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Sustainable Smart Textiles via Photochromic and Bioactive Printing

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Abstract

This innovative method aims to impart enhanced coloristic properties including deeper shade, high color fastness, and a distinctive soft handle as well as valuable functional attributes such as antibacterial activity, ultraviolet (UV) protection, and long-lasting aromatic scent. Moreover, the formulation demonstrated remarkable paste stability, maintaining its performance over extended storage periods. Experimental investigations confirmed that the treated samples exhibited excellent photochromic behavior, vibrant color change under UV exposure, and superior durability against washing and rubbing. Functional analyses revealed notable antibacterial efficacy and effective UV-blocking capacity, in addition to sensory appeal due to the retained fragrance. Scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR) were employed to examine surface morphology and identify functional groups responsible for the observed properties. The results highlight the potential of integrating photochromic dyes and natural oils in textile finishing for innovative, eco-friendly applications with sensory and protective functionalities.

Keywords: Photochromic dyes; Essential oils; Eco-friendly printing; Functional textiles; Antibacterial activity; UV protection; Cotton/PET fabrics; Fragrance-retaining finishes.

1. Introduction

The global textile industry is currently undergoing a transformative shift toward sustainability and multifunctionality, driven by growing environmental concerns, regulatory pressures, and heightened consumer demand for high-performance, eco-conscious products [1]. Traditional dyeing and finishing processes, often reliant on synthetic chemicals, pose significant environmental and health risks due to the discharge of toxic effluents and non-biodegradable residues [2]. In response, researchers have increasingly turned to sustainable coloration technologies and functional finishing strategies that integrate natural, bioactive compounds to minimize environmental impacts and end-use performance of textiles [3-5].

Concurrently, the use of plant-derived essential oils, such as lemon and peppermint oils, has gained attention as a sustainable method to impart antibacterial [6, 7], UV-protective [8], and aromatic functionalities without compromising fabric softness or environmental integrity [1, 9]. This approach presents a promising frontier in textile engineering, where color responsiveness, functional performance, and olfactory aesthetics are harmoniously combined through green chemistry. However, challenges remain in formulating stable, durable, and industrially scalable systems that retain efficacy after multiple laundering cycles and prolonged storage [10]. Storage stability challenges of functional printing pastes have been widely reported in the literature. In this study, such challenges are indirectly addressed through the incorporation of a bioactive agent with thermochromic pigments in a novel formulation approach aimed at enhancing overall performance and compatibility[11-13]. As such, the pursuit of eco-friendly, multifunctional textile treatments represents a pivotal focus in contemporary material science and applied textile research.

One of the most promising strategies for sustainable textile finishing is the use of photochromic dyes, which exhibit reversible color changes under ultraviolet (UV) radiation, enabling the development of smart textiles with responsive visual characteristics. These dyes provide opportunities for applications in fashion, safety wear, and functional textiles where dynamic color behavior is desirable. However, their practical implementation is often challenged by limitations in durability, color depth, and compatibility with sustainable printing [7].

To enhance both aesthetic and functional properties, recent research has focused on combining photochromic systems with plant-based essential oils [14, 15], such as lemon and mint oils, which are rich in naturally occurring bioactive compounds like limonene and menthol. These essential oils are well-known for their antimicrobial, UV-blocking, and aromatic properties, making them ideal candidates for multifunctional textile applications [16]. Additionally, their incorporation has been shown to enhance the fabric's functional properties and improve the printing paste formulation stability, allowing the printing paste to maintain performance over extended storage periods [17]. This research proposes a sustainable approach for developing smart functional textiles through a combined photochromic printing and finishing process with natural essential oils. This method provides a safer alternative to conventional antimicrobial and UV-blocking agents, while evaluating the effects of pigment concentration, binder crosslinking, natural oil finishing, and curing temperature on photochromic prints applied to cotton via flat-screen printing [18-20].

2. Experimental

2.1. Materials

Cotton/PET (50/50) % plain weave full white bleached fabric was used in this current study. The fabric weighs approximately 180 g/m².

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All chemicals used in this study were of commercial or laboratory grade. Dimethylol dihydroxy ethylene urea (DMDHEU), a low-formaldehyde cross-linking agent supplied by Clariant International Ltd., A synthetic binder (DTM®) composed of (polyethyl acrylate-co-methyl methacrylate-co-acrylic acid) with an average molecular weight of 45,000 g/mol and a viscosity of 250 mPa·s. Cefasoft® SMA, an amino-functional polysiloxane microemulsion containing reactive hydroxyl groups (Clariant, Germany), was applied to impart softness, smooth handle, and flexibility to the printed fabrics. Carbolan® DL, a synthetic thickener of textile grade. Tween 80 (polyoxyethylene sorbitan monooleate, ≥98% purity; Sigma-Aldrich). The photochromic pigments used-MC Pigment XCG-11 Red®, XCG-17 New Yellow®, and XCG-19 New Blue®-were obtained from Special Pigments International (SPI, Egypt) and exhibited reversible color changes under ultraviolet (UV) radiation. Bioactive functional additives derived from natural sources, including mint and lemon essential oils (purity ≥ 70%), were purchased from the local market. Magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$) of laboratory reagent grade, procured from a local chemical supplier.

2.2. Methods

2.2.1. Fabric Preparation

Cott/PET fabric was pre-washed, dried, and conditioned at 20 ± 2°C and 65 ± 5% RH.

2.2.2. Printing Paste Preparation

Different printing pastes were prepared under controlled conditions with varying concentrations of photochromic pigments without the addition of essential oils, and in combination with different concentrations of lemon and mint oils. As well as, photochromic pigments were mixed with different concentrations of crosslinker. All other formulation components and conditions were kept constant across the experiments to ensure reliable comparison. Table 1 shows the typical multifunctional printing paste. As well as, the following Fig. presents the main chemical constituents commonly found in both mint & lemon oils [21, 22].

Table (1): Multifunctional printing Paste formulations

Constituent	Concentrations (g/Kg)
Photochromic pigment (3 colors)	(50 – 100 - 150)
Thickening agent	20
Binder	50
Crosslinker	10 - 20
Catalyst	2.5 - 5
Softener	20
Essential oil	15 - 30
Emulsifier	5
Water	Balance to 1000 g

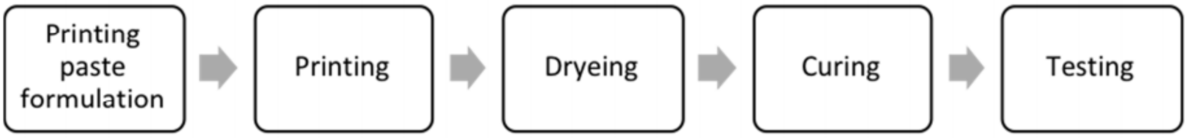


Figure 1: Process schematic diagram

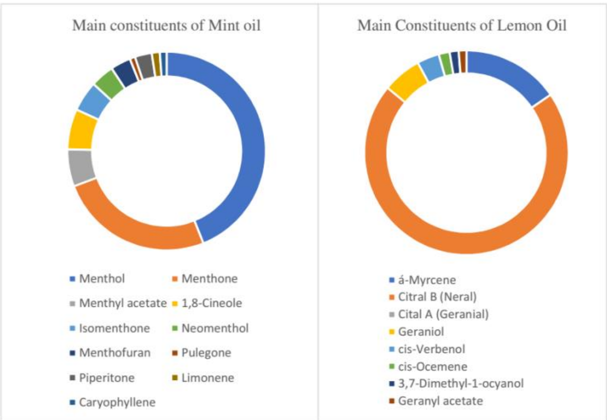


Figure 2: Mint & lemon Oils main Constituents

2.2.3. Printing Process

Flat screen printing was conducted manually using a 43T mesh. The paste was uniformly applied across all samples using the same pressure and squeegee angle. After printing, samples were dried at room temperature for 10 minutes, then cured at different temperatures to assess the effect of temperature on crosslinking efficiency and pigment integrity.

2.2.4. Testing or Measurements

The nitrogen content of both printed and unprinted samples were quantitatively evaluated using the standard analytical procedure: "Kjeldahl method"[23].

The color strength (K/S values) of all fabric samples was determined using a reflectance spectrophotometer. The Kubelka–Munk equation was applied to calculate the color strength according to the following formula [24]:

$$\frac{K}{S} = \frac{(1 - R_{\lambda})^2}{2R_{\lambda}}$$

Where:
K = absorption coefficient
S = scattering coefficient
R = reflectance of the sample at the wavelength of maximum absorption (λ max)

The antibacterial activity of the multifunctionalized photochromic printed samples against both the of Gram-positive pathogenic bacteria *S. aureus* and the Gram-negative *E. coli* was assessed by AATCC TM100-2019 [25].

Ultra Violet-protection Factor (UPF values) was determined by the Australian/New Zealand Standard, AS/NZS 4399: 2017 [26].

The fastness properties of both the control & the multi-functionalized/printed samples to washing, rubbing, were measured by (AATCC 61/2013) [27], (AATCC 8-2016) [28].

The wettability of white samples was evaluated and compared with the functionalized/printed ones, according to the AATCC TM 79-2010 [29].

The printed samples were tested for odor performance following AATCC TM216-2024.

2.2.5. Characterization

FTIR spectroscopic investigation for selected samples was achieved utilizing Nexus 670 FTIR spectrometer, Nicol Co [30].

The configuration of the selected untreated and functionalized/printed fabric samples was examined using a Quanta SEM 250 FEG (Field Emission Gun) equipped with energy dispersive X-ray spectroscopy (EDS). This instrument operates at an accelerating voltage of 30 KV and is provided by FEI Co., Netherlands, to check the surface composition [31].

3. Results and Discussion

In this current work, the effect of different parameters bioactive agents, photochromic pigment concentrations, and the crosslinking agent concentrations on the printing/multifunctional properties was studied. The following discussion investigates the influence of each parameter in detail.

3.1. Optimization of the Type & Concentration of Natural EOs (lemon & mint oils)

Firstly, the effect of type and concentration of bio-active agents, namely mint & lemon oils, on the printing properties expressed by K/S is considered. An increase in both the two oils concentrations from 15g/kg to 30g/kg of printing paste resulted in a noticeable enhancement in K/S values, indicating improved photochromic pigments dispersion and incorporated into the interface film layer of binder onto the fabric surface [32]. As the concentrations used were kept within the appropriate range, no negative effects such as photochromic pigment desorption or barrier formation on the fabric surface. The obtained results demonstrate the variations in the color properties of the photochromic printed fabric samples expressed by K/S, shown in Table 2, the K/S values for the printed fabric samples without the addition of any active bio-agents EOs ranged between (1.9 : 6.1), depending on the photochromic pigment color [33]. The obtained K/S values among the photochromic pigments' shades follow the increasing order yellow < red < blue< None, this increase can be attributed to differences in the chromophore structure and spectral absorption characteristics of each dye. While yellow photochromic pigment usually has simpler chromophoric system and absorbs less light, particularly in the blue region, causing lower K/S values. Red photochromic colors present moderately complicated structures and absorb green and blue wavelengths, leading to intermediate K/S values [34]. On the other hand, blue photochromic colors generally have more extended chromophoric systems that absorb significantly throughout the spectrum of red and orange regions, thereby producing the most pronounced values of K/S under the same printing conditions. These variations are intrinsic to the optical properties of the photochromic colors, regardless the addition of bioactive agents EOs [35].

Additionally, a significant increase in color strength was observed after various types of bio active agents EOs were used in the printing paste formulation, K/S values existence between (1.9: 7.6). The enhancement might be achieved due to the capabilities of EOs to increase the photochromic colors dispersion, enhance the wetting of the fibers, and perhaps be carriers for the color to facilitate its incorporation into the binder film layer onto the fabric surface.

Table (2): Effects of including the bioactive agents (Lemon & mint EOs) in printing formulations on the functional and color properties of the photochromic printed/ functionalized fabrics

EOs	EOs Concentration g/kg	Photochromic pigment color	(N%)	Wetting time (sec)	K/S	UPF	ZI (mm)	
							G+ve, (S.aureus)	G-ve, (E.coli)
None	00	None	00	00	00	8.36	1.2	0.9
	00	MC Pigment XCG-11 Red	0.26	12	3.2	23.4	1.1	0.8
	00	MC Pigment XCG-17 New Yellow	0.27	9	1.9	18.7	0.8	0.5
	00	MC Pigment XCG-19 New Blue	0.31	15	6.1	31.2	3.4	2.1
Mint Oil	15	MC Pigment XCG-11 Red	0.28	20	3.5	46.3	19.7	14.1
	30		0.27	25	3.8	55.3	20.6	16.0
	15	MC Pigment XCG-17 New Yellow	0.28	15	2.1	29.2	18.0	15.9
	30		0.25	18	2.5	38.8	19.1	17.2
	15	MC Pigment XCG-19 New Blue	0.29	30	7.2	48.5	21.4	17.5
	30		0.31	37	7.6	76.2	23.1	19.8
Lemon Oil	15	MC Pigment XCG-11 Red	0.27	14	3.4	36.8	12.2	8.1
	30		0.23	19	3.1	41.7	13.6	9.4
	15	MC Pigment XCG-17 New Yellow	0.28	12	1.9	22.9	10.2	6.5
	30		0.25	15	2.0	27.6	11.9	7.3
	15	MC Pigment XCG-19 New Blue	0.30	22	6.3	33.6	13.9	9.8
	30		0.32	29	6.5	50.2	15.2	11.3

Printing formulation: Photochromic pigment colors (MC Pigment XCG-1 1 Red®, MC Pigment XCG-17 New Yellow®, MC Pigment XCG-19 New Blue® (100 g/kg paste); binder(50 g/kg paste); thickener(20 g/kg); crosslinking agent (20 g/kg paste); silicone softener (20 g/kg); catalyst (5 g/kg paste); Eos (0, 15, 30 g/kg paste).
Thermofixation conditions: drying at room temp; curing at 120°C for 20 minutes. Abbreviations: *K/S*, colour strength; N%, nitrogen content; UPF, UV-protection factor; ZI, zone of inhibition.

The data in Table 2 revealed: that, the highest K/S values were obtained with the photochromic blue color in combination with the mint & lemon oils at a concentration of 30g/Kg (7.6-6.5), followed by 15g/Kg (7.2-6.3) at the same order. Although lemon oil enhanced color strength compared to the control, its K/S values remained lower than those obtained with mint oil. Specifically, mint oil at 30 g/kg (6.5) outperformed lemon oil at the same concentration (6.3). The K/S values followed the order: mint oil (30 g/kg) > mint oil (15 g/kg) > lemon oil (30 g/kg) > lemon oil (15 g/kg) > control. These results clearly demonstrate the superior efficiency of mint oil in enhancing print coating performance, particularly at higher concentrations, highlighting the significant role of bioactive essential oils (EOs) [36].

As for the UV-blocking performance of the printed/multifunctionalised fabric samples as shown in Table 2, the UPF values of only the printed photochromic pigments showed a noticeable increase from yellow to blue. The blue-printed/multifunctionalised samples exhibited the highest UPF value among the three colors tested. The order was: yellow < red < blue < None, can be attributed to the difference in spectral absorption among the pigments [9]. Blue dyes typically absorb a broader quantity of UV and visible spectra due to their more extended conjugated systems, which improves UV-blocking ability. whereas, yellow color absorbs fewer UV radiation, resulting in lower UPF values [34].

With the incorporation of bioactive essential oils (EOs), a considerable improvement in UPF values was observed across all colors. Notably, mint oil produced significantly higher UPF values than lemon oil under identical printing/finishing conditions [33, 37].

The functional UV capability follows the increasing order as follows: mint oil (30 g/Kg) > mint oil (15 g/Kg) > lemon oil (30 g/Kg) > lemon oil (15 g/Kg) > None, clearly indicates that both the type and concentration of oil have a strong influence on UV protection [38, 39]. This enhancement may be attributed to the ability of both two oils to block surface pores, reduce fabric transparency, and possibly create a thin film with the binding agent that scatters or absorbs UV radiation more effectively. Moreover, mint & lemon oils contain UV-absorbing bio active natural compounds, such as: menthol, menthone, limonene, citral B, and phenolic constituents, which either absorb UV radiation or form protective interface film with the other printing formulations onto the surface of the fabric that scatter or reflect the undesirable UV radiations [40, 41].

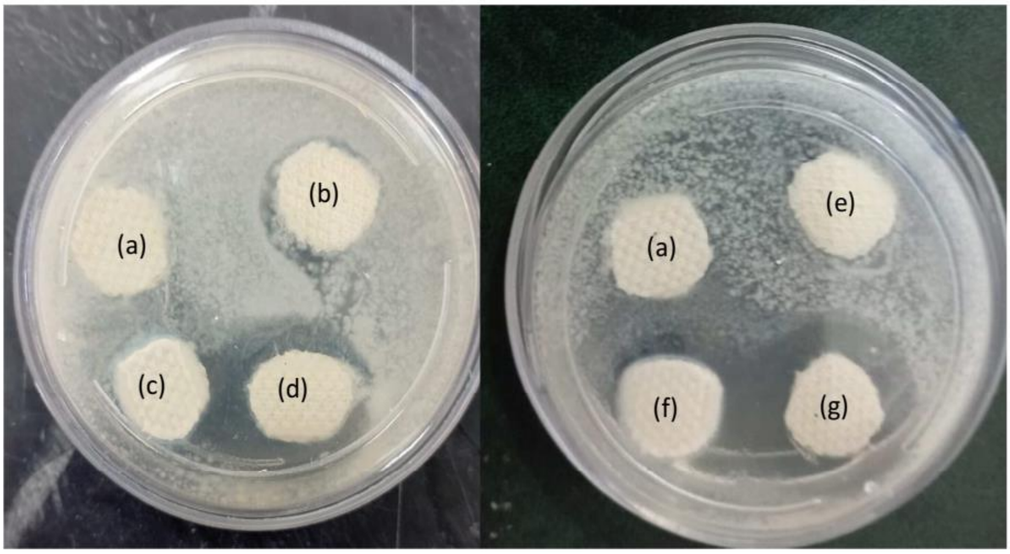


Figure 3: Antibacterial performance of untreated and printed/multifunctionalised C/PET fabric samples with photochromic pigments and essential oils (lemon oil and mint oil)

The antibacterial activity of photochromic printed/multifunctionalised C/PET fabric samples against both Gram+ve (*S. aureus*) and Gram-ve (*E. coli*) pathogenic bacteria was evaluated using the zone of inhibition (ZOI) method. Fig. 2 illustrates the antibacterial performance of seven fabric samples. Sample (a) is untreated C/PET fabric, showing minimal activity. Sample (b-d) are printed with blue and red photochromic pigments at 100 g/kg, exhibiting enhanced antibacterial effect compared to the untreated fabric. Samples (c-f) and (d-g) represent the same photochromic prints with the addition of lemon oil and mint oil, respectively, at 30 g/kg, both demonstrating further improved antibacterial activity, highlighting the positive contribution of bioactive essential oils.

The data in Table 2, demonstrates the noticeable variation among the un-treated, the photochromic prints, as well as the bio-active agents printed/multifunctionalised C/PET fabric samples. Untreated C/PET fabric showed minimal antibacterial activity due to its inert nature and lack of functional agents [42]. Additionally, the photochromic pigments printed fabric samples present variations of the antibacterial values for both the two pathogenic bacteria, Yellow and red printed samples exhibit a marginal improvement in antibacterial behavior, with minimal zones of inhibition against both bacterial strains. However, the blue photochromic pigment shows a relatively more noticeable antibacterial activity, particularly against Gram-positive bacteria. This may be attributed to the certain molecular structure of the blue color, which probably produces reactive oxygen species (ROS) under light exposure or varies surface energy and electrostatic interactions with bacterial cell walls [43, 44].

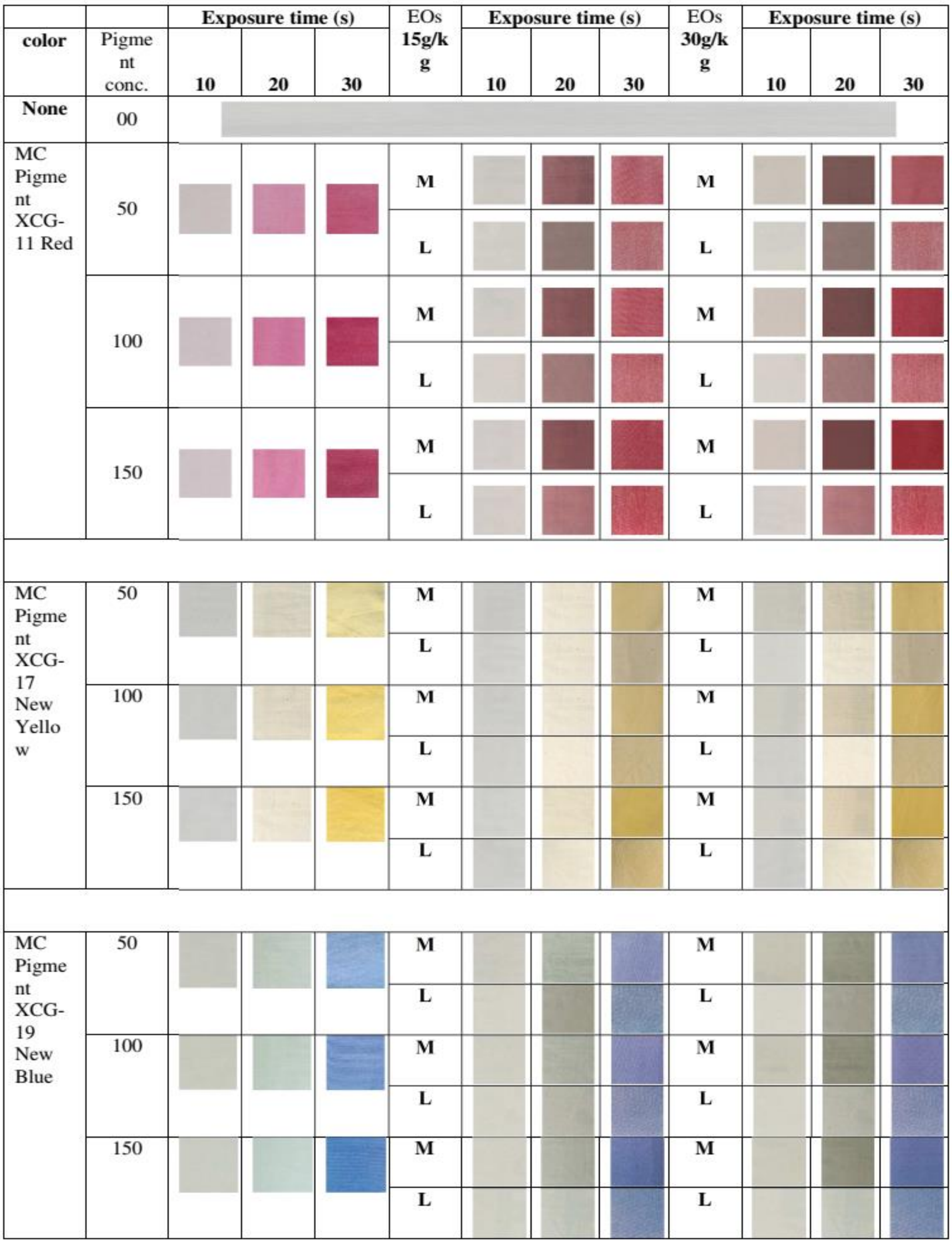
The generation of Reactive Oxygen Species (ROS) in this system is believed to result from the photochemical interaction between photochromic molecules and natural essential oils. Upon exposure to UV light, the photochromic compounds absorb photon energy and transition from the ground state to an excited state, enabling electron or energy transfer to surrounding oxygen molecules. This process leads to the formation of various ROS, such as superoxide radicals ($\bullet O_2^-$), hydrogen peroxide (H_2O_2), and hydroxyl radicals (•OH).

The phenolic and terpenoid constituents of the essential oils (e.g., mint and lemon) act as co-mediators in this process by facilitating electron transfer and stabilizing the generated radicals, thereby enhancing the overall photoreactivity and contributing to both antibacterial activity and UV absorption performance simultaneously.

On the other hand, the inclusion of natural or functional bio agents EOs into the printed/multifunctionalised fabric samples indicates a significant enhancement in antibacterial performance, especially for (*S. aureus*) bacteria. The inhibition zones increased notably in both yellow and red samples, while the blue samples exhibited the highest values when combined with mint oil. Mint oil consistently provided higher antibacterial values among all photochromic pigments, as well as the most significant was observed in the blue color with the mint Oil (30g/Kg) combination, suggesting possible synergistic effect of the blue pigment and active constituents of mint Oil. The variation between *S. aureus* and *E. coli* can be attributed to their cell wall structures: the thick peptidoglycan layer of *S. aureus* makes it more vulnerable to hydrophobic and ROS-generating agents, whereas the lipopolysaccharide-rich outer membrane of *E. coli* acts as a barrier, requiring stronger or more penetrative action for inhibition.

The antibacterial mechanism may include several pathways: i) Photoactivation of photochromic pigments, especially the blue color, may generate ROS such as singlet oxygen or hydroxyl radicals upon UV or visible light exposure, which can damage bacterial cell components, ii) Electrostatic interactions or photophysical effects of the dyes may alter bacterial adhesion and growth on the fabric surface, as well as, Oil additives, particularly mint Oil, which contains phenolic compounds, with known antibacterial properties, which disrupt bacterial membranes or metabolic activity [45, 46].

Table (3): Multifunctional/printed fabric samples



color	Pigment conc.	Exposure time (s) 10	20	30	EOs 15g/kg	Exposure time (s) 10	20	30	EOs 30g/kg	Exposure time (s) 10	20	30
None	00											
MC Pigment XCG-11 Red	50				M				M			
					L				L			
	100				M				M			
					L				L			
	150				M				M			
					L				L			
MC Pigment XCG-17 New Yellow	50				M				M			
					L				L			
	100				M				M			
					L				L			
	150				M				M			
					L				L			
MC Pigment XCG-19 New Blue	50				M				M			
					L				L			
	100				M				M			
					L				L			
	150				M				M			
					L				L			

The statistical analysis for the presented measurements is as follows: the mean K/S value was 3.82 with a standard deviation of 2.24, and the mean UPF value was 36.80 with a standard deviation of 16.38. For the ZI values, the mean of G+ve was 12.84 with a standard deviation of 7.64, while the mean of G-ve was 9.83 with a standard deviation of 6.51. All values are based on 16 replicates for each set of measurements.

The statistical analysis (ANOVA) revealed no significant differences in color strength (K/S) among treatments ($p = 0.86$), indicating stable color development across formulations. However, a significant difference was observed in UV protection (UPF) ($p = 0.04$), confirming the positive impact of essential oils on UV-shielding performance. Moreover, highly significant differences were detected in antibacterial activity against both S. aureus ($p < 0.001$) and E. coli ($p < 0.001$), demonstrating the strong bioactive functionality imparted by the essential oil incorporation, particularly with mint oil.

Table 3 presents the visual appearance of the printed photochromic samples after UV-light source exposure at three different times. Three sets of samples were compared: (i) photochromic prints in three colors, at three pigment concentrations (50, 100, and 150); (ii) the same photochromic prints with the addition of lemon and mint oils at 15%; and (iii) photochromic prints with higher concentrations of lemon and mint oils (30 g/kg). As observed, the samples containing essential oils, particularly at higher concentrations, exhibited more intense and visually distinct color changes under UV irradiation, in agreement with the aforementioned interpretations discussed above.

3.2. Effect of using different concentrations of photochromic pigment colors on the developed functional & printing properties of cotton fabrics

All presented data in Table 4, revealed that the effect of photochromic pigment concentrations (50, 100, 150g/Kg) g/Kg in combination with two bio-based additives namely mint and lemon oils was investigated. All printed/multifunctionalised fabric samples were compared with the non-printed C/PET control sample, which revealed zero properties without any/or more less functional properties. The (N%), representative the presence of functional groups or nitrogenous photochromic residues, showed a direct correlation with pigment concentration and the confirming of the N-content based cross linking agent (DMDHEU), and the results was as follow: i) the concentration (50g/Kg) of the three colors for mint and lemon oils as the same order showed N% for the red, yellow and blue photochromic pigments ≈ (0.21-0.26%), (0.22-0.24%), and (0.24-0.23%), ii) the concentration (100 g/Kg) was (0.27-0.23%), (0.25%), and (0.31-0.32%), iii) as well as, the high concentration (150 g/Kg) values were (0.22-0.24%), (0.26-0.25%), and (0.34-0.33%). The increase in nitrogen content is essentially due to the crosslinker used in the binder system, which is considered N-based compound.

While the yellow and red photochromic pigments contain only trace amounts of nitrogen, the blue pigment exhibits a comparatively higher nitrogen content, which is attributed to its heteroaromatic structure (often involving indoline or spirooxazine derivatives) [47].

Consequently, the measured nitrogen percentage in the printed samples does not originate solely from the pigment itself. Instead, it is mainly influenced by the applied crosslinking agent, since most commercial binders and crosslinkers which contain nitrogen, with all parameters kept constant.

However, K/S values increased correspondingly with photochromic pigment concentration from low to high as follows: (150g/Kg blue + mint) > (100g/Kg red + mint) > (150g/Kg yellow + mint) > None, as well as the values follow the same order for lemon oil. An increase in photochromic pigment concentration led to a corresponding increase in K/S values, particularly with the addition of bio active oils most remarkably in the blue-colored fabric samples. Generally, mint oil consistently produced the highest K/S values, which may be attributed to its ability to form a surface film that enhances the color depth properties [48].

Table (4): Effect of using different concentrations of photochromic pigment colors on the developed functional & printing properties of C/PET fabric samples

Photochromic pigment color	Concentration g/kg	EO_s g/Kg	(N%)	K/S	UPF	ZI (mm) G+ve, *(S.aureus)*	ZI (mm) G-ve, *(E.coli)*	WF	RF
None	-	**None**	00	0.03	00	00	00	00	00
Ranbar Red DP1610	50	**Mint**	0.21	2.7	33.5	18.9	15.5	5	4-5
		Lemon	0.26	2.1	28.2	12.9	8.8	4-5	4-5
	100	**Mint**	0.27	3.8	55.3	20.6	16.0	4-5	4-5
		Lemon	0.23	3.1	41.7	13.6	9.4	4	4-5
	150	**Mint**	0.22	4.9	64.4	19.5	16.4	2-3	3-4
		Lemon	0.24	3.8	43.6	13.3	9.5	2	2-3
Ranbar Yellow GS3080	50	**Mint**	0.24	1.8	26.7	19.1	14.3	4-5	4
		Lemon	0.23	1.4	20.9	11.7	6.4	3-4	3
	100	**Mint**	0.25	2.5	38.8	19.1	17.2	4	3-4
		Lemon	0.25	2.0	27.6	11.9	7.3	3-4	3-4
	150	**Mint**	0.26	3.6	45.7	19.3	17.1	2	2-3
		Lemon	0.25	3.1	44.2	11.4	7.5	1-2	1-2
Ranbar Blue GS5030	50	**Mint**	0.224	3.9	38.1	22.8	19.3	5	4-5
		Lemon	0.215	2.8	29.6	14.7	10.9	4	4-5
	100	**Mint**	0.31	7.6	76.2	23.1	19.8	4-5	4
		Lemon	0.32	6.5	50.2	15.2	11.3	3-4	3-4
	150	**Mint**	0.34	9.5	92.1	24.0	20.1	3	2-3
		Lemon	0.33	8.3	63.4	15.9	12.0	2-3	2

Printing formulation: Photochromic pigment colors (MC Pigment XCG-1 1 Red®, MC Pigment XCG-17 New Yellow®, MC Pigment XCG-19 New Blue® (00, 50, 100, and 150 g/kg paste); binder(50 g/kg paste); thickener(20 g/kg); crosslinking agent (20 g/kg paste); silicone softener (20 g/kg); catalyst (5 g/kg paste); EO_s (30 g/kg paste).

Thermofixation conditions: drying at room temp; curing at 120°C for 20 minutes.

Abbreviations: K/S, colour strength; N%, nitrogen content; UPF, UV-protection factor; ZI, zone of inhibition; WF, washing fastness; RF, rubbing fastness.

Remarkably, the enhancement in UV-blocking capacity correlated directly with increased pigment concentration, and type of photochromic color, particularly when combined with the bio active additives, most significantly in blue-printed/multifunctionalised fabric samples. The UPF values showen in table 4, demonstrate that the variations of values follow the decreasing order: (blue 150 g/Kg+mint) > (red 150 g/Kg+mint) > (yellow 150 g/Kg+mint) > None. with all other parameters kept constant. The high UV-blocking efficiency is attributed to the photochromic pigment's aromatic rings and conjugated systems, which effectively absorb UV radiation, as well as the bio active constituents in mint and lemon oils may have added UV-blocking phytochemicals enhancing the UV-blocking capability [49, 50].

On another hand, the results in table 4 clearly demonstrate that the antibacterial activity enhanced significantly with higher photochromic concentration (50, 100, 150) g/Kg, in particular with mint & lemon oils against both Gram-positive and Gram-negative strains of bacteria and all values follow the increasing order: None < (50 g/Kg + lemon oil) (14.7 – 10.9 mm) < (100 g/Kg + lemon oil) (15.2 – 11.3 mm) < (150 g/Kg + lemon oil) (15.9 – 12.0) < (50 g/Kg + mint oil) (22.8 – 19.3) < (100 g/Kg + mint oil) (23.1 – 19.8 mm) < (150 g/Kg + mint oil) (24.0 - 20.1 mm).

The imparted antibacterial efficiency of the treated fabrics can be explained through different mechanisms: i) certain photochromic pigments, particularly the blue color, generates reactive oxygen species (ROS) upon exposure to light (UV or visible), which can damage bacterial cell membranes and internal proteins, thereby inhibiting growth or causing cell death. ii) the hydrophobic components of the essential oils, such as lemon and mint oils, interact with the lipid bilayers of bacterial membranes, disrupting their integrity and leading to leakage of cellular contents. iii) the printing and finishing process introduces additional surface functional groups on the fabric, enhancing the adsorption of bacterial cells onto the textile surface. This adsorption increases the contact between the bacteria and the active antibacterial agents (ROS and oils), further amplifying the inhibitory effect. Collectively, these mechanisms-ROS generation, membrane disruption by hydrophobic oils, and enhanced bacterial adsorption-work synergistically to impart significant antibacterial activity to the treated fabrics [51]. Remarkably, while increasing the concentration of red and yellow photochromic pigments had no significant impact on antibacterial resistance, the concentrations of blue color particularly at higher concentration enhanced the antibacterial synergetic effect with the bio active agents EOs This implies that the blue pigment may interfere with the oil's active components, whereas in the case of red and yellow pigments, the antibacterial effect seems to remain predominantly driven by the essential oils [52].

All samples exhibited acceptable washing fastness according to AATCC 61: Low concentration samples exhibited 3–4, medium concentration 4, and high concentration 4–5.

Rubbing Fastness: Dry rubbing fastness remained stable across samples (scale 4–5), but wet rubbing decreased slightly at higher dye concentrations: Low: 4 (wet), Medium: 3–4, High: 3 (wet) due to higher surface dye accumulation [53].
The washing fastness properties were evaluated as shown in table 4, at lower pigment concentrations, with red and blue showing the most noticeable values, followed by yellow. In contrast, the lowest fastness levels were detected at higher pigment concentrations, maintaining the same order of performance. Similarly, rubbing fastness followed a similar tendency, where the highest imparted values attained at lower pigment concentrations, with red and blue bettering yellow. However, higher pigment concentrations resulted in lower rubbing fastness values, following the same color order. These observations were made under controlled conditions with all other variables kept constant.

The statistical analysis (ANOVA) revealed a significant effect of pigment concentration on both color strength (K/S) and UV protection (UPF) ($p < 0.01$), confirming that higher pigment loading enhanced optical and protective performance. In contrast, nitrogen content (N%) showed no significant variation ($p = 0.42$), indicating consistent fixation of bioactive components. Antibacterial activity exhibited highly significant differences ($p < 0.001$), with mint oil–treated fabrics showing the strongest inhibition zones. However, increasing pigment concentration beyond 100 g/kg led to a slight reduction in washing and rubbing fastness, suggesting a trade-off between intensity and durability.

3.3. Effect crosslinker concentration on the color/functional properties of C/PET fabrics
Table 5 shows a distinguished impact on several functional properties. As crosslinker concentration increased, (N%) on the printed/multifunctionalised fabric samples also raised, demonstrating a higher degree of the chemical interaction and the progressive crosslinking reactions. As well as, this developed network formation contributed to enhance the K/S values, particularly at the high concentration of the crosslinking agent (DMDHEU), proposing better pigment fixation and color depth due to stronger entrapment of pigment molecules within the crosslinked matrix. However, the photochromic printed/multifunctionalised fabric samples with higher crosslinking agent concentrations revealed increased UV protection values. This can be attributed to the formation of a thick film layer onto the fabric surface that performances as a more effective UV block. The thick polymeric network may also reduce the harmful UV-rays penetration, which may assist protect the skin from UV radiation [54, 55].

Table (5): Effect of using different crosslinker concentrations on the durability of functional/color imparted properties of cellulosic fabrics

Photochromic pigment color	crosslinker Concentrations g/kg	EOs g/Kg	(N%)	K/S	UPF	ZI (mm) G+ve, (S.aureus)	ZI (mm) G-ve, (E.coli)	WF	RF
None	00	None	00	0.03	7	00	00	00	00
MC Pigment XCG-11 Red	10	Mint	0.15	2.8	39.5	19.4	15.1	3	2-3
	20		0.27	3.8	55.3	20.6	16.0	4-5	4-5
	30		0.31	3.9	57.2	18.4	14.8	5	5
	10	Lemon	0.12	2.2	28.6	11.7	6.4	2-3	2
	20		0.23	3.1	41.7	13.6	9.4	4	4-5
	30		0.29	3.0	43.2	11.1	8.5	4-5	5
MC Pigment XCG-17 New Yellow	10	Mint	0.14	1.7	25.8	16.2	14.3	3	3
	20		0.25	2.5	38.8	19.1	17.2	4	3-4
	30		0.32	2.6	40.1	15.9	13.4	4-5	4-5
	10	Lemon	0.15	1.1	16.5	10.4	5.9	2	2-3
	20		0.25	2.0	27.6	11.9	7.3	3-4	3-4
	30		0.31	2.2	28.4	9.8	5.5	4-5	4-5
MC Pigment XCG-19 New Blue	10	Mint	0.19	5.3	52.3	18.6	14.9	1-2	2
	20		0.31	7.6	76.2	23.1	19.8	4-5	4
	30		037	7.9	75.7	18.5	14.7	5	4-5
	10	Lemon	0.21	4.9	35.6	13.6	10.1	1	1-2
	20		0.32	6.5	50.2	15.2	11.3	3-4	3-4
	30		0.34	7.0	51.5	12.6	9.7	4	4

Printing formulation: Photochromic pigment colors (MC Pigment XCG-1 1 Red®, MC Pigment XCG-17 New Yellow®, MC Pigment XCG-19 New Blue® (100 g/kg paste); binder(50,100 g/kg paste); thickener(20 g/kg); crosslinking agent (20 g/kg paste); silicone softener (20 g/kg); catalyst (5 g/kg paste); EO_s (30 g/kg paste).

Thermofixation conditions: drying at room temp; curing at 120°C for 20 minutes.

Abbreviations: *K/S*, colour strength; N%, nitrogen content; UPF, UV-protection factor; ZI, zone of inhibition.

On another hand, a minor regression in antibacterial activity was observed at high crosslinker concentrations. This reduction is likely due to the restricted mobility of essential oils within the strongly crosslinked network, limiting their availability to interact with bacterial cells. However, at optimal crosslinker concentration (20 g/Kg), the network performs to support oil retention while still allowing sufficient release for antibacterial functionality. Over all, the increased crosslinker content significantly improved the washing fastness washing & rubbing properties [56].

The crosslinking network enhances the fixation of both pigment molecules and the bio-functional agents (mint & lemon) EOs; thereby minimizing their leakage during laundering. The superior durability and functional performance of fabrics treated with mint or lemon essential oils can be explained by their interaction with the crosslinked network.

The crosslinked structure promotes effective entrapment of the oils on the fabric surface, prolonging their activity. At higher concentrations of crosslinker (30 g/kg), the essential oils further reinforce the polymeric matrix, forming a compact and stable printing interface. Additionally, the oils may function as plasticizers or interact synergistically with the polymer network, resulting in a flexible yet robust surface film that enhances color fastness, mechanical stability, and the longevity of the fabric's functional properties [57].

The statistical analysis (ANOVA) indicated a significant effect of crosslinker concentration on both color strength (K/S) and UV protection (UPF) ($p < 0.01$), confirming that increased crosslinking enhanced color fixation and durability of the functional finish. Nitrogen content (N%) also increased moderately with higher crosslinker levels, reflecting improved bonding between the bioactive agents and the fabric matrix. Antibacterial activity showed highly significant differences ($p < 0.001$), with the best inhibition zones recorded at 20 g/kg crosslinker in the presence of mint oil, demonstrating an optimal balance between fixation and bioactivity. Furthermore, washing and rubbing fastness values improved consistently with increased crosslinker concentration, highlighting the crucial role of crosslinking in maintaining multifunctional performance after repeated use.

3.4. Effect of different fixation temperature & time on the coloration/multifunctionalization performance of C/PET fabrics

Fixation temperature plays an essential role in determining the interaction between the photochromic pigment's molecules, the bio active constituents (EOs), and the substrate. All date showed in Table 6, investigates the influence of varying fixation temperatures on the performance and durability of three photochromic pigments in combination with two different types of bio active agents namely mint and lemon oils. The results cover a wide range of functional and sensory properties, including scent intensity (SI), color strength (K/S), UV-protection factor (UPF), antibacterial activity (ZI), and fastness properties to both washing and rubbing [58].

Overall, increasing temperature tends to enhance pigment fixation efficiency, especially with the mint oil. However, the thermal sensitivity of photochromic compounds poses a challenge: excessive heat can degrade their reversible coloration/functional properties. The optimal temperature range varied slightly depending on the photochromic pigment color, oil type, and all other constituents in the paste formulation. all samples fixed at room temperature for different times exhibit the most noticeable and effective scent of the oils prior to washing. This is expected, as the low-temperature conditions conserved the volatile compounds within the oil formulations. Room temperatures provided a low performance in K/S values, due to the less fixation between pigment and finishing agent's and the substrate, therefore incomplete diffusion, resulting in weaker color intensity. As well as the UPF values were insignificants, this attributed to the incomplete fixation of the formation paste onto the fabric surface. The antibacterial property noted a remarkable values between (8.7-23.2) for *S.aureus*, and (4.7-20.4) for the *Ecoli*, as consequences of the bio active oils free constituents, which capable inhibit the bacterial cell wall and causing the bacterial death. Fixation at lower temperatures led to weaker bonding, with substantial pigment loss after washing or rubbing [59].

Table (6): Effect of using different fixation conditions on the functional/coloring developed properties of C/PET

Fixation temp.	Fixation Time		SI			K/S			UPF			ZI (mm)						WF			RF		
			R	Y	B	R	Y	B	R	Y	B	G+ve, (*S.aureus*)			G-ve, (*E.coli*)			R	Y	B	R	Y	B
												R	Y	B	R	Y	B						
·		·																					
Room		Mint	5	5	5	2.9	1.5	5.1	17.3	13.7	38.2	14.8	13.7	16.3	11.5	10.9	12.1	2	1-2	2	2-3	1	1
		Lemon	5	5	5	2.2	1.3	5.2	18.7	14.3	29.4	9.6	8.7	9.6	5.8	4.7	6.5	1-2	1-2	2	2-3	1-2	1-2
100	10	Mint	5	5	5	3.1	1.9	6.7	3.6	18.9	44.7	18.1	16.1	18.5	13.7	13.6	13.4	3-4	2	3	3	2	2
		Lemon	4	4	4	2.3	1.4	5.4	25.1	16.5	35.6	10.4	9.9	11.8	6.5	5.1	9.1	2-3	2	2-3	3	2	2
	20	Mint	5	5	5	3.4	2.1	7.1	39.7	21.7	52.3	18.7	17.5	20.9	14.1	14.3	16.7	3-4	3	3-4	4-4	3	2-3
		Lemon	4	4	4	2.7	1.7	5.8	30.3	19.6	39.7	11.4	10.7	12.6	8.1	5.7	9.6	3	2-3	3	3-4	2-3	3
120	10	Mint	5	5	5	3.5	2.3	7.4	43.8	29.4	68.8	19.1	18.3	22.4	14.8	15.1	18.4	4	3-4	4	4	3	3-4
		Lemon	4	4	4	2.8	1.8	6.2	35.5	23.9	45.4	12.8	11.2	14.5	8.5	6.4	10.5	3-4	3	3	4	3	3-4
	20	Mint	5	5	5	3.8	2.5	7.6	55.3	38.8	76.2	20.6	19.1	23.1	16.0	17.2	19.8	4-5	4	4-5	4-5	3-4	4
		Lemon	4	4	4	3.1	2.0	6.5	41.7	27.6	50.2	13.6	11.9	15.2	9.4	7.3	11.3	4	3-4	3-4	4-5	3-4	3-4
140	5	Mint	3	3	3	3.8	2.4	7.8	54.8	37.7	73.2	19.7	18.6	22.6	15.3	15.7	18.4	4	4	3-4	4-5	3-4	4
		Lemon	2	2	2	3.2	2.1	6.3	42.4	27.4	48.5	13.1	11.3	14.8	8.8	6.2	10.9	4-5	4	4	4-5	3-4	3-4
	10	Mint	2	2	2	3.7	2.6	7.9	55.6	38.2	75.8	20.1	18.8	22.9	15.7	16.4	18.7	4-5	4-5	4-5	4-5	4	4
		Lemon	1	1	1	3.1	1.9	6.5	4.8	26.9	49.7	13.5	11.4	15.0	9.1	6.5	11.2	4-5	4-5	4-5	5	4	4
160	3	Mint	0	0	0	4.0	2.4	7.5	55.6	39.1	76.3	20.7	19.3	23.2	16.1	17.3	19.7	5	5	4-5	5	5	4-5
		Lemon	0	0	0	2.9	1.9	6.4	42.1	27.8	51.1	13.5	11.8	15.2	9.3	7.0	11.5	5	5	4-5	5	5	4-5
	5	Mint	0	0	0	3.5	2.1	6.8	56.6	39.4	77.2	21.1	19.5	15.3	16.4	17.6	20.4	5	5	4-5	5	5	5
		Lemon	0	0	0	2.8	1.9	6.2	42.8	28.1	51.4	14.3	12.2	15.6	9.7	8.0	12.1	5	5	4-5	5	5	5

Printing formulation: Photochromic pigment colors (MC Pigment XCG-1 1 Red®, MC Pigment XCG-17 New Yellow®, MC Pigment XCG-19 New Blue® (100 g/kg paste); binder(50 g/kg paste); thickener(20 g/kg); crosslinking agent (20 g/kg paste); silicone softener (20 g/kg); catalyst (5 g/kg paste); EO_s (30 g/kg paste).

Thermofixation conditions: drying at room temp; curing at (room temp 25, 100, 120, 140, 160°C) for different times. Abbreviations: **SI, scent intensity;** *K/S*, colour strength; N%, nitrogen content; UPF, UV-protection factor; ZI, zone of inhibition; R, photochromic pigment red; Y, photochromic pigment yellow; B, photochromic pigment blue

While moderate temperatures (~100–120°C) for (~10–20m), have a significant effect on the imparted coloring and functional properties. A significant improvement was observed in the overall fastness properties at the fixation temperatures, particularly at 100°C and 120°C for 20 minutes. The K/S values showed distinguished enhancement, especially with the blue photochromic pigment, where the deepest shade and highest color strength were recorded under these conditions. Similarly, UPF values were remarkably high with the blue pigment fixed at 120°C for 20 minutes, indicating excellent UV-blocking capabilities. As well as the antibacterial activity also improved substantially, particularly against Gram-positive bacteria (*S.aureus*), suggesting that the fixation conditions enhanced the functional integration of antibacterial agents or dye components with intrinsic antimicrobial properties [60].

Regarding washing and rubbing fastness, both properties shown a progressive enhancement between 100°C and 120°C, with the highest durability observed at 120°C for 20 minutes. This indicates that this temperature range offers an optimal balance between pigment fixation and structural stability. Moreover, the moderate fixation temperatures (100°C–120°C) did not significantly compromise the odor characteristics of the treated samples. Although there was a slight reduction in scent intensity compared to high temperature fixation, the aroma remained noticeably present and within acceptable sensory levels. This demonstrates that the moderate heat was sufficient to fix the pigments and enhance functional properties without causing excessive loss of volatile aromatic compounds in the oil medium [61].

On the other hand, fixation at higher temperatures, particularly in the range of 140°C to 160°C, resulted in excellent performance in terms of durability and functionality. These temperatures significantly enhanced washing fastness, and provided strong antibacterial activity, especially against both Gram-positive and Gram-negative bacteria. In addition, UPF values increased substantially, indicating superior UV protection under these conditions. However, there is a high performance in the functional properties but, it observed a considerable loss in scent intensity, as the raised temperatures probably caused evaporation or degradation of the volatile aromatic compounds present in the oil-based formulations. Furthermore, high temperatures, particularly at 160°C for 5 minutes negatively impacted the color values, especially with certain pigments such as the blue photochromic, leading to noticeable color fading or instability. This proposes that while high temperatures improve fastness and functionality, they can compromise aesthetic and sensory properties if not carefully controlled [7, 62].

3.5. Effect of durability or Fastness Properties and Functional Performance

The printed/multifunctionalised fabric samples demonstrate remarkable durability in terms of washing and rubbing fastness, both after a single wash and even after 15 cycles. No significant deterioration was witnessed in most of the imparted coloring and functional properties, indicating that the coating maintained its reliability under typical mechanical and chemical parameters. The imparted color properties were affected to a certain extent; however, the changes remained within acceptable limits and did not compromise the overall coloring or functional appeal of the substrates. More notably, the Ultraviolet Protection Factor (UPF) remained stable, showing no significant decline even after 15 washes, which confirms the robustness of the applied printing/finishing system in providing long-lasting UV shielding capacity. As well as, the antibacterial activity sustained to exhibit strong efficacy, demonstrating that the antimicrobial agents remained active and strongly adhered onto the fabric surface. Both the color fastness and the functional properties promoted greatly from the robust crosslinking network established by the applied binder system, in conjunction with the synergistic effect of the bioactive oil-based constituents, which contributed to the overall performance retention [5, 7, 63].

On another hand, the only property that showed a noticeable decline was fragrance retention, which reduced progressively with repeated washing. This can be attributed to the gradual volatilization or partial removal of the aromatic compounds and volatile compounds during laundering. Unlike the crosslinked functional components, these fragrance agents are more susceptible to being washed away or degraded, especially under thermal and detergent action [64].

The statistical analysis (ANOVA) revealed a highly significant effect of fixation temperature and time on all evaluated properties ($p < 0.001$). The optimal performance was achieved at 120°C for 20 minutes, where samples exhibited the highest color strength (K/S up to 7.6), superior UV protection (UPF up to 76.2), and strong antibacterial zones (up to 23.1 mm for S. aureus). Increasing temperature beyond this point (≥140°C) caused a slight decline in color intensity and bioactivity, likely due to thermal degradation of photochromic pigments and essential oil components. In contrast, lower fixation temperatures (<100°C) resulted in incomplete curing, reflected by weaker functional properties and lower durability. Washing and rubbing fastness reached excellent levels (grade 4–5) at 160°C for short fixation times (3–5 min), demonstrating the balance between thermal efficiency and structural stability.

All the corresponding data and results are presented in Table 7. The relationship between color strength (K/S) and pigment–binder interaction was clarified, emphasizing that stronger molecular adhesion enhances pigment fixation, explaining the observed efficiency order (blue > red > yellow) due to the higher conjugation degree of blue chromophores. The enhancement in UV protection (UPF) was quantitatively correlated with K/S values, as increased pigment absorption and the aromatic conjugation of photochromic molecules, along with UV-absorbing essential oils (limonene and menthol), synergistically reduce UV transmittance. Antibacterial activity was attributed to the UV-triggered generation of reactive oxygen species (ROS), such as singlet oxygen and hydroxyl radicals, which oxidize bacterial membranes; the greater susceptibility of S. aureus compared to E. coli reflects structural differences in their cell walls. Fragrance durability was explained through diffusion and volatilization kinetics, where essential oil loss occurs gradually during washing, while crosslinking agents and silicone softeners retard diffusion and prolong scent retention. FTIR spectra confirmed functionalization through characteristic peaks (C=O, O–H, Si–O–Si), supported by SEM micrographs showing smooth, well-coated surfaces. Finally, EDX results were clarified, indicating that Na and K signals originated from auxiliary materials in the formulation rather than new compound formation.

`Table (7): Durability of the imparted functional and coloration properties to wash

Photochromic pigment color		SI		K/S		UPF		ZI (mm)				WF		RF	
								G+ve, (*S.aureus*)	G-ve, (*E.coli*)	G+ve, (*S.aureus*)	G-ve, (*E.coli*)				
		After 1 washing cycle	After 15 washing cycles	After 1 washing cycle	After 15 washing cycles	After 1 washing cycle	After 15 washing cycles	After 1 washing cycle		After 15 washing cycles		After 1 washing cycle	After 15 washing cycles	After 1 washing cycle	After 15 washing cycles
None															
MC Pigment XCG-11 Red	Mint	5	3	3.8	3.7	55.3	34.2	20.6	16.0	17.2	13.1	4-5	4-5	4-5	4
	Lemon	4	2	3.1	3.1	41.7	40.5	13.6	9.4	11.6	7.5	4	3-4	4-5	4
MC Pigment XCG-17 New Yellow	Mint	5	3	2.5	2.4	38.8	28.4	19.1	17.2	17.6	15.3	4	4	3-4	3
	Lemon	4	2	2.0	1.9	27.6	26.7	11.9	7.3	9.8	5.4	3-4	3	3-4	3
MC Pigment XCG-19 New Blue	Mint	5	3	7.6	7.6	76.2	75.5	23.1	19.8	20.5	17.3	4-5	4	4	3-4
	Lemon	4	2	6.5	6.3	50.2	50.0	15.2	11.3	13.5	10.1	3-4	4	3-4	3

Printing formulation: Photochromic pigment colors (MC Pigment XCG-1 1 Red®, MC Pigment XCG-17 New Yellow®, MC Pigment XCG-19 New Blue® (100 g/kg paste); binder(50,100 g/kg paste); thickener(20 g/kg); crosslinking agent (20 g/kg paste); silicone softener (20 g/kg); catalyst (5 g/kg paste); EO_s (30 g/kg paste).
Thermofixation conditions: drying at room temp; curing at 120°C for 20 minutes.
Abbreviations: *K/S*, colour strength; N%, nitrogen content; UPF, UV-protection factor; ZI, zone of inhibition.

The interaction of essential oils with the binder/pigment system plays a crucial role in enhancing the multifunctional properties of the treated textiles. The active aromatic compounds present in mint and lemon oils, such as menthol and limonene, can form hydrogen bonds or Van der Waals interactions with the binder and pigment molecules, thereby improving dye fixation and color strength on the fibers. These compounds also contain conjugated ring structures capable of absorbing UV radiation, contributing to enhanced UV protection. Additionally, the antimicrobial activity arises from the ability of these bioactive molecules to disrupt bacterial cell membranes, thereby inhibiting microbial growth on the fabric surface. Fixation temperature is another key factor, as higher temperatures promote deeper penetration and stronger binding of the pigment within the fibers, increasing color durability, but may also accelerate the volatilization of essential oils, reducing their functional efficacy. An optimal fixation temperature thus ensures a balance between pigment stability and retention of the volatile oils, maintaining both color performance and bioactive functionality. These findings are in agreement with recent literature, which demonstrates that incorporating natural bioactive compounds into dyeing systems can sustainably enhance the protective and functional properties of textiles.

3.6. Characterization

3.6.1. FTIR Spectroscopic Analysis

FTIR analysis was conducted to investigate the chemical structure and confirm the presence of functional groups resulting from the applied treatment. The spectrum of the multifunctional/printed fabric samples revealed characteristic absorption bands corresponding to specific chemical bonds, indicating successful printing/finishing of the fabric surface. A strong and broad absorption band observed around ~1884 cm^{-1} is attributed to highly conjugated carbonyl group or structurally strained moiety, which is likely associated with the photochromic blue pigment incorporated into the sample. Peaks in the region of ~2197 cm^{-1} falls within the visible light and is characteristic of the active-colored form of the blue photochromic pigment [65-67]

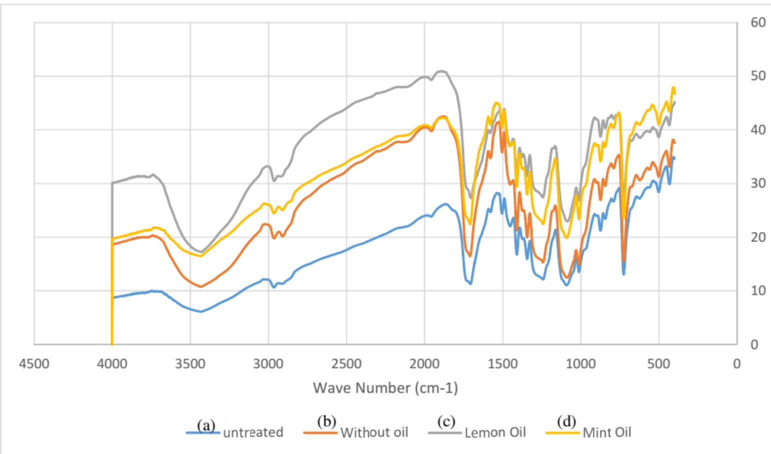


Figure 4: FTIR Spectra Comparison of the selected Samples: (a), untreated fabric; (b) printed fabric with blue photochromic pigment; (c), printed/multifunctionalised fabric with lemon oil; and (d), printed/multifunctionalised fabric with mint oil

Notably, a distinct peak at ~1738-1750 cm^{-1} was detected in the treated fabric, corresponding to the C=O stretching of ester or carboxylic functional groups, indicating the incorporation of crosslinking agents or oil-derived materials. The presence of new bands in the region of ~3200-3600 cm^{-1}, typically assigned to O-H stretching, 1000-1300 assigned to C-O-C stretching, further supports the formation of ester or ether linkages as a result of chemical bonding between the binder system and the fiber surface [68, 69].

Compared to the untreated sample, these spectral changes confirm that the treatment led to significant chemical modifications at the molecular level. The appearance or enhancement of functional group peaks in the treated fabric suggests the successful immobilization of bioactive or functional components, which is consistent with the observed improvement in performance properties such as antibacterial activity, UV protection, and washing durability [70, 71].

3.6.2. SEM and EDX Analysis

Scanning Electron Microscopy (SEM) was carried out to evaluate the surface morphology of the fabric before and after printing/finishing. The blank sample exhibited a relatively smooth and homogeneous fiber surface. In contrast, the treated fabric showed a distinct morphological change, with the appearance of surface roughness and a thin layer of deposited material uniformly covering the fiber surface. These features suggest the successful deposition and fixation of the treatment formulation onto the fabric matrix.

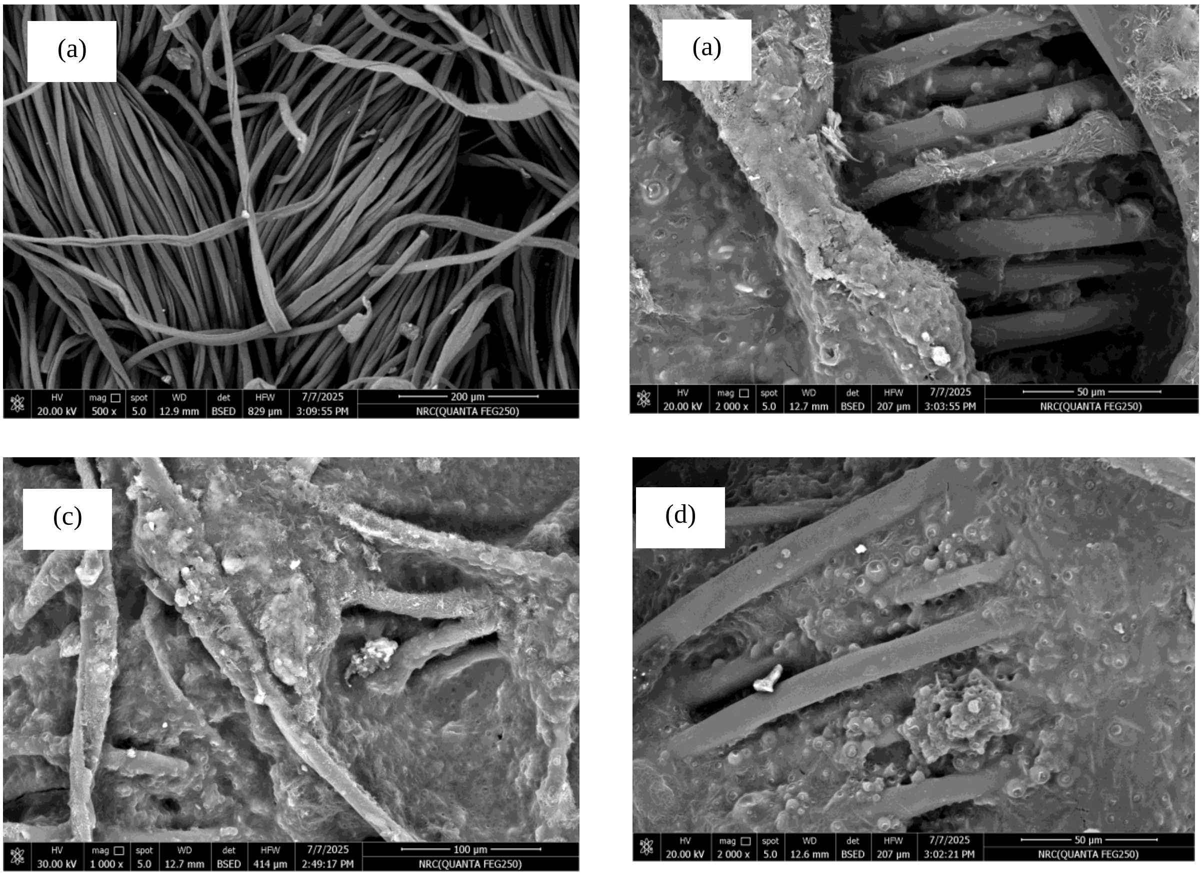


Figure 5: SEM micrographs: (a) Blank untreated C/PET fabric samples, (b–d) different areas of the printed/multifunctionalised sample with blue photochromic pigment and mint oil (concentration of 30 g/kg).

High-magnification SEM images revealed the presence of granular or film-like structures, indicating the formation of a coating layer, possibly resulting from the binder and functional additives used in the finishing process. The absence of cracks or phase separation within the coating suggests good compatibility and adhesion between the treatment system and the fiber substrate [72].

To complement the morphological observations, Energy Dispersive X-ray Spectroscopy (EDX) analysis was conducted to assess the elemental composition of the treated surface. The EDX spectrum confirmed the presence of key elements such as carbon (C), oxygen (O), and additional elements like nitrogen (N), NaK depending on the functional additives incorporated. The presence of NaK in the EDX spectra does not indicate the existence of a real Na-K alloy. Rather, it reflects the overlapping detection of sodium and potassium peaks, which are sometimes displayed together by the analysis software. The presence of sodium and potassium can be attributed to some of the printing auxiliaries, such as emulsifiers, binders, or softeners, which are often stabilized or formulated with alkali salts. Therefore, the detection of NaK is related to these auxiliary components of the printing paste rather than to the functional materials (photochromic pigment or mint oil).

The detection of these elements, which were absent in significantly lower amounts in the untreated fabric, supports the successful application and fixation of the treatment agents.

Overall, the SEM and EDX analyses provide strong evidence of effective surface modification, both in terms of morphological changes and elemental enrichment, which align with the enhanced functional performance observed in the treated fabric.

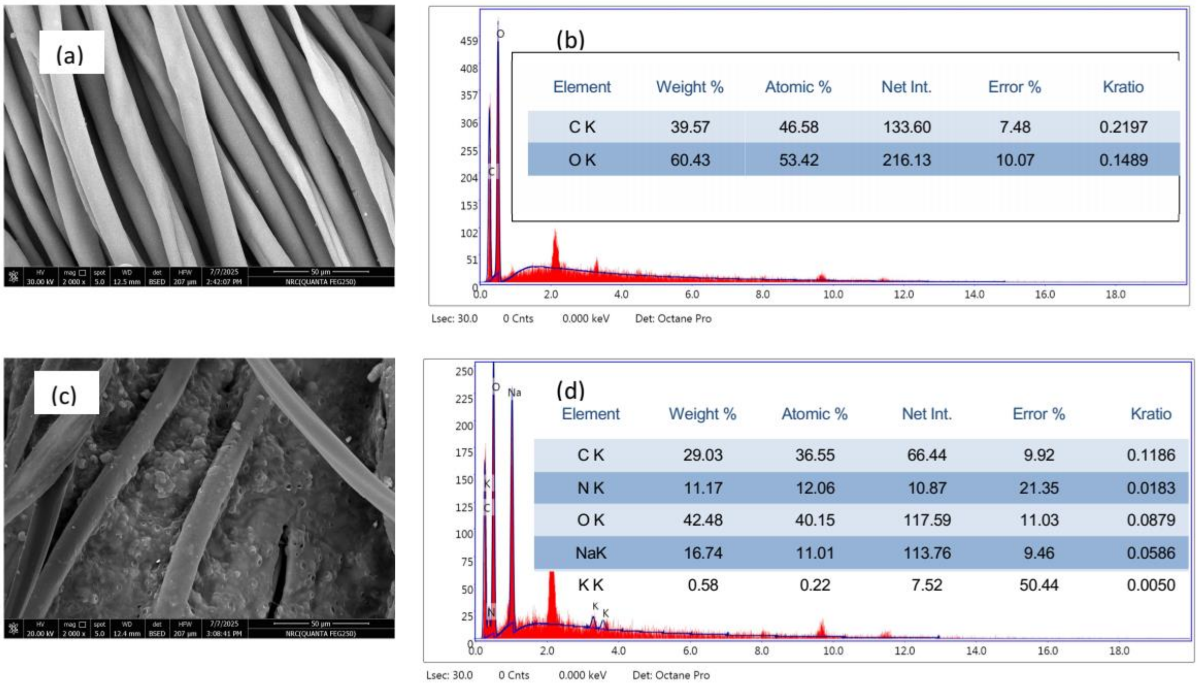


Figure 6: SEM and EDX graphs: (a) Blank untreated C/PET fabric, (b) EDX spectrum of the blank sample, (c) SEM image of the printed/multifunctionalised fabric with blue photochromic pigment and mint oil at the highest concentration, and (d) EDX spectrum corresponding to the printed sample

4. **Conclusion**

The comprehensive evaluation of the treated fabric clearly demonstrates the success of the applied finishing system in imparting durable and multifunctional performance. The treatment exhibited excellent fastness properties to washing and rubbing, with minimal deterioration even after 15 laundering cycles. Functional attributes such as UV protection (UPF) and antibacterial activity remained consistently high, indicating strong durability and stability of the active agents. The treated samples exhibited excellent durability, maintaining high color strength ($K/S \approx 7.6$) and strong UV protection ($UPF \approx 75.5$) even after 15 washing cycles, along with very good color fastness ratings (4–5), confirming the stability and multifunctional performance of the developed system.

Analytical techniques supported these findings: FTIR spectra confirmed the formation of new chemical bonds and functional groups, indicating successful chemical grafting and crosslinking at the molecular level. SEM analysis revealed a uniform and coherent coating on the fiber surface, while EDX elemental mapping verified the presence and distribution of key functional elements, further validating the effectiveness of the treatment.

Despite a slight decline in fragrance retention after repeated washing likely due to the volatility and partial removal of aroma compounds the overall performance profile remained robust. These results highlight the potential of this finishing system for use in high-performance textile applications where long-term functionality is essential. The integration of bioactive oils, durable binders, and optimized processing conditions proved to be a highly effective strategy for developing sustainable and resilient textile finishes.

5. Conflicts of interest

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

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