TMMOB Tekstil Mühendisleri Odası
UCTEA Chamber of Textile Engineers
Tekstil ve Mühendis
Journal of Textiles and Engineer

Yıl (Year) : 2025/1
Cilt (Vol) : 32
Sayı (No) : 137

Araştırma Makalesi / Research Article

SUSTAINABLE TEXTILES COLORED WITH TEA WASTE IN THE PRINTING PROCESS

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Gönderilme Tarihi / Received: 20.11.2024
Kabul Tarihi / Accepted: 13.01.2025

ABSTRACT: The primary aim of the study is to explore the use of tea waste, a natural and sustainable material, as an alternative to synthetic dyes that pose risks to human health and the environment in the printing process of 100% cotton fabrics. For this purpose, tea waste was processed using an extraction method to obtain a natural dye extract, which was then added to the printing paste to carry out the printing process. To enhance the wash durability of fabrics dyed with the natural dye derived from tea waste, a softener formulation was modified by incorporating different ratios of quaternary ammonium compounds. The study investigated the applicability of tea waste extract in dyeing 100% cotton woven fabrics and examined the wash fastness of these fabrics. Fastness tests were conducted on the dyed fabrics in accordance with relevant standards, and the results showed that the fastness values were at the highest levels based on the gray scale evaluation. SEM was employed to perform characterization analyses on tea waste and fabric samples. Additionally, SEM-EDX was used to analyze the elemental composition of the materials. According to thes test results, it was found that cotton fabric dyed using tea waste as a natural dye pigment had the highest K/S value when compared to untreated fabric. Fastness properties did not change significantly after application or washing processes. According to SEM analysis, it was determined that the chemical particles of the printing paste were located between the fibers of the treated samples. By repurposing tea waste for use in textile finishing, the study contributes to the production of sustainable textile products.

Keywords*:* Sustainability, woven fabric, tea waste, extraction, printing

BASKI PROSESİNDE ÇAY ATIKLARIYLA RENKLENDİRİLEN SÜRDÜRÜLEBİLİR TEKSTİLLER

ÖZ: Çalışmanın temel amacı, insan sağlığına ve çevreye karşı tehlike oluşturan sentetik boyarmaddelere alternatif olarak doğal ve sürdürülebilir özellikteki çay posası ile %100 pamuklu kumaşların baskı prosesinde renklendirilmesini kapsamaktadır. Bu amaçla sentetik boyarmadde yerine çay atığının ekstraksiyon yöntemi ile doğal boyarmadde ekstratı elde edilmiş ve ardından çay atığının ekstraktesi baskı patına ilave edilmiş ve baskı işlemi gerçekleştirilmiştir. Çay atıklarından elde edilen doğal boyarmaddenin tekrarlanan yıkamalara karşı dayanıklı hale gelebilmesi için yumuşatıcı apre reçetesine farklı oranlarda kuaterner amonyum bileşiği ilave edilmiştir. Çalışma kapsamında, bu yöntem kullanılarak %100 pamuklu dokuma kumaşların renklendirilmesinde çay atığı ekstraktının uygulanabilirliği araştırılmış ve çay atığı ile renklendirilen %100 pamuklu dokuma kumaşların yıkama dayanımları incelenmiştir. Elde edilen kumaşların ilgili standartlar doğrultusunda haslık testleri yapılmıştır. Test sonuçları incelendiğinde, haslık değerlerinin gri skalaya göre en üst seviyelerde olduğu gözlemlenmiştir. SEM ile atık çay posasının ve kumaş numunelerinin karakterizasyon analizleri, SEM-EDX ile materyalin temel bileşenleri incelenmiştir. Test sonuçlarına göre çay posası ile baskı işlemi görmüş kumaşın K/S renk verimi değeri işlem görmemiş kumaşa göre en yüksek seviyede olduğu görülmüştür. İşlem veya yıkama işleminden sonra haslık değerleinin ciddi derecede değişim göstermediği belirlenmiştir. SEM görüntülerine göre, işlem görmüş numunlerde lifler arası kimyasal birikmeler tespit edilmiştir. Böylece çay atıklarının geri kazanımı ve tekstil terbiyesinde kullanımı sağlanarak sürdürülebilir tekstil ürünleri üretilmiştir.

Anahtar Kelimeler: Sürdürülebilirlik, dokuma kumaş, çay atığı, ekstrakte, baskı

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DOI: *https://doi.org/10.7216/teksmuh.1593823* *www.tekstilvemuhendis.org.tr*

1. INTRODUCTION

In the textile industry, auxiliary chemicals and in particular synthetic dyes used in processes such as dyeing and finishing, contribute significantly to environmental pollution. These substances often contain hazardous compounds that can contaminate water, air, and soil, posing risks to ecosystems and can lead to adverse health effects in humans through exposure or to consumption of the contaminated resources [1]. Among the synthetic dyes used for dyeing textiles, there is the use of azo dyes with high wash fastness and color brilliance [2]. However these dye groups have been found to have toxic, carcinogenic effects and pollute the environment [3-8], while also posing serious health risks to workers, including acute and chronic diseases, as well as kidney, brain, central nervous system, and reproductive problems due to exposure to dye waste [9-12]. Recently, it has been observed that due to the identified disadvantages of synthetic dyes, the popularity of natural dyes as an alternative [13-15] for dyeing processes of textile surfaces carried out different methods is increasing. Plants, algae, and insects have long been used as natural sources of dyes in textile dyeing. Examples include root dyes, such as madder and woad, which produce bright reds and blues, respectively; pomegranate peels, known for their yellow and brown hues; and cochineal, an insect-based dye that produces rich reds. Similarly, turmeric, which is extracted from the rhizome of the plant, is often used for its bright yellow color. Other examples include indigo, which is extracted from the indigofera plant and produces deep blue hues, and saffron, which is extracted from the crocus flower and imparts golden yellow hues. These natural dyes not only offer a broad spectrum of color but are also a more sustainable and environmentally friendly alternative to synthetic dyes, making them valuable for traditional and modern textile applications [16-20]. Despite their sustainability and vibrant color properties, however, natural dyes often have to contend with considerable problems when it comes to washing fastness. The dyes tend to bond weaker with the textile fibers compared to synthetic dyes, causing the colors to fade or bleed during washing. Factors such as the lack of strong chemical fixatives and the variability of natural dye compositions also contribute to their limited durability. This problem has limited the widespread use of natural dyes in industrial applications, where high demands are placed on performance standards, including the durability of the color [21-24]. Mordants create chemical bonds between the dye and the fabric, increasing the absorption of the dye and improving fastness properties such as wash, light and rub fastness [25-27]. It is known that one of the most important and popular cationic agent used in the textile sector is a quaternary ammonium salt [28]. The use of this substance provides achieving intense and permanent colors on the fiber and reduces the hydrolysis of dyed fabrics by ensuring fixation on the fiber. This results in wastewater containing less hydrolyzed dye during washing, thus reducing wastewater pollution [29]. When researching colouring techniques with natural pigments, it becomes clear that both conventional and environmentally friendly methods are used. There are various approaches, such as applying the dye directly to the fabric or yarn or other application techniques [30, 31].

There are several studies in the literature that deal with natural dyeing processes for various textile materials. In one of them, yarn was dyed with extracts of black carrot and blueberry waste using different mordants. The results showed that fabrics dyed with blueberry waste had low fastness values, while those dyed with black carrot waste showed higher fastness values [32]. In another study, pomegranate peels, raisins, quince peels, tea leaves and apple leaves were extracted to dye wool yarn using different mordants [33]. When recent studies are investigated, it could be determined that reddish-brown natural dye extracted from walnut shells was used to dye wool fabrics by ultrasonic irradiation [34]. In another study, hemp fabrics were dyed together with extracts of *Buddleja officinalis* flowers using natural mordants, and as a result of the study, it was found that the color fastness of the fabrics improved [35]. In another study, environmentally friendly dye solutions were prepared by extracting natural pigments and applied to fabrics by dipping, including eco-printing techniques [36]. However, specialized studies conducted on a laboratory scale may not be sufficient for industrial applications. It is therefore essential to expand research to industrial-scale methods to effectively produce sustainable and environmentally friendly textile products in large quantities to meet the needs of the textile industry [37]. It is known that most studies in the literature use plant extracts and extracts of natural substances as natural colourant; however, it was found that there are few studies on the extraction of colourants from natural wastes [38-41]. Especially in Türkiye, the high consumption of tea and the large amounts of its waste allow these wastes to be evaluated in different areas. Although there are few studies in the literature specifically focused on tea waste [42,43], no similar studies have been found in the literature on the coloring of 100% cotton woven fabrics using tea waste extraction with the rotary printing technique, either at the laboratory or industrial scale, where acceptable fastness values and repeated washing resistance have been achieved in our study. This study fills an important gap in the literature by demonstrating the practical application of waste tea as a sustainable and scalable natural dye source, addressing both environmental concerns and industrial requirements. Unlike other natural dyeing researches, which often focuses on small-scale or laboratory-based experiments, this work bridges the divide between ecological sustainability and industrial scalability. It highlights how waste materials, such as tea pulp, can be effectively utilized to reduce reliance on synthetic dyes without requiring advanced technologies or additional synthesized materials. This study aimed to minimize the negative impacts of synthetic dyes on the environment and human health, resulting in the production of "sustainable" textile products in industrial scale. To achieve this, a natural dyestuff was extracted from eco-friendly and environmentally sustainable tea waste, which was then used to color textile surfaces using the rotation printing technique. In doing so, both the recovery and utilization of tea waste were accomplished, and textile products free from synthetic dyes were created with sustainable properties. The study presents an innovative green solution for coloring fabrics with natural dyes.

2. MATERIAL VE METHOD

2.1 Material

This study, used 100% cotton plain weave fabrics, made from Ne 30/1 yarns with a density of 25 weft/cm and 33 warp/cm. The fabrics were pretreated with a desizing enzyme (Genkim, Türkiye) and a wetting agent (ER-SA, Türkiye) on an OSTHOFF-SENGE 42327 WUPPERTAL desizing machine. The fabrics were then bleached on a MENZEL continuous bleaching machine with bleaching agent (ER-SA, Türkiye), NaOH (32 Bé) (Borkim Kimya, Türkiye) and H_2O_2 (Tempo Kimya, Türkiye). Wax-based softener (Akkim, Türkiye), polysiloxane compounds (Akkim, Türkiye), fabric softeners (Rudolf Duraner, Türkiye) and quaternary ammonium compounds (Tex-Tek, Türkiye) were used. The tea was supplied by Caykur factory, located in Rize, Türkiye.

2.2. Method

2.2.1. Pre-treatment Method

The fabrics were first pretreated to prepare them for the rotary printing process. Details of the pretreatment procedures and the chemicals used can be found in Table 1. The desizing process was carried out at a speed of 70 m/min for 3 minutes at a temperature of 60°C. The bleaching process was completed in 20 minutes at a speed of 80 m/min. After tea extraction, the fabrics were printed and finished with softeners and quaternary ammonium compounds, which are used for 100% cotton fabrics. Technical information on these agents can be found in Table 2. The recipe for the printing paste can be found in Table 3.

2.2.2. Dye Extraction and Preparation of Printing Paste

In order to dye extraction of tea waste, 100 g of tea waste was kept with 900 ml of water for 1 hour. Then the opening of the beaker was closed and allowed to infuse for 30 minutes. After the brewing process, the residues of the tea and the colored liquid were separated using a 150 mesh strainer. The resulting solution is mixed with water and dye-free printing paste and prepared for use in the rotary printing process (Figure 1). The printing paste formulation used is listed in Table 3. Printing screens with a thickness of 150 mesh were used in the rotary printing machine. After the printing process, the fabrics were dried at 100°C for 10 minutes.

Table 1. Pre-treatment processes and the chemicals used

Process Step	Machine Name	Chemical Substances	Supplier Company	Amount of Chemical Substance Used
Desizing process	OSTHOFF-SENGE 42327 WUPPERTAL	Amylase desizing enyzme	Genkim, Türkiye	0.1%
		Nonionic surfactant combination	Er-Sa, Türkiye	0.1%
Bleaching process	MENZEL continuous processing machine	Monohydrate 2-(2-butox-ethoxy) ethanol-combined agent	Er-Sa, Türkiye	0.8%
		NaOH	Borkim Chemical, Türkiye	2.5%
		H_2O_2	Tempo, Chemical, Türkiye	3%

Table 2. Materials used in the padding method and technical information

Chemical Structure	Ionity	Supplied Company
A mixture of organic and synthetic waxes	Non-ionic	Akkim, Türkiye
Polysiloxane compound micro	Non-ionic	Akkim, Türkiye
A mixture of polyethylene and waxes	Non-ionic	Rudolf Duraner, Türkiye
Quaternary ammonium compound	Cationic	Tex-Tek, Türkiye

Table 3. Used Printing Paste Recipe

Chemical Substance Name	Structure of Chemical Substances	The Amount of Use (g/kg)	Supplied Company
Alginate	Sodium Alginate	15	CHT Chemical, Türkiye
Soda	Sodium bicarbonate	30	ETİSODA, Türkiye
Ludigol	Sodium meta nitro benzene sulfonate	20	APANİMEX, India
Thickener	Acrylic-based polymer	25	MYD Chemical, Türkiye
Urea	46% Nitrogen	100	İGSAŞ, Türkiye

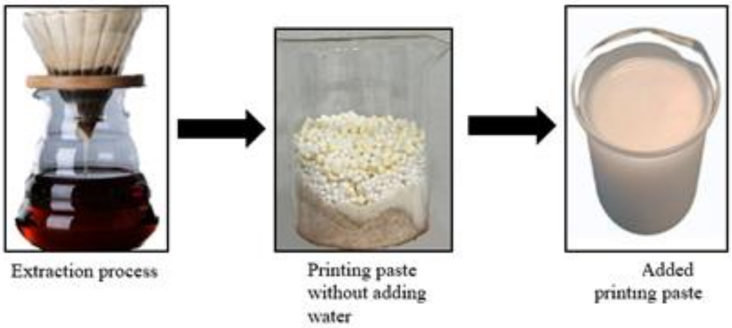


Figure 1. Combination of printing paste and tea waste extract

2.2.3 Padding Method

A quaternary ammonium compound was used to bind the natural dye obtained from tea waste to the fabrics and thus increase their resistance to repeated washing. Various application recipes were developed in the study by incorporating different proportions of the quaternary ammonium compound into the fabric softener finishing solution used in the padding technique (Table 4).

The prepared formulations were applied to 100% cotton fabrics that had completed the printing process with an 80% wet-pick-up ratio in an ATAC pad machine and then dried in an ATAC oven at 100°C for 4-5 minutes. The schematic of the entire pad application is shown in Figure 2. The overall process flow diagram used in this study is shown in Figure 3.

2.3. Washing Process

The fabric samples were washed 20 times in an Altus household washing machine according to the ISO 6330-2012 standard and expressed as a 20W code. For drying, the samples were dried in an Arcelik brand drying machine at 40°C for 30 minutes. Finally, the fabric samples were conditioned for 24 hours under standard atmospheric conditions at a temperature of 20°C ±2 and a relative humidity of 65°C to prepare them for testing.

2.4. Applied tests

2.4.1 Performance Tests

Physical tests and analyses of fabric samples were carried out. Full details of the tests and the associated tests can be found in Table 5 [44].

Table 4. Recipe information to be used for the padding method

Prescription Code	A Mixture of organic and synthetic waxes (g/kg)	Polysiloxane compound micro emulsion (g/kg)	A Mixture of Polyethylene and Waxes (g/kg)	Quaternary Ammonium Compound (g/kg)
R01	20	20	5	75
R02	20	20	5	100

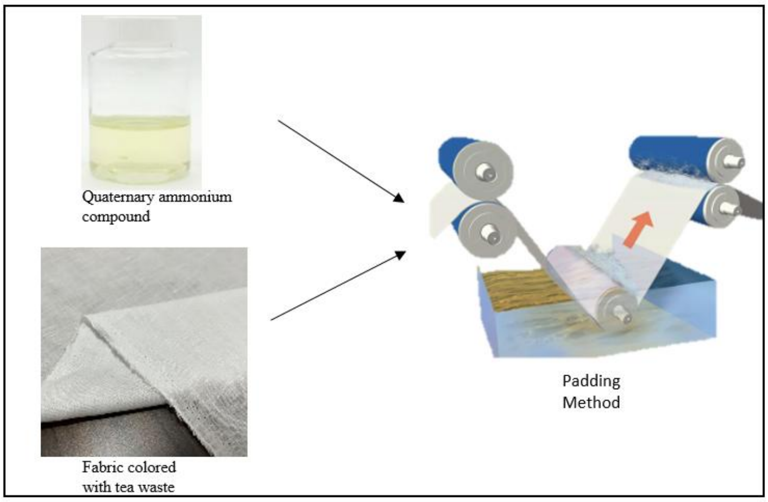


Figure 2. Padding method construction

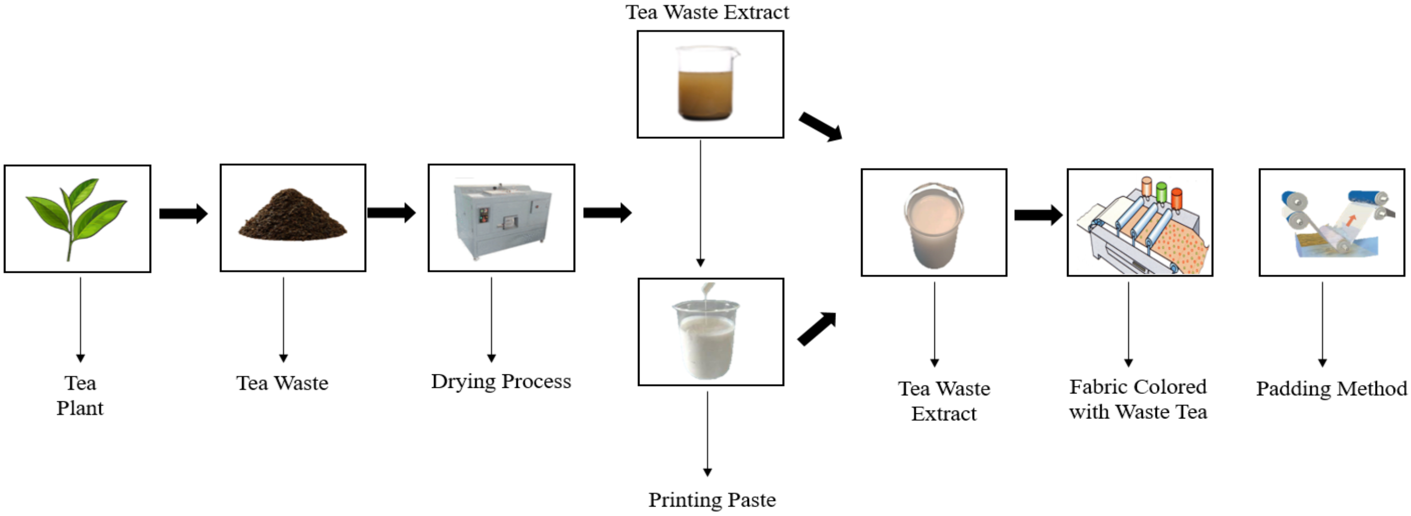


Figure 3. Applied process stages

Table 5. Performance Tests Standard

Test Type	Standard	Devices Used
Tear Strength	TS EN ISO 13937–2	James Heal Titan 2

2.4.2 Fastness Tests

Chemical tests and analyses of samples were carried out. A comprehensive breakdown of the relevant detailed tests and the associated standards can be found in Table 6 [45-48].

Table 6. Fastness Tests and Standards

Test Type	Standard	Devices Used
Washing Fastness	TS EN ISO 105-C06	Perspirometer, Stove
Acidic Sweat Fastness	TS EN ISO 105-E04	Perspirometer, Stove
Alkaline Sweat Fastness	TS EN ISO 105-E04	Perspirometer, Stove
Water Fastness	TS EN ISO 105-E01	Perspirometer, Stove
Dry Rubbing Fastness	TS EN ISO 105-X12	Crockmeter
Wet Rubbing Fastness	TS EN ISO 105-X12	Crockmeter

2.4.3 Color Measurement

The measurements were performed with a GretagMacbeth X-Rite Color i7 Benchtop spectrophotometer, was D65 daylight, with a standard observer of 10°. The test measured the L*,a*,b* and K/S values. The color difference was calculated using Formula 1, while the Kubelka-Munk equation is shown in Formula 2, where K, S and R are the absorption coefficients, slip coefficient and reflectance of the samples, respectively. ΔE is the numerical expression for the perceptual difference between two colors by determining the distance of a color in color space relative to the reference color [49].

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{0,5} \quad (1)$$

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

2.4.4 Scanning Electron Microscope (SEM) Analysis

The SEM and SEM-EDX analysis, which shows the basic components and morphological structures of the material [50], was carried out on the textile surfaces after PI-Au coating using the LEO 1430VP device at a magnification of 5000x.

2.4.5 Statistical Analysis

Results obtained from study IBM SPSS statistic 23 package program statistically evaluated by using one way-ANOVA with 95% confidence interval. The analysis was performed in one way-ANOVA with 95% confidence interval. With the ANOVA test, the effect of the amount of quaternary ammonium compound used on the results was examined and variables with a “p” value less than 0.05 were considered significant. In addition, pairwise comparisons between groups were made using the Tukey method.

3. RESULT AND DISCUSSIONS

3.1 Performance Test Results

Figure 4 shows the results of the tear strength tests of fabric samples with the untreated (R00), R01 and R02 formulations, and Figure 5 shows their 20-repeated washed versions.

Figure 4 shows that the tear strength of the treated fabrics has increased in both the weft and warp directions compared to the untreated fabrics. In addition to the various chemical softeners used in this study, the increase in tearing strength is attributed to quaternary ammonium compounds, which are known to chemically bind to cotton fabric [51]. It is known that the quaternary ammonium compound increases the tear strength of cotton fibers by increasing their elasticity and durability. This allows the fibers to increase their resistance to external influences [52-54].

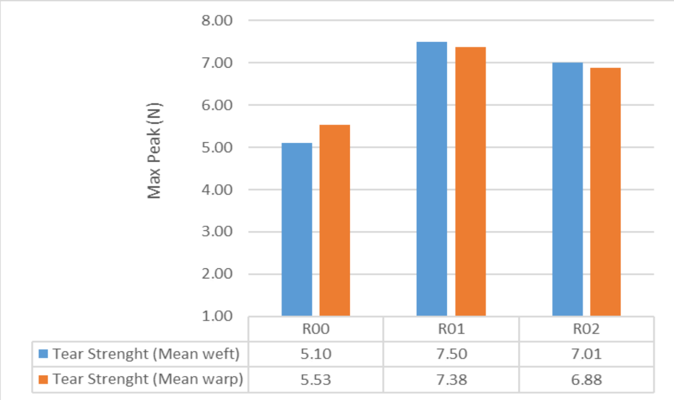


Figure 4. Tearing strength test results of R00 (untreated), R01 and R02

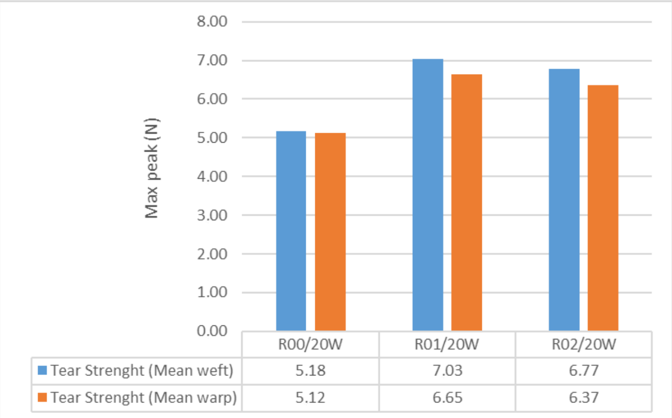


Figure 5. Tearing strength test results of R00/20W, R01/20W and R02/20W

According to Figure 5, after 20 repeated washings, a loss of approximately 5% in tear strength values was observed in both warp and weft directions of all fabrics. It was considered that the combined effects of chemical treatments that alter the fiber structure and mechanical strength which cause microdamage are the main reasons for the decrease in tear strength of cotton fabrics during washing [55,56].

3.2 Fastness Test Results

Figure 6 shows the fastness test results of fabric samples belonging to the recipes of untreated (R00), R01 and R02, and their 20 repeated washing versions are shown in Figure 7.

Quaternary ammonium compounds are a group of chemical agents commonly used in the processing of cotton fabrics, primarily as softeners and antistatic agents. These compounds release positively charged ions on the fabric surface, making the fabric softer and smoother. Additionally, they have binding properties that help enhance the adherence of dyes and other processing chemicals to the fabric. As stated in the literature [57,58] when used on cotton fabrics, quaternary ammonium compounds generally do not negatively affect fastness tests. These compounds have been observed to improve color retention, wash durability, and provide flexibility and softness to the fabric. As a result, here it proves that the quarter ammonium salt used in the study has no negative effect on the fastness properties of the fabrics. According to Figure 6, it was determined that all fastness values of both processed and unprocessed fabrics had the similar high levels. After 20 repeated washes, there was no noticeable change in all fastness values when compared to unwashed fabrics (Figure 7).

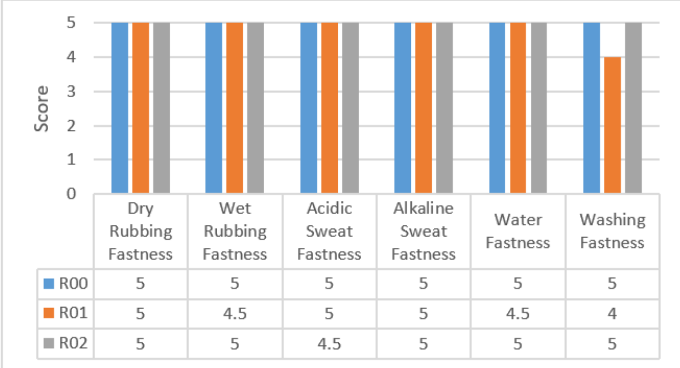


Figure 6. Fastness test results of R00 (untreated), R01 and R02

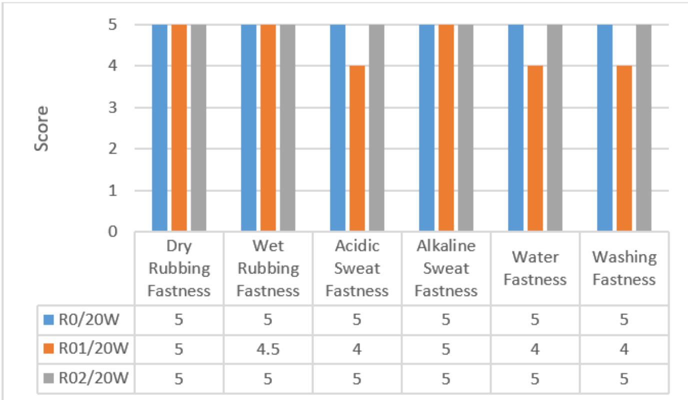


Figure 7. Fastness test results of R00W (untreated), R01/20W and R02/20W

Figure 8. Fabric images of R01 and R02 without washing and with 20 repeated washings(20W)

Table 7. Unwashed and washed color measurement results of untreated and treated fabrics

Prescription Code	L*	a*	b*	ΔE	K/S
R00	94.78	-0.09	3.40	0.76	-
R00/20W	92.70	-0.27	3.35	0.76	-
R01	81.36	2.76	16.27	2.24	0.60
R01/20W	85.50	1.52	14.86	2.24	0.47
R02	79.67	2.99	16.43	3.66	0.69
R02/20W	84.43	1.32	12.17	3.66	0.47

3.3 Color Measurement Results

In the color space, the a* and b* axes in the vertical position form the planar color table. A positive a* value represents red, and a negative value represents green. A positive b* value represents yellow, and a negative value represents blue. The point where these two axes intersect represents the colorless point. Vertically from the colorless point, the colorless axis consisting of white-gray-black is located and is called the L* axis. This axis passes through the colorless point. The L* (brightness) value includes values from 0 to 100 (from black to White [59,60].

CIELAB values of unwashed and washed samples of untreated and treated fabrics are presented in Table 7. Quaternary ammonium compound is often used as a fixative in the natural dyeing of cotton fabrics. As seen in Table 7, the increase in the amount of quaternary ammonium compound decreased the L* value of the fabric samples. The color tends to decrease as the amount of quaternary ammonium compound increased. When the results are examined, it is seen that the yellow color tone is dominant because the b* value of both fabric samples (R01 and R02) is higher than a* and has positive values. It can be seen that the K/S values in Table 7 are between 0.69 and 0.0. It was found that cotton fabric dyed using tea waste as a natural dye pigment had the highest K/S value when compared to untreated fabric. When the K/S values of the samples applied with different amounts of quaternary ammonium compounds were examined, it was concluded that the recipe containing high amounts of quaternary ammonium (R2) increased the color yield. When ΔE values are examined, it is seen that the color difference in fabrics increases as a result of 20 repeated washings and therefore the color cannot be preserved. As a result, it was observed that as the amount of use of the quaternary ammonium compound increased, the color yield increased. Fabric images of R01 and R02 without washing and with 20 repeated washings (20W) are shown in Figure 8.

3.4 Scanning Electron Microscope (SEM) Analysis

3.4.1 SEM Analysis

Figure 9 presents SEM micrographs of the solid form of waste tea (a) and fabric samples: untreated fabric (R00, b) and treated samples (R01, c; R02, d). In Figure 9(a), the micrographs reveal the presence of distinct particles associated with waste tea, characterized by their irregular shapes and varying sizes, indicative of its heterogeneous composition. These particles suggest potential for interaction with fabric surfaces due to their structural features. Figure 9(b) shows the surface morphology of the untreated fabric (R00), where no visible accumulation of chemical substances is observed. The fiber structure appears smooth and intact, without any surface modifications or extraneous material deposition. In contrast, Figures 9(c) and 9(d) illustrate the treated fabric samples (R01 and R02), where noticeable deposition of chemical particles is evident. These particles, originating from the printing paste, are distributed predominantly between the fibers. The adhesion and distribution patterns of these particles vary slightly between R01 and R02, potentially influenced by the formulation parameters. The presence of these particles indicates successful application of the printing paste, enhancing the fabric's surface functionality. Overall, the SEM analysis highlights the significant differences in surface morphology between untreated and treated fabrics, demonstrating the effectiveness of the applied treatments in modifying the fabric surface.

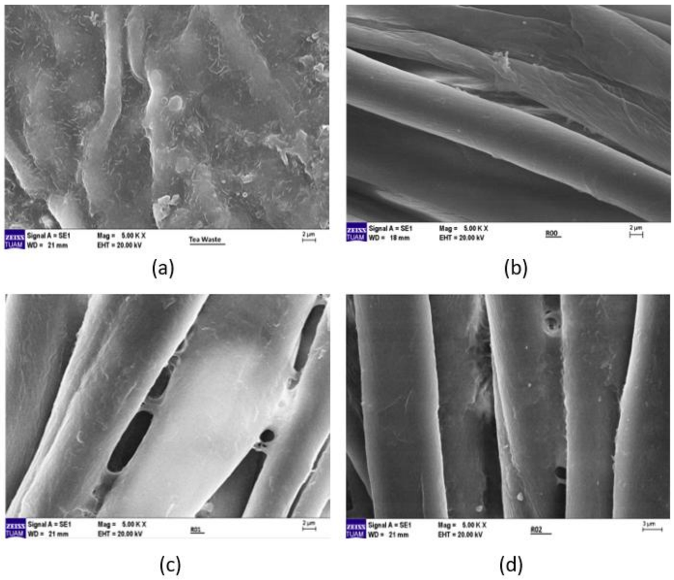
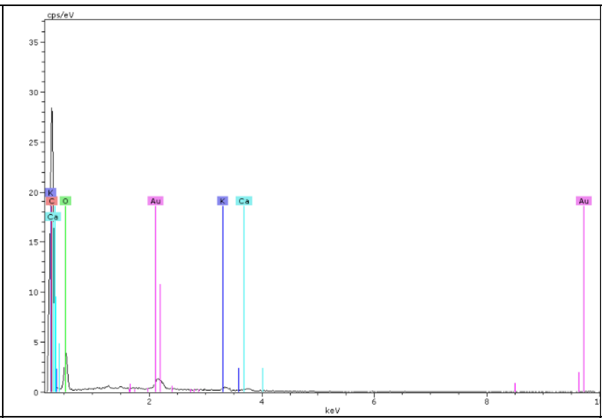


Figure 9. SEM images **a.** Tea waste, **b.** R00, **c.** R01, **d.** R02, respectively

3.4.2 SEM-EDX Analysis

SEM micrographs of the tea waste in the solid form (a) and the fabric samples of R00 (b), R01 (c), R02 (d) are given in Figure 10.

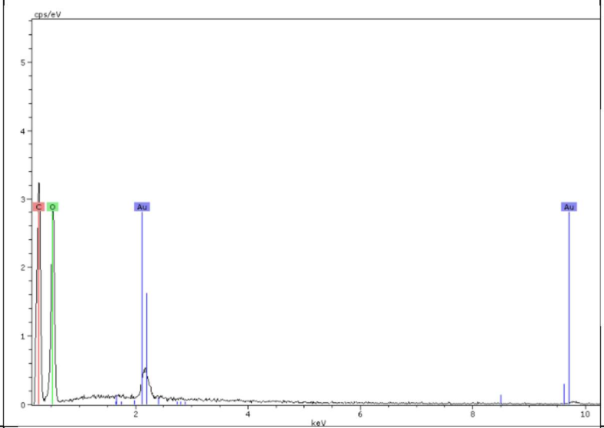
(a)



Spectra: object

Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	68801	57.73	57.73	64.79
Oxygen	K series	9569	41.48	41.48	34.94
Potassium	K series	1261	0.42	0.42	0.14
Calcium	K series	1037	0.37	0.37	0.12
		Total:	100.0 %		

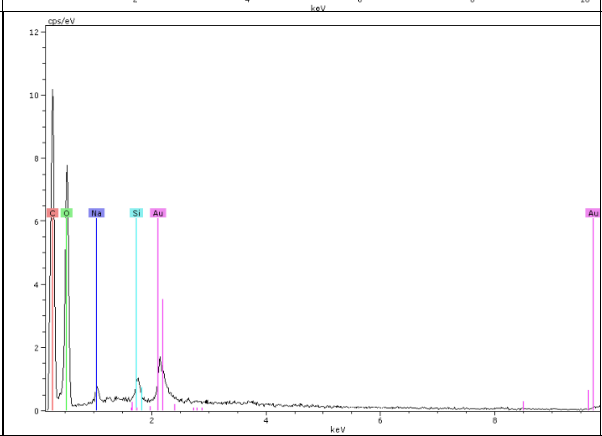
(b)



Spectra: object

Element	Series	Net	unn. C [wt.-%]	Norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	13062		31.33	39.42
Oxygen	K series	11080		63.72	60.20
		Total:	100.0 %		

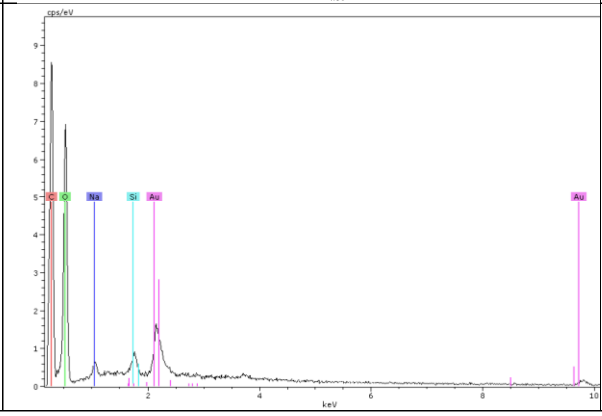
(c)



Spectra: object

Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	26941	33.46	33.47	40.35
Oxygen	K series	20618	64.75	64.76	58.61
Sodium	K series	1786	1.12	1.12	0.70
Silicon	K series	2393	0.66	0.66	0.34
		Total:	100.0 %		

(d)



Spectra: object

Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	25750	32.55	32.55	39.28
Oxygen	K series	21284	66.23	66.23	60.00
Sodium	K series	1653	0.82	0.82	0.52
Silicon	K series	1889	0.41	0.41	0.21
		Total:	100.0 %		

Figure 10. SEM-EDX graphs and element percentages table of **a.** tea waste, **b.** R00, **c.** R01, **d.**R02

Figure 10 presents the elemental analysis conducted via SEM-EDX, providing valuable insights into the composition of tea waste and treated/untreated fabric samples. In Figure 10a, the analysis of tea waste reveals the predominant presence of elements such as carbon (C), oxygen (O), potassium (K), and calcium (Ca). These findings are consistent with the inherent composition of tea waste, as supported by prior studies [61–63]. For instance, one study identified tea waste as comprising primarily carbon (54.78%) with a minor nitrogen content (2.45%), while another reported 2.23% nitrogen and 1.209% potassium, alongside a significant oxygen component These results highlight the natural abundance of organic and inorganic elements in tea waste, making it a versatile material for various applications. In Figure 10b, the untreated 100% cotton fabric contains only carbon (C) and oxygen (O), which is in alignment with literature values for natural cotton fibers. These elements reflect the cellulose-based structure of cotton, composed primarily of carbohydrate polymers rich in carbon and oxygen [64-66]. The impregnated and treated fabrics, analyzed in Figures 10c and 10d, display a more complex elemental composition. The presence of silicon (Si) is attributed to the application of a polysiloxane compound used during the impregnation process to impart a soft touch to the fabric. Polysiloxane compounds are characterized by their Si–O–Si bonds, formed through the bonding of silicon atoms with oxygen. This distinct chemical structure is evident in the SEM-EDX spectra and confirms the successful integration of the polysiloxane compound into the fabric [67-69]. Additionally, sodium (Na) is detected in the treated fabric samples. Its presence can be traced back to the use of a quaternary ammonium compound in the padding method, applied during the fabric treatment. Quaternary ammonium compounds often contain sodium, either as part of their molecular structure or as salts like sodium benzoate. Literature suggests that these surfactants are versatile and can form homogeneous solutions, such as with cyclohexane, which enhances their application in textile treatments [70]. Thus, the sodium molecules observed in Figures 10c and 10d are likely residues from the quaternary ammonium compound used in the process.

The elemental analysis by SEM-EDX provides a detailed understanding of the chemical transformations and material integrations achieved through treatment, highlighting the unique contributions of tea waste, polysiloxane, and quaternary ammonium compounds in modifying the fabric properties.

3.4.3 Statistical Analysis

The average values of the tear strength (N) test results in weft and warp directions of all fabrics used in the study are shown in Figure 4 and Figure 5. Statistical analysis of the data was performed at 95% confidence interval. Since the P value=0.000<0.05 in the ANOVA of the tear strength of both directions of the fabrics, it shows that there are significant differences between the tear strengths. In the homogeneity of variances test results, since p=0.73>0.05 for breaking strength in weft direction and p=0.113>0.05 for breaking strength in warp direction, Ho hypothesis is accepted, which proves that there is a homogeneous distribution between the groups. Since there was a homogeneous distribution between the groups, multiple comparisons were made with the Tukey method. A pairwise comparison of the tear strengths of the fabrics in the weft direction is presented in Table 8 and in the warp direction in Table 9. In the tables, the mean difference is accepted as significant at 0.05 level. The data shown with * indicates that there is a significant difference between the two groups. When the data shown with * are examined, it is seen that all values in Table 8 and Table 9 are less than 0.05 and there is no statistical difference in the pairwise comparisons of the groups.

Table 8. ANOVA pairwise comparison of tearing strength results of fabrics in weft direction

Prescription Code	R0	R1	R2	R0/20W	R1/20W	R2/20W
R0	-	0.000*	0.000*	1.000	0.000*	0.000*
R1	0.000*	-	0.545	0.000*	0.588	0.155
R2	0.000*	0.545	-	0.000*	1.000	0.958
R0/20W	1.000	0.000*	0.000*	-	0.000*	0.000*
R1/20W	0.000*	0.588	1.000	0.000*	-	0.942
R2/20W	0.000*	0.155	0.958	0.000*	0.942	-

Table 9. ANOVA pairwise comparison of tearing strength results of fabrics in warp direction

Prescription Code	R0	R1	R2	R0/20W	R1/20W	R2/20W
R0	-	0.000*	0.000*	0.237	0.000*	0.001*
R1	0.000*	-	0.094	0.000	0.005*	0.000*
R2	0.000*	0.094	-	0.000*	0.791	0.840
R0/20W	0.237	0.000*	0.000*	-	0.000*	0.000*
R1/20W	0.000*	0.005*	0.791	0.000*	-	0.629
R2/20W	0.001*	0.000*	0.840*	0.000*	0.015*	-

4. CONCLUSION

Natural dyes are increasingly recognized as viable alternatives to synthetic dyes, which are associated with carcinogenicity, mutagenicity, and significant environmental harm. Due to their biodegradability and eco-friendly nature, natural dyes hold great promise for reducing the environmental footprint of the textile industry. This study aimed to leverage waste tea—a natural, ecological, and sustainable material—to color textile surfaces without relying on synthetic dyes, both at the laboratory and industrial scale. This innovative approach not only contributed to the upcycling of waste materials but also resulted in textile surfaces dyed with an environmentally friendly and renewable resource. To achieve this, 100% cotton woven fabrics were dyed using natural dyes extracted from waste tea through an efficient extraction process. The rotary printing technique was employed for dye application, ensuring uniformity and scalability. In the finishing process, the fabrics were treated with a quaternary ammonium compound to enhance the bond between the natural dye and the fabric fibers, significantly improving washing resistance. Durability tests confirmed that the dyed fabrics withstood up to 20 repeated washing cycles without significant loss of color. Moreover, physical and chemical performance tests were conducted on the fabric samples in accordance with industry standards. The results indicated that the applied chemicals, including the quaternary ammonium compound and softeners, did not compromise the structural integrity or performance of the fabrics. Advanced surface and elemental analyses using SEM and SEM-EDX revealed key elemental components associated with the quaternary ammonium compound and softeners, confirming their integration into the fabric matrix. The successful dyeing of the fabrics with waste tea was further validated by an increase in K/S values, indicating effective coloration. This study demonstrates the feasibility of producing sustainable textile products on an industrial scale using waste tea, a natural and upcycled material. Importantly, this process required no additional advanced technology or synthesized materials, showcasing its practicality and cost-effectiveness for large-scale applications. The findings underscore the potential of tea waste as a valuable resource for sustainable textile production, opening pathways for the exploration of other waste materials for similar applications. Future studies are planned to explore the use of natural cross-linkers as alternatives to synthetic finishing agents. Such investigations aim to further enhance the environmental compatibility and sustainability of the dyeing process while maintaining or improving fabric performance characteristics. By integrating natural cross-linkers, this approach could pioneer even greener solutions for textile manufacturing. By aligning with principles of sustainability and circularity, this study not only highlights the environmental and economic benefits of natural dyes but also positions waste materials as critical resources in the transition to greener textile manufacturing processes.

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