Research Article

Environmentally Friendly Textile Printing Methods: Examining Natural Dyes as Alternatives

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Received: 11 December 2024
Revised: 02 May 2025
2nd Revised: 12 August 2025
Accepted: 15 August 2025
Published: 27 August 2025

Reference: Kinli, Y. M., Göde, C., Ertun, İ. S., & Alsan, S. (2024). Environmentally friendly textile printing methods: Examining natural dyes as alternatives. The European Journal of Research and Development, 5(1), 113-129.

Abstract

The textile industry has significant environmental, economic, and social impacts, extending beyond production to marketing and consumption. High energy and water usage, synthetic chemical pollution, and the fast fashion model contribute to ecosystem disruption, resource depletion, and hazardous waste generation. Sustainable transformation in this sector is critical, particularly in dyeing and printing processes, which are among the most environmentally damaging stages. Natural dyes present a promising alternative due to their biodegradability and lower ecological footprint. However, technical limitations such as low colorfastness and inconsistent results hinder their industrial adoption. This study investigates the performance of algae-based natural dyes developed using Algaeing technology. Algae dyes offer high colorfastness, seasonal color consistency, and significantly reduce environmental impacts—cutting greenhouse gas emissions by up to 70% and water usage by up to 98%. Free from toxic substances, they promote a safer, more sustainable textile dyeing process. The research highlights the potential of algae dyes as a viable solution for improving sustainability in the textile industry.

Keywords: *Textile industry, sustainability, natural dyes, dyestuff, printing*

1. Introduction

Sustainability is a comprehensive concept that aims to manage environmental, economic, and social factors in a balanced manner [1]. The environmental impacts of the textile sector are not limited to the production process alone but also extend to the marketing and consumption stages. High amounts of energy and clean water are consumed throughout stages such as fiber production, yarn spinning, weaving, knitting, finishing, and garment manufacturing [3]. Starting from agricultural production, this process contributes to environmental pollution and disrupts the balance of ecosystems [2].

Moreover, the fast fashion phenomenon, reinforced by consumption-driven marketing strategies, significantly shortens product life cycles. Rapidly changing collections lead to overproduction, waste generation, and resource inefficiency [4]. Waste derived particularly from textiles dyed with synthetic substances contaminates the environment directly and contributes to severe pollution problems. These types of waste are often classified as hazardous.

Industrialization, population growth, technological advancement, globalization, and certain ideological paradigms have historically increased production and consumption rates. As a result, nature, the environment, animals, and plants have been perceived as infinite and disposable resources. At present, not only the natural environment but also human health and social values are suffering significant harm. The rapid rise in consumption puts immense pressure on natural resources, causing severe damage to ecosystems. Under the current global system, natural resources are being depleted rapidly, environmental degradation is accelerating, human health is at risk, and a wide range of economic, ecological, and social problems are emerging. Additionally, the excessive use of water and chemicals in production processes, irresponsible resource consumption, and the release of waste into nature negatively affect essential life sources such as air, water, and soil, thereby endangering planetary sustainability. The economic benefits of development cannot legitimize the global-scale issues it creates [7].

Reevaluating the textile industry in the context of sustainability and reducing its environmental impact is of critical importance globally. Efficient use of natural resources during production, reducing harmful chemicals, and promoting eco-friendly alternatives such as natural dyes are fundamental to this transformation. In this regard, integrating traditional knowledge with modern ecological approaches will significantly contribute to both environmental and social sustainability.

To achieve sustainability in the textile sector, an environmentally conscious approach must be adopted at every stage of production—from raw material to final product. It is crucial to prioritize materials that are non-toxic, durable, biodegradable, and recyclable. However, the question of how sustainability can be ensured specifically in the dyeing and printing processes of textile products remains a topic of ongoing debate [6].

Natural dyeing techniques have historically been utilized by humanity for centuries and were a fundamental component of textile production in the pre-industrial era. However, the rise of synthetic chemicals and mass production after the Industrial Revolution greatly diminished the use of natural dyes. In recent years, the scientifically documented negative effects of synthetic dyes on human health and the environment have raised awareness and accelerated the search for alternatives. In contrast, natural dyes exhibit far fewer environmental impacts and are more readily biodegradable [5].

New technologies and applications developed to enhance the performance and environmental sustainability of natural dyes are promising. Nonetheless, there are several technical challenges associated with natural dyes, such as low colorfastness, limited affinity to textile surfaces, and difficulties in reproducing consistent results. Factors like color stability and cost-efficiency limit the widespread industrial adoption of natural dyes, highlighting the need for further scientific research [8].

Despite their environmental benefits, many researchers emphasize the technical limitations that hinder the broader use of natural dyes in industry. One of the main issues is the poor color durability. Natural dyes often suffer from low affinity, uneven coloration, and fading. To mitigate these problems and fix the dyes onto fabrics, mordants—typically metal salts that are not always eco-friendly—are commonly used [9].

Furthermore, achieving consistent color shades is a major challenge, as the colors obtained depend on numerous variables such as the properties of the dye plant, harvest season, plant variety, growing conditions, soil composition, and climate. Some natural dyes are pH-sensitive; the pH level and mineral content of the water used also influence the final color. While these unique colors are considered an advantage in niche applications, standardizing and reproducing consistent colors is often not feasible [10].

In addition, natural dyeing processes are time-consuming and costly. Compared to synthetic dyes, achieving similar color intensity with natural dyes requires more water and raw material. Each production cycle aimed at replicating the same color involves substantial water, energy, and dye consumption, which poses another challenge to sustainability.

This study examines the dyeing and printing performance of natural dyes derived from algae using Algaeing technology. Compared to traditional natural dyes, algae-based dyes demonstrate high colorfastness and ensure color consistency across seasons.

Moreover, this innovative technology offers significant environmental benefits. It reduces greenhouse gas emissions by up to 70% and water usage by up to 98%. It also ensures water savings during the dyeing and printing processes and minimizes emissions.

Algae dyes do not contain toxic chemicals, pesticides, or bisphenols, creating a healthier environment for both production workers and end users.

2. Materials and Methods

As part of the project study, a woven fabric composed of 80% cotton and 20% viscose was produced using air-jet weaving machines. The constructional specifications of the produced fabric are presented in the table below.

Table 1: Constructional Properties of the Sample Woven Fabric

Property	**Specification**
Weave Type	1x1 Plain Weave
Warp Yarn Count	30/1 Ne Open-End
Warp Density	29 ends/cm
Weft Yarn Count	30/1 Ne Open-End
Weft Density	26 picks/cm
Fabric Weight (GSM)	124 g/m²

Fabric Width	197 cm

Pigment printing will be applied to the greige fabric with the constructional properties described above, using an algae-based dye. In this study, all processes up to the printing stage are carried out in accordance with the standard pigment printing procedure. The steps of the pigment printing process to be applied are outlined below.

Table 2: Pigment Printing Process Steps Used in This Study

No	Process Steps
1	Singeing and Desizing
2	Bleaching
3	Washing and Drying
4	Stentering (Pre – treatment)
5	Pigment Printing
6	Fixation
7	Stentering with Finishing
8	Calendering
9	Quality Control

The pre-treatment stages that prepare the woven greige fabric for the printing process constitute the first four steps of the overall procedure. Within the scope of the pigment printing process, the names of the chemicals used in these initial four pre-treatment steps are provided in the table below.

Table 3: Chemicals Used in the First Four Pre-Treatment Steps: Quantities and Purposes

No	Process Steps	Chemical(s) Used	Purpose of the Step
1	Singeing and Desizing	Desizing Enzyme Wetting Agent	The protruding fibers on the surface of the cotton yarns are removed through

			singeing. Additionally, the sizing materials applied to warp yarns to prevent breakage during weaving are removed, preparing the fabric for uniform printing.
2	Bleaching	Hydrogen Peroxide Stabilizer Wetting Agent	The natural yellowish color of the cotton is eliminated during the bleaching process to achieve a cleaner and whiter fabric surface.
3	Washing and Drying	Acetic Acid	Residual chemicals remaining on the fabric surface are removed through thorough washing.
4	Stentering (Pre – treatment)	—	The fabric is dimensionally stabilized and brought to the required width in accordance with the printing template before the dyeing process.

For the woven fabric prepared for the printing stage, a pigment printing paste is formulated. Unlike standard pigment printing recipes, this study utilizes only algae-based dye and a specific thickener developed exclusively for this dye. The names of the chemical substances used in the printing and finishing processes are listed in the table below.

Table 4: Chemicals Used in the Last Five Process Steps: Quantities and PurposesUsed in the First Four Pre-Treatment Steps: Quantities and Purposes

No	Process Steps	Chemical(s) Used	Purpose of the Step
5	Pigment Printing	Natural Pigment Dye (Algaeing dye)	Enhances the aesthetic appeal of the woven fabric through the printing method,

			transforming it into a finished product.
		Natural Thickener (Algaeing thickener)	Ensures proper viscosity and print paste consistency specific to the algae-based dye.
6	Fixation	—	Fixes the pigment dye onto the fabric surface after printing, ensuring durability and fastness.
7	Stentering with Finishing	Polyethylene	Provides softness to the fabric following pigment printing.
		Nonionic Softener	Enhances fabric hand feel and contributes to smooth texture.
8	Calendering	—	Adds surface gloss and smoothness to the fabric.
9	Quality Control	—	Final inspection to ensure the product meets required quality standards.

According to the standard pigment printing recipe, the most critical stages of the process in this study are the printing and subsequent finishing steps. For the printing stage, two different pattern numbers were selected, and corresponding screens were prepared for application via the rotary screen printing method. Details regarding the printing process and post-printing adjustments based on the pattern design are presented in the table below.

Parameter	Value
Pattern Number	201834
Screen Width	180 cm
Mesh Count	155 mesh
Squeegee Type	No. 10
Fabric Quality	VS172
Machine Speed	25 m/min
Printing Machine (Reggiani) No	3
Machine Record No	405
Printing Condition	Printed at 100% viscosity
Alga Thickener Consumption	5 g/kg
Fixation Process	
Fixation Machine No	426
Temperature	150°C
Duration	5 min
Stentering Process (After Printing)	
Stenter Machine No	209 (with softening treatment)
Coverage Ratio	60%

Figure 1:Settings for Printing and Post-Printing Process Steps of Trial 1

Parameter	Value
Pattern Number	205588
Screen Width	180 cm
Mesh Count	125 mesh
Squeegee Type	No. 16
Fabric Quality	VS172
Machine Speed	15 m/min
Printing Machine (Reggiani) No	3
Machine Record No	406
Printing Condition	Printed at 100% viscosity
Alga Thickener Consumption	5 g/kg
Fixation Process	
Fixation Machine No	426
Temperature	150°C
Duration	5 minutes
Stentering Process (After Printing)	
Stenter Machine No	209 (with softening treatment)
Coverage Ratio	71.40%

Figure 2:Settings for Printing and Post-Printing Process Steps of Trial 2

The purpose of the two experimental trials conducted within the scope of the natural dyeing study was to anticipate potential issues that may arise due to differences in pattern design and machine settings. However, no problems were encountered during either of the trials.

In this study, two different patterns were selected for Trial 1 and Trial 2, and production was carried out at different scales for each pattern.

Table 5: Product Dimensions Used in Trial 1 and Trial 2

Trial	Pattern Name	Duvet Cover (1 piece)	Pillowcase (2 pieces)
Trial 1	Jattevelmo	140 × 200 cm	80 × 80 cm
Trial 2	Dot Pattern	150 × 200 cm	50 × 60 cm

3. Testing and Experimental Procedures

Within the scope of our study, the two experimental trials were subjected to the following tests in the finishing laboratory of Menderes Tekstil.

Table 6:Tests Performed

Resistance to Pilling
Tensile Strength
Tearing Strength- Single Tear
Appearance After Wash-1 Wash
Appearance After Wash-10 Washes
Dimensinal Change After Washing and Drying
Colour Fastness to Artificial Light – Xenon Arc Fading Lamp Test
Colour Fastness to Perspiration
Colour Fastness to Rubbing
Colour Fastness to Saliva
Colour Fastness to Washing
Colour Fastness to Water
Flammability 45° Angle Test
Alkylhenolethoxylates (APEO)&Alkylphenols (AP) Content
Formaldehyde Content
Ph Determination

menderes

REPORT NUMBER: 23 000 DATE:27.11.2023

DESIGN NAME/NUMBER: 201834 - JATTEVALLMO

QUALITY: VS172

TESTS	STANDARD METHOD	REQUIREMENTS	COLOR	**JATTEVALLMO** **80%Cotton-20%Viscose** **YARN COUNT** Warp: 30 Ne Weft: 30 Ne **Construction Density** Warp: 86 th/inch Weft: 66 th/inch **Fabric Weight:** 122 g/sqm	
				dry	wet
RUBBING	ISO 105 X12	dry:4 wet:3	BEIGE	4/5	4
				staining	color change
CF TO PERSPIRATION	ISO 105 E04	staining:4 color change:4	BEIGE	4/5	3/4
CF TO WATER	ISO 105 E01	staining:3/4 color change:3/4	BEIGE	4/5	3/4
CF TO WASHING	ISO 105 C06	staining:4 color change:4	BEIGE	4/5	3/4
CF TO SALIVA AND PERSPIRATION	ISO 105 E04	staining:4 color change:4	BEIGE	4/5	3/4
CF TO LIGHT	ISO 105 B02	4/5	BEIGE	6	
APPEARANCE AFTER 10 WASH	ISO 6330	-	-	Will be tested at external test laboratory	
PİLLİNG	ISO 12945 /2	3	BEIGE	4	
				warp	weft
DIMENSIONAL STABILITY	ISO 6330	+2 / -4 %	-	-3,2	-1,9
FABRIC TENSILE	ISO 13934-1	min:250 N	-	364 N	300 N
TEAR STRENGHT	ISO 13937-2	min:8 N	-	8,0 N	8,1 N
FABRIC WEIGHT	ISO 3801	122 gr/m² (117,1 - 128,1)	-	122,5	

Figure 3:Test Results

Figure 4:Laboratory Test Results of Trial 1 Fabrics (Menderes Tekstil)

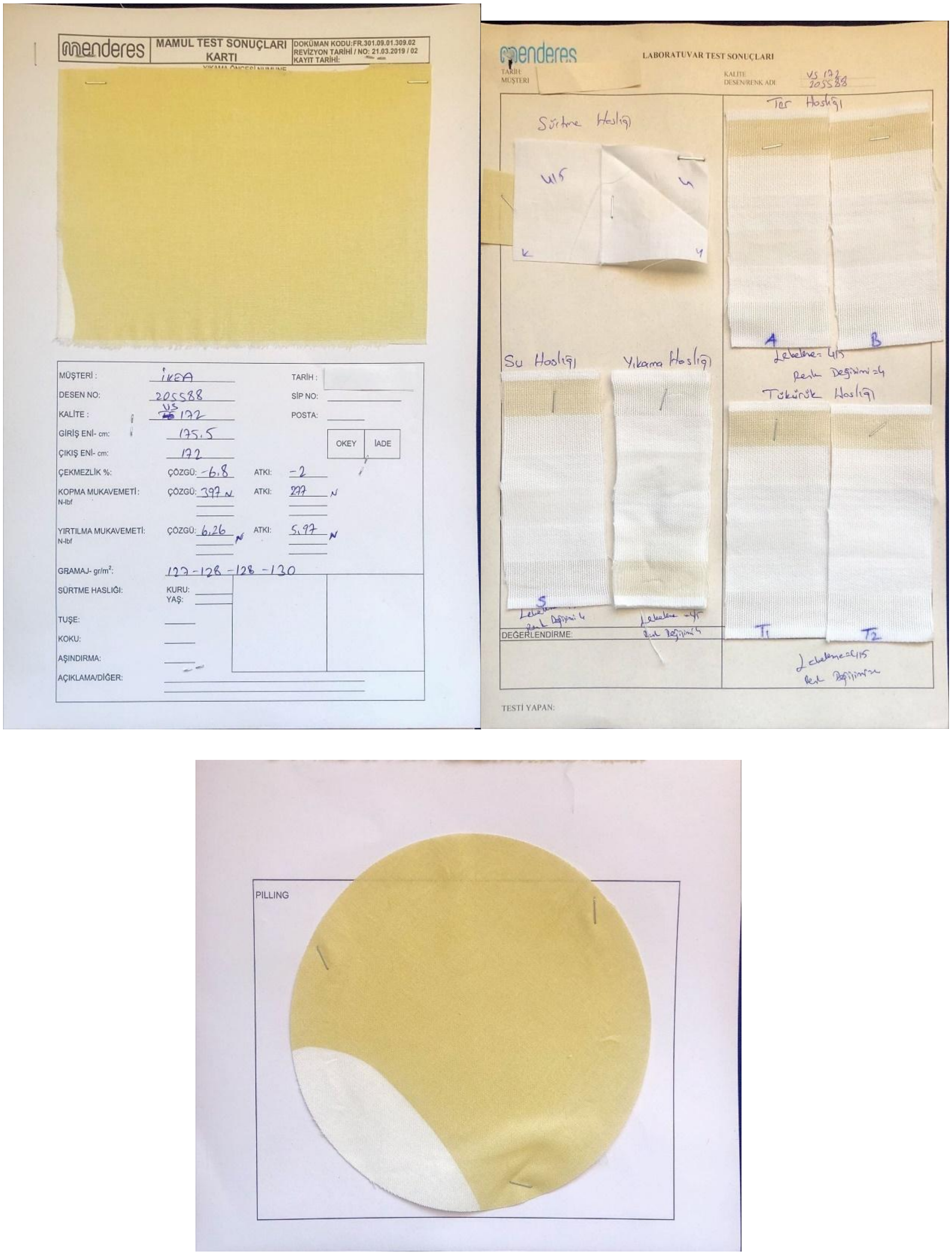

Figure 5:Laboratory Test Results of Trial 2 Fabrics (Menderes Tekstil)

4. Discussion

The results obtained from the tests conducted at the accredited Intertek laboratory are summarized as follows:

- **Pilling (Surface Fuzzing and Formation of Pills):** Desired levels of performance were achieved. The surface enhancement typically obtained through binder-based coating in pigment printing was similarly observed with the use of algae-based dyes.
- **Tensile and Tear Strength:** The values obtained are consistent with those previously recorded on pigment-printed fabrics, indicating no loss of mechanical durability due to algae dye use.
- **Appearance After Washing:** Cracks were observed on the printed areas of the fabric after washing. However, these cracks were significantly reduced by ironing at a medium heat (three-dot setting). Similar improvements were recorded after 1, 5, and 10 washing cycles with post-wash ironing.
- **Dimensional Stability After Washing:** Results were found to be acceptable.
  - Warp direction: –1.5%
  - Weft direction: –3.0%
    Notably, pigment-printed fabrics typically yield better shrinkage values since they do not undergo mercerization.
- **Colour Fastness to Migration into PVC:** This test is particularly relevant for products used in tumble dryers with PVC-coated inner drums. The result was 4–5 (on a scale of 1–5), indicating that the fabric does not stain the surface—an acceptable outcome.
- **Colour Fastness to Light (for Yellow Shades):** A value of 6 was obtained on a scale of 1 to 8. This is above average for light shades, which typically score around 3, making this result highly satisfactory.
- **Colour Fastness to Perspiration:** A score of 4–5 (out of 5) was recorded for both staining and color change. The results are considered favorable.
- **Colour Fastness to Rubbing:** This is often a challenge for pigment dyes. However, both dry and wet rubbing tests yielded values of 4–5, indicating excellent performance.
- **Colour Fastness to Saliva:** A score of 4–5 (out of 5) was achieved. The results are positive and suitable for close-to-skin textile use.

- **Colour Fastness to Washing:**
  - Color change: 3 (out of 5)
  - Staining on multifiber fabrics (acetate, cotton, nylon, polyester, acrylic, wool): 4–5
    While the color change is moderate, the staining results are considered good.
- **Colour Fastness to Water:**
  - Color change: 4–5
  - Staining on adjacent fabrics: 4–5
    Overall, the water fastness performance is evaluated as positive.
- **Alkylphenolethoxylates (APEO) & Alkylphenols (AP):** These substances were not detected in the samples. Since APEO and AP are banned due to their harmful effects on human health and are often found in wetting agents and stain removers, this result is very favorable.
- **Formaldehyde Content:** The measured value was 25 ppm. Although this slightly exceeds the customer's requested maximum of 20 ppm, it is well below the OEKO-TEX® Standard 100 – Class II limit of 75 ppm (for adult products). Therefore, the result is not considered negative for the intended end use.
- **pH Value:** The measured pH was 5.5, which falls within the acceptable range of 4.0 to 7.5. Thus, the result is considered suitable for skin contact.
- **Flame Retardancy:** The fabric passed the flame retardancy test, and the results were evaluated as positive.

5. Conclusion

- In contrast to conventional natural dyeing techniques, which often require mordanting (to fix the dye onto the fabric), successful results were obtained in this study without the need for a mordanting process.
- Common problems observed in traditional natural dyeing, such as uneven dyeing and poor fastness, were not encountered. The dyeing quality and color fastness values were found to be satisfactory.
- The textile products produced in this study are sustainable and support an environmentally responsible production approach.
- Based on the raw materials and processes used, the final products are 100% recyclable, contributing both to reducing environmental impact and supporting a circular economy.

- A new product range has been developed, addressing current market demands while also providing a foundation for alternative designs and production variations.
- The industrial applicability of algae-based natural pigment dye—used as a sustainable dye source—has been successfully demonstrated.
- Despite changes in pattern design and machinery, stable production conditions were maintained, enhancing the flexibility and applicability of the process.
- A production infrastructure focused on export markets was established, offering a competitive advantage in international trade.
- The reduction in chemical usage contributed to a healthier and safer working environment, supporting occupational health and safety goals.

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