- Mild plasticization effect, leading to increased chain mobility.
- Temporary reduction in glass transition temperature (T_g).
- Increased free volume facilitating disperse dye vapor diffusion during transfer printing at 205°C.

Table 3: Effect of concentration of clove oil on the colour strength of transfer printed PET fabric with orange disperse dye in relation to sonication time intervals

Concentration Of Clove Oil (g/100g fiber)	Sonication Time (min)	Colour Strength (K/S)	
		Thermal Fixation	Without Fixation
0	0	20.2	20.2
5	1	22.4	20.3
	5	26.4	22.32
10	1	23.7	20.7
	5	23.9	20.23
15	1	22.3	20.4
	5	23.54	20.4

Fixation: 105°C, 30 min.

Transfer Printing: 205°C, 30 sec

However, increasing the clove oil concentration to 10 and 15 g/100g fiber did not yield proportional increases in K/S. In fact, at 15 g/100g fiber, the K/S values (22.3 and 23.54 with fixation) were slightly lower than the optimum achieved at 5 g/100g fiber. This slight decline at higher concentrations could be attributed to the formation of a surface layer of excess oil that may hinder uniform dye transfer or even promote the aggregation of dye molecules on the fiber surface, preventing their deep penetration [51].

Table 4: Influence of clove oil concentration and curing technique on the transfer printability and colour strength of PET fabrics printed with red disperse dye

Concentration of Clove Oil (g/100g fibre)	Colour Strength (K/S)		Relative Color Strength %	
	Thermally	Microwave	Thermally	Microwave
0	16.06	16.06	100	100
5	16.83	19.02	104.8	118.4
10	16.08	17.7	100.1	110.2
12	13.8	14.7	85.9	91.5
15	13.5	14.0	84.1	87.2

Treatment: padding 100% pick up at room temp, Sonication 7 min, curing thermally, 105°C, 30 min and microwave, 100% power, 60 sec and transfer Printing 205°C, 30 s.

This trend is further confirmed in Table 4, which explores a wider range of concentrations for a red disperse dye. For the untreated polyester fabric, the colour strength recorded under both curing conditions was identical (K/S = 16.06), corresponding to a relative colour strength of 100%. This value represents the baseline printability of the untreated PET fabric. After treatment with clove oil, noticeable variations in colour strength were observed depending on both the concentration of the finishing agent and the curing method. Here, the optimum color strength was also observed at the lowest concentration tested (5 g/100g fiber). At a concentration of 5 g/100 g fibre, the colour strength increased slightly under thermal curing to 16.83 (104.8%), indicating a moderate improvement in dye fixation. A more pronounced increase was observed for the microwave-cured sample, where the K/S value reached 19.02 (118.4%), representing the highest colour yield among all tested samples. This enhancement suggests that a low concentration of clove oil may modify the fiber surface in a way that facilitates better dye diffusion and fixation during the transfer printing process.

When the concentration of clove oil increased to 10 g/100 g fibre, the colour strength remained nearly unchanged under thermal curing (K/S = 16.08, relative strength 100.1%), indicating that this concentration does not significantly alter the dyeing behavior compared with the untreated fabric. In contrast, microwave curing still produced a noticeable increase in colour yield (K/S = 17.7, relative strength 110.2%). This result suggests that microwave irradiation may promote a more uniform distribution or partial penetration of the finishing agent into the polyester structure, which could enhance dye transfer efficiency.

However, further increases in clove oil concentration resulted in a gradual decrease in colour strength for both curing methods. At 12 g/100 g fibre, the K/S value decreased to 13.8 (85.9%) under thermal curing and 14.7 (91.5%) under microwave curing. A similar trend was observed at 15 g/100 g fibre, where the colour strength decreased further to 13.5 (84.1%) and 14.0 (87.2%) for thermal and microwave curing, respectively. The reduction in colour yield at higher concentrations can be attributed to the formation of a thicker hydrophobic layer on the fiber surface. Such a layer may act as a barrier that restricts dye diffusion from the transfer paper to the polyester substrate during the high-temperature printing stage [25-35].

Comparing the two curing techniques, microwave treatment consistently produced higher K/S values than thermal curing at all clove oil concentrations. This behavior may be associated with the different heating mechanisms involved in microwave processing. Microwave irradiation generates volumetric heating through the interaction of electromagnetic waves with polar molecules, which can enhance molecular mobility and promote a more homogeneous distribution of the finishing agent within the fiber structure. Consequently, dye

molecules may diffuse more effectively into the polyester matrix during transfer printing, resulting in improved colour strength [50-56].

3.2.2 Effect of Clove Oil Concentration on Colour Yield of Transfer-Printed PET/Cotton Blends

The results presented in Tables (5 and 6) illustrate the influence of clove oil concentration, sonication time, and fixation technique on the transfer printability of polyester/cotton blend fabrics using disperse dyes. The untreated polyester/cotton blend exhibited a relatively low colour strength ($K/S \approx 4.44$ – 4.46). This behavior is expected because disperse dyes exhibit strong affinity for hydrophobic polyester fibres but have negligible interaction with cotton fibres due to their non-ionic nature and low water solubility. Consequently, in blended fabrics the effective dyeable fraction is limited to the polyester component, resulting in lower overall colour depth compared with 100% polyester substrates [36-47]. Following treatment with clove oil, a substantial increase in colour strength was observed. For example, at a concentration of 5 g/100 g fibre, the colour strength increased from 4.44 to 5.68 after 1 min sonication and further increased to 6.52 when the sonication time was extended to 5 min under thermal fixation conditions. This improvement suggests that clove oil acts as a carrier or swelling agent that facilitates the diffusion of disperse dye molecules into the polyester phase of the blend.

A more pronounced enhancement was obtained at 10 g/100 g fibre, where the colour strength reached 7.08 after 5 min sonication, representing the highest value recorded in Table 5. The increase in colour yield can be attributed to the plasticizing effect of clove oil on the polyester component. Essential oils contain aromatic and slightly polar constituents that can penetrate the amorphous regions of polyester, increase polymer chain mobility and promote dye diffusion during the transfer printing process. Similar carrier-assisted diffusion mechanisms have been widely reported for disperse dyeing of polyester fibres [3-5]. In blended fabrics, the improvement in colour strength may also be influenced by additional interfacial interactions. While cotton fibres do not chemically bind disperse dyes, the presence of clove oil may lead to partial deposition of oil molecules on the cotton surface. This thin organic layer may temporarily retain a portion of the sublimated dye during transfer printing, thereby contributing to the overall colour yield of the fabric. However, further increasing the oil concentration to 15 g/100 g fibre resulted in a reduction in colour strength ($K/S \approx 5.54$ – 6.13). This decrease can be explained by excessive accumulation of oil on the fibre surface, which may form a hydrophobic barrier that limits the penetration of dye vapour into the polyester structure. Similar behavior has been reported in carrier-assisted dyeing systems, where excessive carrier concentration can inhibit dye diffusion by creating a surface film that restricts mass transfer.

The effect of microwave fixation was also examined for treated samples. As shown in Table 5, microwave exposure times between 30 and 60 s produced moderate colour strength values ranging from $K/S \approx 5.86$ to 6.08 at a clove oil concentration of 15 g/100 g fibre. Although microwave fixation significantly reduces processing time, the increase in colour strength with longer exposure times was relatively limited. This behavior may be related to the dielectric properties of polyester fibres. Polyester exhibits relatively low dielectric loss and therefore absorbs microwave energy less efficiently than more polar fibres such as cotton. As a result, microwave heating mainly affects residual moisture within the fabric rather than inducing substantial structural modification in the polyester phase [32].

The influence of clove oil concentration on colour strength is further confirmed by the results shown in Table 6 for transfer printing with a red disperse dye. The untreated blend again exhibited a low K/S value (≈ 4.46), whereas treatment with 5 g/100 g fibre significantly increased the colour strength to 6.5 and 6.6 under thermal and microwave curing, respectively. This corresponds to a relative colour strength of approximately 146–148% compared with the untreated fabric. Increasing the concentration to 10 g/100 g fibre still produced enhanced colour yield ($K/S \approx 6.03$ – 6.08), although slightly lower than that observed at 5%. At higher concentrations (12–15 g/100 g fibre), a gradual decline in colour strength was observed, confirming the previously discussed barrier effect associated with excessive oil deposition on the fibre surface. Nevertheless, the treated fabrics maintained colour strength values significantly higher than those of the untreated blend, indicating the effectiveness of clove oil as a natural carrier for improving disperse dye transfer onto polyester-containing fabrics.

Table 5: Effect of concentration of clove oil on printability of polyester/cotton blend with orange disperse dye in relation to fixation method and sonication time

Fixation Method	Concentration of Oil (g/100g fibre)	Sonication Time (min)	Colour Strength (K/S)
Thermo-fixation	0	0	4.44
	5	1	5.68
		5	6.52
	10	1	5.76
		5	7.08
	15	1	5.54

		5	6.13
Microwave for: 30s			5.86
45s	15	5	5.98
60s			6.08

Treatment: Padding pick up 100% at room temp, thermal: 105°C, 30 min, Microwave 100% power, Printing: 205°C, 30 s.

Table 6: Influence of clove oil concentration and curing method on colour strength of transfer-printed polyester/cotton blend fabrics using red disperse dye

Concentration of Clove Oil (g/100g fibre)	Colour Strength (K/S)		Relative Colour Strength %	
	Thermally	microwave	Thermally	Microwave
0	4.46	4.46	100%	100%
5	6.5	6.6	145.7	148
10	6.03	6.08	135	136.3
12	5.7	6.0	127.8	134.5
15	5.5	5.63	123.3	126.2

Treatment: padding 100% pick up, room temp, Sonication 7 min, Curing: thermal, 105°C, 30 min, microwave, 100% power, 60 s, Printing 205°C, 30s.

3.2.3 Synergistic Effect of Microwave Fixation

The study investigated microwave irradiation as an alternative, rapid fixation method following the clove oil treatment. The results consistently show that microwave fixation is highly effective and often superior to conventional thermal fixation [30-34].

Table 7: Effect of fixation time exposure to microwave irradiation on transfer printability of PET with orange disperse dye

Microwave Fixation Time (s)	Color Strength (K/S)
0	20.2
30	20.5
45	20.7
60	20.8

Treatment: padding pick up 100%, 15 g/100g fiber, sonication: 5 min, printing, 205°C, 30 s

Table 7 demonstrates a direct correlation between microwave fixation time and color strength on PET. Increasing the fixation time from 0 to 60 seconds resulted in a steady increase in K/S from 20.2 to 20.8. This can be attributed to the volumetric and rapid heating nature of microwaves [52-55]. Microwave energy interacts directly with the polar molecules within the clove oil and the fiber, causing them to oscillate and generate heat from within. This internal heating mechanism leads to faster and more uniform swelling of the polyester, allowing for efficient dye diffusion in a much shorter time compared to the 30 min oven fixation.

The superiority of microwave fixation is clear in Tables (4-6). The blend fabric treated with 5 g/100g fiber of clove oil, microwave fixation produced a higher K/S (6.6) and relative K/S (148%) compared to thermal fixation (6.5 K/S, 145.7%). This pattern is even more pronounced for 100% PET in Table 4, where the K/S values for microwave-fixed samples are consistently higher than their thermally fixed counterparts across all concentrations. For example, at the optimal 5 g/100g fiber concentration, the K/S for microwave fixation was 19.02, significantly higher than the 16.83 achieved with thermal fixation. This confirms that microwave energy not only accelerates the fixation process but also enhances the efficiency of the carrier treatment, leading to a more opened fiber structure and, consequently, greater dye uptake.

3.2.4 Influence of Sonication Time

Sonication time is another critical parameter that influences the effectiveness of clove oil treatment. The data from Tables 8 and 9 reveal a clear trend; color strength increases with sonication time up to an optimal point, after which it decreases.

Table 8: Effect of sonication time of clove oil treatment on the printability of polyester/cotton blend fabrics using thermal and microwave curing techniques

Sonication Time (min)	Colour Strength (K/S)		Relative Colour Strength %	
	Thermal	Microwave	Thermal	Microwave
0	4.46	4.46	100	100
1	5.1	5.6	114.3	125.6
3	5.3	5.8	118.8	130.0
7	6.5	6.6	145.7	148.0
10	4.09	4.14	91.7	92.8

Treatment: padding 100% pick, 5 g/100 g fibre, room temp, Curing: 105°C, 30 min; Microwave, 100% power, 60 s, Printing: 205°C, 30 s.

The effect of sonication time on fibre printability is shown for the blend fabric (Table 8) and PET (Table 9). For the blend (Table 8), color strength progressively increased from 4.46 K/S (control) to a maximum of 6.5 (thermal) and 6.6 (microwave) at 7 minutes of sonication. Similarly, for PET (Table 9), the maximum K/S was achieved at 7 minutes sonication for both fixation methods, with the microwave-fixed sample reaching 19.02 K/S. The improvement is due to the mechanical and cavitation effects of ultrasound [6]. Ultrasound enhances the dispersion of clove oil in the treatment bath and promotes its diffusion into the fiber matrix by disrupting the boundary layer at the fiber-liquid interface. This ensures a more uniform and thorough uptake of the carrier. However, extending the sonication time to 10 minutes in both cases resulted in a significant drop in color strength. This decrease is likely due to over-sonication, which may cause the dispersion of clove oil to become unstable, leading to the re-agglomeration of oil droplets. This would result in an uneven treatment or even the partial desorption of the oil from the fiber surface before the fixation step, ultimately reducing its carrier efficiency [54].

Table 9: Effect of sonication time of clove oil treatment on transfer printability of PET using different curing techniques.

Sonication Time (min)	Colour Strength (K/S)		Relative Colour Strength %	
	Thermal	Microwave	Thermal	Microwave
0	16.06	16.06	100	100
1	16.06	16.09	100	100.2
5	16.08	16.43	100.1	102.3
7	16.83	19.02	104.8	118.4
10	15.43	15.9	96.1	99.0

Treatment: padding 100% pick, 5 g/100 g fibre, room temp, Curing: 105°C, 30 min; Microwave, 100% power, 60 s, Printing: 205°C, 30 s.

3.2.5 Effect of Transfer Printing Temperature and Duration

The results summarized in Table 10 demonstrate the combined influence of transfer printing temperature and printing duration on the colour strength of untreated and clove-oil-treated polyester (PET) and polyester/cotton blend fabrics printed with disperse dye. At the lower printing temperature of 160 °C, both untreated polyester and polyester/cotton blend fabrics exhibited very low colour strength values even after extended printing times. The K/S values of untreated PET increased only slightly from 0.68 at 5 min to 1.74 at 20 min, while the untreated blend showed similarly limited values ranging from 0.62 to 1.18. This behavior is consistent with the thermally activated diffusion mechanism of disperse dyes in polyester fibres. Diffusion of disperse dyes into PET primarily occurs in the amorphous regions of the polymer and becomes significant only when the fibre approaches or exceeds its glass transition temperature ($T_g \approx 80-85$ °C). However, efficient dye penetration generally requires higher temperatures where polymer chain mobility increases sufficiently to allow dye molecules to migrate into the fibre interior [40-44].

Following treatment with clove oil, a clear improvement in colour strength was observed at the same temperature. At 160 °C, treated PET samples exhibited K/S values increasing from 0.96 to 2.71 as printing time increased from 5 to 20 min. Similarly, the treated polyester/cotton blend showed higher colour yield, increasing from 1.07 to 1.81 over the same time interval. This enhancement can be explained by the carrier-like behavior of clove oil components. Essential oils contain relatively small aromatic molecules capable of diffusing into amorphous regions of polyester. These molecules can temporarily reduce intermolecular interactions within the polymer matrix, producing a plasticization effect that increases segmental mobility of polymer chains. Consequently, the free volume within the fibre structure increases, lowering activation energy required for dye diffusion and allowing dye molecules to penetrate the fibre at temperatures below the conventional transfer-printing range [66-68].

The influence of clove oil treatment becomes even more pronounced at the higher printing temperature of 180 °C, which is close to the typical temperature used in industrial transfer printing of polyester fabrics. Under these conditions, untreated PET fabrics showed a gradual increase in colour strength from 2.77 at 5 min to 5.4 at 20 min, reflecting increased dye diffusion with prolonged exposure time. However, the treated PET samples exhibited significantly higher colour yield, with K/S values increasing from 4.15 to 8.88 over the same time interval. This substantial increase indicates that clove oil treatment enhances the accessibility of disperse dye molecules to the internal structure of polyester fibres, allowing more efficient diffusion and fixation during the transfer printing process.

A similar trend was observed for the polyester/cotton blend fabrics, although the overall colour strength remained lower than that of pure polyester. At 180 °C, untreated blend samples exhibited K/S values between 1.34 and 3.23, while treated samples reached values ranging from 1.86 to 3.99. The progressive increase in colour strength with increasing printing time at both temperatures indicates that dye transfer and diffusion are strongly time-dependent processes governed by concentration gradients and molecular mobility, which can be described by Fickian diffusion behavior. Longer exposure times allow more dye molecules to

sublime from the transfer paper and diffuse into the fibre interior, thereby increasing the measured K/S values. When combined with the plasticizing effect of clove oil, this leads to more efficient dye penetration and improved colour yield [45,62-68].

Table 10: Influence of transfer printing temperature and time on colour strength of untreated and clove-oil-treated polyester and its cotton blend fabrics printed with disperse dye

Sample	Temperature (°C)	Colour Strength (K/S)			
		5 min	10 min	15 min	20 min
Untreated PET	160	0.68	0.77	1.08	1.74
Treated PET		0.96	1.39	1.94	2.71
Untreated PET	180	2.77	2.76	4.89	5.40
Treated PET		4.15	4.15	7.36	8.88
Untreated PET/Cotton Blend	160	0.62	0.82	1.17	1.18
Treated PET/Cotton Blend		1.07	1.07	1.36	1.81
Untreated PET/Cotton Blend	180	1.34	1.99	2.75	3.23
Treated PET/Cotton Blend		1.86	2.60	3.83	3.99

Treatment conditions: 5 g /100 g fibre, padding, 100% pickup, thermal curing: 105 °C, 30 min.

3.3 Fastness Properties of Transfer-Printed Polyester and Its Cotton Blend Fabrics

3.3.1 Influence of Clove Oil Concentration on Fastness Performance

The fastness properties of transfer-printed polyester/cotton blend and polyester fabrics treated with clove oil were evaluated in terms of washing, rubbing, perspiration, and light fastness. Clove oil was applied as a natural carrier to enhance the transfer printing of disperse dyes on polyester-containing fabrics. The influence of carrier concentration was investigated under both conventional thermal curing and microwave curing conditions. Although colour strength values are presented in the tables for reference, the following discussion focuses mainly on the durability of the printed colour [53-55].

3.3.1.1. Polyester/Cotton Blend Fabrics

The fastness data presented in Tables 11 and 12 indicate that clove oil treatment generally improves the durability of the printed colour on polyester/cotton blend fabrics. The untreated control samples exhibited moderate fastness ratings, typically within the 3–4 range, which reflects the limited fixation of disperse dyes in the polyester component of the blend. After treatment with clove oil, noticeable improvements in washing, rubbing, and perspiration fastness were observed. The highest overall fastness ratings were generally obtained at 10 g/100 g fibre, where washing staining values reached grade 5, while dry rubbing fastness approached grade 5 under both curing methods. These results suggest that the carrier treatment facilitates more effective diffusion of dye molecules into the polyester phase of the blend [9-20].

Improved dye diffusion leads to a more uniform distribution of dye molecules within the fibre structure. When dye molecules penetrate deeper into the polyester matrix, they become less susceptible to removal during mechanical action or washing processes. In contrast, dyes located mainly on the fibre surface are more easily removed during laundering or rubbing. At higher clove oil concentrations (12–15 g/100 g fibre), a slight decline in fastness ratings was observed. This behaviour may be related to excessive deposition of the carrier on the fibre surface. Residual oil layers can partially interfere with dye fixation or promote limited dye migration during washing or perspiration exposure, which slightly reduces fastness performance [15-20].

Light fastness also showed a clear improvement after carrier treatment. The untreated blend exhibited a rating of approximately grade 4, whereas treated fabrics reached grades 6 and 6–7, particularly at 10 g/100 g fibre. The improvement in light stability can be attributed to deeper dye penetration within the polyester component of the blend. Dye molecules located inside the fibre are less exposed to oxygen and ultraviolet radiation, which reduces the rate of photochemical degradation [56-59].

Table 11: Influence of clove oil concentration on fastness properties of transfer-printed polyester/cotton blend fabrics using thermal curing

Concentration of clove oil (g/100g fibre)	Colour Strength (K/S) Thermal	Washing Fastness		Rubbing Fastness		Perspiration Fastness				Light Fastness
		St.	Alt.	wet	dry	Acidic		Alkaline		
						St.	Alt.	St.	Alt.	
0	4.46	3-4	4	3	3-4	4	3-4	3	3-4	4
5	6.5	4-5	4-5	4	4-5	4-5	4-5	4	4-5	6
10	6.03	5	5	4-5	5	5	4-5	5	5	6-7
12	5.7	4	4-5	4-5	4-5	4	4-5	4-5	5	6
15	5.5	4-5	4-5	4-5	5	4	4-5	4-5	5	5-6

Table 12: Influence of clove oil concentration on fastness properties of transfer-printed polyester/cotton blend fabrics using microwave curing.

Concentration of clove oil (g/100g fibre)	Colour Strength (K/S) Microwave	Washing Fastness		Rubbing Fastness		Perspiration Fastness				Light Fastness
		St.	Alt.	wet	dry	Acidic		Alkaline		
						St.	Alt.	St.	Alt.	
0	4.46	3-4	4	3	3-4	4	3-4	3	3-4	4
5	6.6	5	4-5	4	4-5	4-5	5	4-5	5	6
10	6.08	5	5	5	5	5	5	5	4-5	6-7
12	6.0	4-5	4-5	4-5	5	4-5	4-5	4-5	5	6
15	5.63	4	4-5	4-5	5	5	5	4-5	5	5-6

3.3.1.2. Polyester Fabrics

Similar trends were observed for the 100% polyester fabrics (Tables 13 and 14). The untreated polyester samples already exhibited relatively good fastness properties, with ratings generally around grade 4 for washing, rubbing, and perspiration. After clove oil treatment, the fastness performance improved further, particularly at 5–10 g/100 g fibre concentrations. Washing fastness values increased to grades 4–5 and 5, indicating improved dye fixation within the polyester structure. Rubbing fastness also showed slight improvements under both wet and dry conditions, suggesting that the dye molecules were more effectively embedded within the fibre interior rather than remaining on the surface. Perspiration fastness results under both acidic and alkaline conditions followed a similar pattern. Treated samples generally exhibited ratings between 4–5 and 5, demonstrating enhanced resistance to dye removal under simulated perspiration environments. These improvements can be attributed to the carrier-induced increase in polymer chain mobility during the printing process, which facilitates deeper diffusion of the dye molecules into the polyester matrix.

Table 13: Influence of clove oil concentration on colour strength and fastness properties of transfer-printed polyester fabrics using thermal curing

Concentration of Clove Oil (g/100g fibre)	Colour Strength (K/S) Thermal	Washing Fastness		Rubbing Fastness		Perspiration Fastness				Light Fastness
		St.	Alt.	wet	dry	Acidic		Alkaline		
						St.	Alt.	St.	Alt.	
0	16.06	4	4	3	3-4	4	4	3-4	4	4-5
5	16.83	4-5	4-5	4	4-5	4-5	4-5	4	4-5	6
10	16.08	5	5	4-5	5	5	5	4-5	5	6-7
12	13.8	4-5	4-5	5	5	4-5	4-5	5	5	6-7
15	13.5	5	5	4-5	5	5	5	4-5	4-5	6

Table 14: Influence of clove oil concentration on colour strength and fastness properties of transfer-printed polyester fabrics using microwave curing

Concentration of Clove Oil (g/100g fibre)	Colour Strength (K/S) microwave	Washing Fastness		Rubbing Fastness		Perspiration Fastness				Light Fastness
		St.	Alt.	wet	dry	Acidic		Alkaline		
						St.	Alt.	St.	Alt.	
0	16.06	4	4	3	3-4	4	4	3-4	4	4-5
5	19.02	5	5	4-5	5	4-5	5	4-5	4-5	6-7
10	17.7	4-5	5	4-5	5	5	4-5	5	5	6
12	14.7	4-5	4-5	4	4-5	4-5	5	4-5	4-5	6-7
15	14.0	4-5	4-5	4	4-5	5	5	4-5	5	6

Light fastness values also improved after clove oil treatment. While the untreated polyester showed a rating of approximately 4–5, treated samples reached grades 6–7 at several concentrations under both curing methods. Deeper dye penetration into the fibre interior likely provides greater protection of the dye molecules from ultraviolet radiation, thereby enhancing photostability.

3.3.1.3. Effect of Curing Method

Comparison of thermal and microwave curing methods indicates that both techniques produced similar trends in fastness performance. Microwave curing occasionally resulted in slightly higher colour strength values (Tables 11-14), but the overall fastness ratings remained comparable for the two curing techniques. This suggests that microwave curing can achieve adequate dye fixation while significantly reducing processing time due to rapid volumetric heating.

3.3.2 Influence of Sonication Time on Fastness Performance

3.3.2.1 Polyester/Cotton Blend Fabrics

The influence of sonication time during clove oil treatment on the fastness properties of transfer-printed polyester/cotton blend fabrics is presented in Tables 15 and 16. Sonication is applied to promote the formation of a stable dispersion of clove oil within the treatment bath, thereby improving its interaction with the fibre surface. As sonication time increased from 0 to 7 min, a gradual improvement in several fastness properties was observed for both curing methods [61-68].

Table 15: Effect of sonication time of clove oil treatment on fastness properties of printed cotton/polyester blend using thermal curing

Sonication time (min)	Colour Strength (K/S)	Washing Fastness		Rubbing Fastness		Perspiration Fastness				Light Fastness
		St.	Alt.	wet	dry	Acidic		Alkaline		
						St.	Alt.	St.	Alt.	
0	4.46	3-4	4	3	3-4	4	3-4	3	3-4	4
1	5.1	4-5	4-5	4	4-5	4	4-5	5	4-5	6
3	5.3	5	4-5	4-5	4-5	5	5	4-5	4-5	6-7
7	6.5	4-5	5	4	4-5	4-5	5	4-5	5	6
10	4.09	4-5	4-5	4	5	4	4-5	5	4-5	6-7

The untreated blend exhibited moderate fastness ratings, typically within the 3–4 range for washing and rubbing fastness. After clove oil treatment, washing fastness values improved noticeably, reaching grades 4–5 to 5 at intermediate sonication times. A similar improvement was observed for rubbing fastness under both wet and dry conditions. These results suggest that improved dispersion of clove oil during sonication enhances the penetration of disperse dye molecules into the polyester component of the blend, thereby reducing the amount of loosely bound surface dye that can be removed during mechanical action [60-68].

Table 16: Effect of sonication time of clove oil treatment on fastness properties of printed cotton/polyester blend using microwave curing

Sonication time (min)	Colour Strength (K/S)	Washing Fastness		Rubbing Fastness		Perspiration Fastness				Light Fastness
		St.	Alt.	wet	dry	Acidic		Alkaline		
						St.	Alt.	St.	Alt.	
0	4.46	3-4	4	3	3-4	4	3-4	3	3-4	4
1	5.6	4	4-5	4	4	4	4-5	4-5	4	5-6
3	5.8	4-5	4-5	4-5	4-5	4-5	5	4-5	4	6-7
7	6.6	5	5	5	4-5	5	5	5	5	6
10	4.14	4-5	5	4-5	5	4-5	5	5	4-5	6-7

Perspiration fastness also showed improved resistance under both acidic and alkaline conditions. At moderate sonication times (3–7 min), staining and colour change ratings generally increased to 4–5 or higher, indicating stronger retention of dye molecules within the fibre structure. The improvement in fastness behavior is consistent with more efficient carrier action, which facilitates dye diffusion into the amorphous regions of polyester. Light fastness similarly benefited from the treatment. The untreated blend exhibited a light fastness rating of approximately grade 4, whereas treated samples reached grades 6–7 at several sonication conditions. Improved light stability can be attributed to deeper dye penetration within the polyester phase of the blend, where dye molecules are less exposed to photo-oxidative degradation caused by ultraviolet radiation.

The most consistent fastness performance was observed at approximately 7 min of sonication, where washing, rubbing, and perspiration fastness values were generally highest for both curing techniques. At longer sonication times (10 min), the colour strength decreased substantially, although the fastness ratings remained relatively stable. This behavior suggests that excessive sonication may negatively affect the efficiency of the carrier system, possibly due to partial degradation of clove oil components or destabilization of the dispersion, which limits effective dye uptake while still allowing moderate fixation of the absorbed dye. Overall, the results demonstrate that controlled sonication enhances the effectiveness of clove oil as a carrier, improving dye penetration and consequently the durability of the printed colour on polyester/cotton blend fabrics.

3.3.2.2. Polyester Fabrics

A comparable trend was observed for 100% polyester fabrics, although the overall fastness ratings were generally higher due to the greater affinity of disperse dyes for polyester fibres (Tables 17, 18).

Increasing sonication time improved washing, rubbing, and perspiration fastness up to an optimum level, with the best overall performance obtained at approximately 7 min of sonication. At this condition, washing and rubbing fastness values frequently approached grade 5, indicating excellent resistance to dye removal during laundering or mechanical friction. Perspiration fastness also showed strong stability under both acidic and alkaline conditions. These improvements reflect the enhanced diffusion of dye molecules into the polyester matrix when the clove oil carrier is effectively dispersed.

Light fastness was particularly high for polyester fabrics, reaching grades 6–7 in several cases, especially for samples treated with clove oil and cured using microwave irradiation. The high photostability can be attributed to deeper dye entrapment within the fibre interior, where exposure to oxygen and ultraviolet radiation is reduced. When sonication time was extended to 10 min, a slight decline in fastness consistency was observed alongside the reduction in colour strength. This indicates that excessive sonication may partially degrade or destabilize the carrier system, limiting its ability to promote efficient dye diffusion.

Table 17: Effect of sonication time of clove oil treatment on fastness properties of PET using thermal curing

Sonication time (min)	Colour Strength (K/S)	Washing Fastness		Rubbing Fastness		Perspiration Fastness				Light Fastness
		St.	Alt.	wet	dry	Acidic		Alkaline		
						St.	Alt.	St.	Alt.	
0	16.06	4	4	3	3-4	4	4	3-4	4	4-5
1	16.06	4	4-5	4	4	4-5	4-5	4	4	5
3	16.08	4-5	4	4	4-5	4-5	4-5	5	5	5-6
7	16.83	5	4-5	5	5	5	5	5	4-5	6-7
10	15.43	4-5	4	4-5	5	4-5	5	4-5	5	6

Table 18: Effect of sonication time of clove oil treatment on fastness properties of printed PET using microwave curing

Sonication time (min)	Colour Strength (K/S)	Washing Fastness		Rubbing Fastness		Perspiration Fastness				Light Fastness
		St.	Alt.	wet	dry	Acidic		Alkaline		
						St.	Alt.	St.	Alt.	
0	16.06	4	4	3	3-4	4	4	3-4	4	4-5
1	16.09	4-5	4-5	4	4-5	4-5	4-5	5	5	6
3	16.43	4-5	4-5	4	4-5	4-5	5	4-5	4-5	6-7
7	19.02	5	5	4-5	5	5	5	5	5	7
10	15.9	5	4-5	4	4-5	4-5	4-5	5	4-5	5-6

The results confirm that sonication plays an important role in optimizing the performance of clove oil as a bio-based carrier for disperse dye transfer printing. Proper sonication promotes uniform dispersion of the oil phase, which facilitates dye penetration and improves colour durability. An optimal sonication time of approximately 7 min provides the best balance between colour strength and fastness performance for both polyester and polyester/cotton blend fabrics. These findings further demonstrate that natural essential oils such as clove oil can be successfully integrated into textile printing systems to enhance dye fixation and durability while offering a more environmentally compatible alternative to conventional synthetic carriers.

IV. Conclusions

This study establishes an efficient and sustainable strategy for enhancing the sublimation transfer printability of polyester (PET) and polyester/cotton blended fabrics through clove oil-assisted surface modification. The results demonstrate that the incorporation of clove oil as a bio-based carrier significantly improves dye uptake and color strength (K/S), primarily due to enhanced dye diffusion and improved fibre–dye interactions during thermo-fixation.

Process optimization revealed that a clove oil concentration of 5% combined with controlled sonication (7 min) provides the most favorable conditions for achieving uniform dye distribution and maximum color yield. Excessive sonication adversely affected performance, indicating the importance of maintaining structural stability of the active components.

Microwave curing proved to be more effective in promoting dye fixation and enhancing color strength compared with conventional thermal curing, owing to its rapid and uniform heating mechanism. However, thermal curing exhibited slightly improved performance in terms of washing and rubbing fastness, suggesting differences in fixation behavior under varying thermal conditions.

In addition, the treatment induced measurable changes in wettability, reflecting modifications in surface energy that contribute to improved dye transfer efficiency. The overall enhancement in color fastness further confirms improved dye fixation within the fibre structure.

These findings highlight the potential of clove oil as a sustainable alternative to conventional carriers in transfer printing, particularly for polyester/cotton blends where differential dye affinity remains a critical limitation.

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