



Review

# Ecological Approaches to Textile Dyeing: A Review

Livia Lara , Isabel Cabral  and Joana Cunha 

Centre for Textile Science and Technology (2C2T), Department of Textile Engineering, University of Minho, 4800-058 Guimarães, Portugal; diascabral@gmail.com (I.C.); jcunha@det.uminho.pt (J.C.)

\* Correspondence: liviarlara@gmail.com

**Abstract:** Conventional dyeing processes currently practiced in the textile industry have a great environmental impact, mainly in relation to the quantity and pollution of water, use of toxic chemicals, atmospheric emissions, and high energy consumption. This study aims to discuss the relationship between the variables that involve conventional dyeing processes and environmental issues. It presents the mapping of the materials and emerging technologies for ecological coloration, specifically for the pretreatment and dyeing stages. Regarding pretreatment, it discusses biochemical (enzymes) and physical treatment (ultraviolet radiation, plasma, and ozone technology) approaches. With respect to the dyeing processes, it addresses ecological materials (natural dyes) and emerging technologies (such as plasma, supercritical CO<sub>2</sub>, AirDye<sup>®</sup>, ultrasonic, microwave, Nano-Dye<sup>™</sup>, and electrochemical). Given the importance of ecological coloration, this study provides important reflections on the urgency of resolving issues related to barriers and economic viability in the implementation of the alternatives presented and demonstrates the need to develop educational projects to prepare fashion and textile professionals.

**Keywords:** ecological coloration; emerging technologies; sustainable fashion



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**Citation:** Lara, L.; Cabral, I.; Cunha, J. Ecological Approaches to Textile Dyeing: A Review. *Sustainability* **2022**, *14*, 8353. <https://doi.org/10.3390/su14148353>

Academic Editors: Marc A. Rosen, Ting Chi and Huantian Cao

Received: 30 April 2022

Accepted: 5 July 2022

Published: 7 July 2022

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## 1. Introduction

The textile industry is considered one of the major environment polluting sectors, with an estimated 20% of all water pollution caused by textile treatments, such as coloration processes [1,2]. In conventional textile dyeing, 1 tonne of fabric could result in the pollution of up to 200 tonnes of water. The wastewater produced in textile processes is highly colored and contains complex concentrations of chemicals, such as salt, dye, detergents, peroxides, and heavy metals [3–5]. In addition to water pollution, other environmental issues emerge from the burning of fossil fuels, which result in atmospheric emissions and contribute to climate change and greenhouse gases. The United Nations' 2030 Agenda for Sustainable Development presents a broad and ambitious vision of the dimensions for social, economic, and environmental development [6]. The goals of this vision extend to the advancement of sustainability in the textile industry, making urgent the need to rethink conventional dyeing processes. However, how can the coloration process be sustainable?

Textile dyeing is a dynamic process, with many interrelated variables, such as the nature of the fibers, the format of the textile substrate, the chemical composition of the products, the class of dyes, the method, and the typology of the equipment. All these variables directly influence each step of the process. For textile professionals, especially designers, to understand environmental issues and the potential of ecological alternatives, it is necessary to start with fundamental knowledge about textile dyeing. This study presents an overview of conventional dyeing processes that enables a discussion of the relationship between the variables involved in each step and addresses the main critical points. Based on this approach, we map the main ecological alternatives for pretreatment and dyeing. Furthermore, this study establishes a basis for future discussions on the importance of training the designer and textile professionals who work in the industry, enabling them to acquire updated knowledge and to develop critical thinking about new materials and

processes. In addition, this study considers the economic and technological feasibility of incorporating emerging technologies, as well as the engagement of the textile industry in incorporating ecological dyeing practices.

## 2. Research Methods

The conceptual framework for this review was based on a consideration of existing literature in developing a new perspective that integrates sustainability into textile coloration processes. The strategy we used to collect and analyze the data was the qualitative methodology, following the line of reasoning that begins with an understanding of the fundamentals and issues related to the impacts of dyeing processes and, consequently, a search for solutions, as shown in Figure 1.

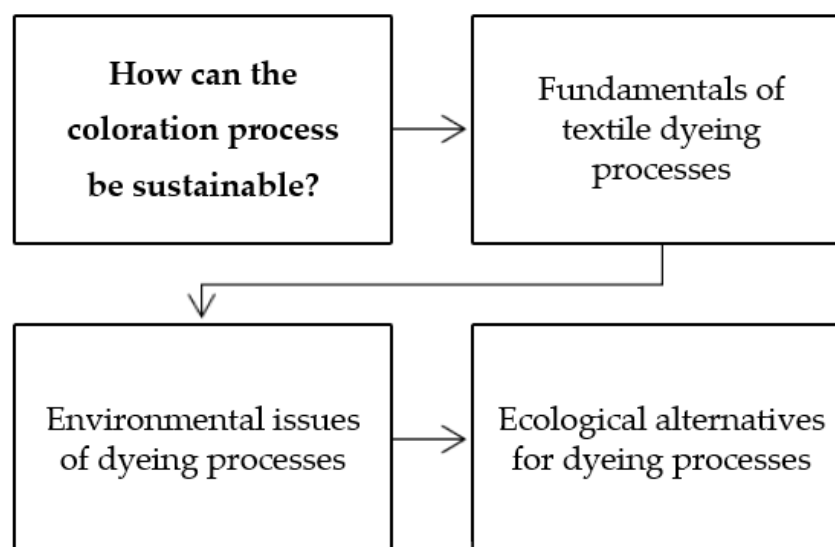


Figure 1. Research design reasoning line.

The initial research was carried out with the keywords “dyeing textile” and “sustainable textile dyeing process,” retaining only the materials available on the B-ON (Online Knowledge Library), open access articles, and RepositoriUM (University of Minho), through the following search platforms: SCOPUS, ScienceDirect, and Google Scholar. After exhaustively reading the abstracts, we selected the most relevant articles; articles that did not add new information in the area were discarded. The main authors of the selected articles were identified on the basis of the articles’ citations, and the main environmental issues addressed in the articles were identified (as discussed in Section 3.1), together with the main emerging materials and technologies (as described in Section 4). Our main reflections on the problems considered in this study and the identified alternative solutions are presented in Section 5.

## 3. Conventional Textile Dyeing Processes

Textile coloration is an ancient art. It is a physical-chemical modification of textile substrates so that reflected light creates a perception of color [7]. Fundamentally, dyeing is a process of uniform applying and fixing the colorant, together with the use of appropriate auxiliary chemicals [1,8]. Dyeing techniques vary, depending on the nature of the materials, the dye class, the shape of the textile substrate, and the equipment. The textile dyeing process can be carried out on fibers, yarns, fabrics, nonwoven materials, or final garments. The dyeing process for fabrics is predominant, but fiber dyeing is generally practiced to obtain *mélange* and *cambric* effects. Yarn dyeing, on the other hand, is carried out to produce stripes and checks, while garment dyeing is practiced when product replacement must take place in a short time [9].

The textile substrate can be produced with a variety of different fibers: natural, synthetic, or mixed. Fibers are the foundation for all textile products and can either be natural or human-made (manufactured or human-regenerated) [10]. Natural fibers are those that occur in nature. They can be divided into two main types: vegetable or cellulosic fibers (cotton, linen, sisal, and jute) and animal or protein fibers (silk, wool, and cashmere). Manufactured, or human-made, fibers can be classified as synthetic polymers (polyester, polyamide, and acrylic), regenerated fibers (viscose, modal, and acetate), and inorganic (carbon, glass, ceramic, and metallic).

The choice of the textile material, particularly in relation to the origin of the fiber, influences the subsequent textile processing processes, including dyeing. Accordingly, the relationship between the nature of the textile fiber and the dyeing process must be considered. The nature of the textile substrate influences the choice of dye class and, therefore, this variable is closely related to the environmental impact of the dyeing process. Fibers have a wide range of physical, mechanical, and chemical properties [10]. The properties of fibers are dependent on their chemical compositions, and those properties are a prerequisite consideration in choosing the colorant and chemical additives for the dyeing process.

The colorant is a substance, in the form of a dye or pigment, that is capable of imparting its color to a particular textile substrate. Dye is an organic molecule that is soluble in water (or that can be made soluble for its application); it can come from natural or synthetic material sources. Natural dyes are extracted from plants, animals, minerals, and microbes [11], as shown in Figure 2. Synthetic dyes are made from synthetic resources, such as chemicals, petroleum byproducts, and earth minerals [12].

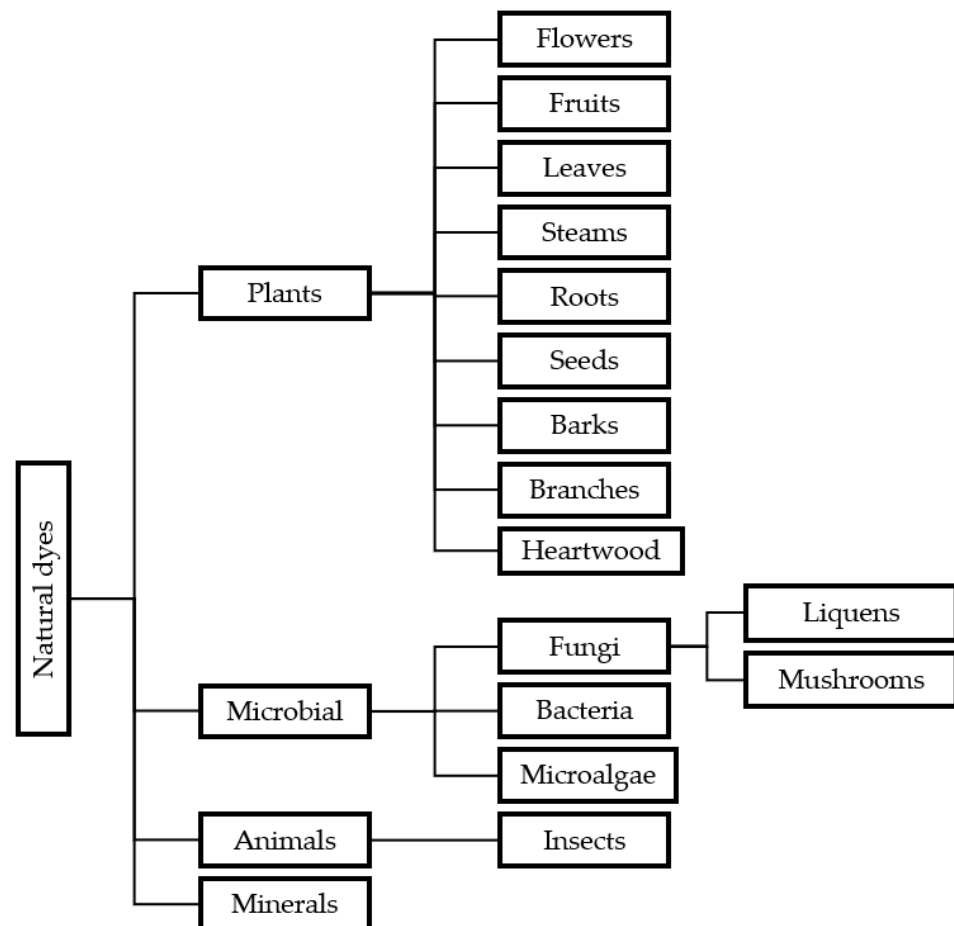


Figure 2. Classification of natural dyes based on their origin/source.

The use of natural dyes represents only 1% of the total dyed textile substrates [13]. After the discovery of mauveine by Henry Perkin in 1856, the use of natural dyes was substantially reduced [14], mainly due to the limited number of colors, medium fastness properties (the fastness of dyeing is a measure of its resistance to fading, or color change, upon exposure to a given agency or treatment [15]), low yield, and non-reproducibility [16]. In contrast, the use of synthetic dyes increased exponentially due to the wide range of colors, good fastness properties, ease of application, and reproducible shades [16]. The annual production of synthetic dyes corresponds to  $7 \times 10^7$  tonnes; the textile industry consumes approximately 10,000 tonnes of these dyes [17], and it is estimated that 280,000 tonnes of dyes are discharged into wastewater each year. For the production of some dyes, it is necessary to use heavy metals, such as mercury, chromium, cadmium, lead, or arsenic [18,19].

Many sustainability questions can be raised regarding the choice between natural and synthetic dyes. Issues related to the use of natural dyes include the production limitations, poor fastness, the properties of dyes, and substantivity. Substantivity refers to the attraction of the dye to the fiber, so that the dye in the solution gradually wears out as it is absorbed by the fibers [15].

The properties of dyes can improve with a solution containing mordants [15]. Mordants are substances that have an affinity for both textile fibers and dyes; therefore, they act as a link between the fiber and the dye [11]. There are different types of mordants, such as metallic salts, tannic mordants, and oil mordants. Metal mordants, such as aluminum, chromium, iron, and copper salts, are used to obtain acceptable levels of fastness in the contexts of washing and light. However, metal mordants, except for aluminum and iron, are considered to be toxic and can cause extreme pollution; therefore, they should only be used within environmentally permissible limits [20].

Regarding the use of synthetic dyes, the questions include the toxicity of wastewater generated by these dyes, for humans and for the environment. Approximately 70% of the dyes used to dye fabrics are not absorbed by the fabric and, consequently, they are discarded in the effluent [21]. In addition, some synthetic dyes can cause human health problems, such as allergic skin reactions, runny or stuffy noses, watery or prickly eyes, wheezing, chest tightness, shortness of breath, and occupational asthma [2,8].

The dye class influences the chemicals that will be used, the steps necessary for the preparation of the textile substrate, and the equipment used for the dyeing process. Before the dyeing process, pretreatment steps must be carried out on the textile substrate [16]. The goals of the pretreatment process are as follows [1,8,17]:

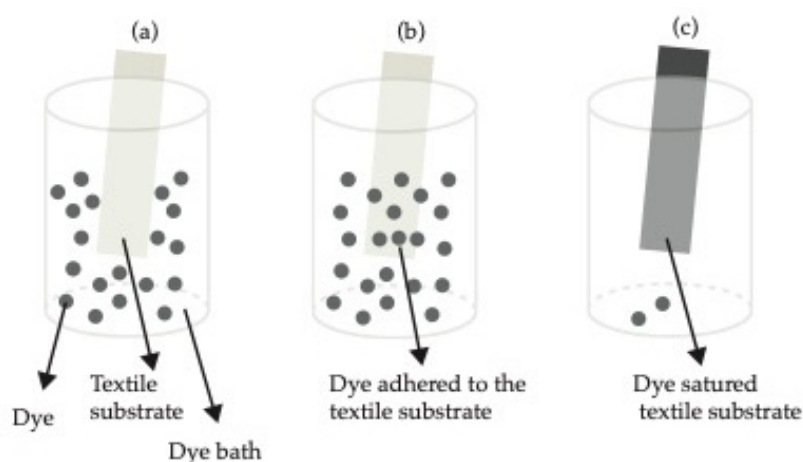
- Improving the absorption of dyes and chemicals in subsequent processes;
- Achieving an even water absorption value;
- Removing all types of impurities;
- Encouraging the absence of creases and wrinkles; and
- Achieving a high whiteness value.

The textile substrate pretreatment has a great impact on the quality of the dyeing results and each step has a specific function, as shown in Table 1. The sequence of preparatory pretreatment steps varies, depending on the nature of the textile substrate and the dye, as well as on the quantity of the water and chemicals that are required for each step [22,23]. Therefore, the environmental impact of dyeing processes is directly influenced by the substantivity of the dye with the fibers.

In general, the pretreatment process involves the use of water and chemicals. It is estimated that 150 L of water are used to produce 1 kg of fabric [29]. This high volume of initial water results in the same volume of wastewater [26]. After the pretreatment steps, the textile substrate is ready to receive the colorant. Dyeing processes involve migration, adsorption, and diffusion (Figure 3).

**Table 1.** Description of the pretreatment textile substrate.

Pretreatment	Objective	Water (L/Tonne Products)
Desizing	Sizes are added to the textile substrate to improve the mechanical strength of the fibers during the weaving process [23]. Desizing consists of removing the bonding material using acid, alkali or oxidant. This process occurs because the presence of any sizing materials, such as starch, polyvinyl alcohol, and guar gum, could hinder the penetration of dyes and chemicals inside the fiber [1,24,25].	2500–21,000 [26]
Scouring	The pretreatment stage for the purification of textiles involves boiling of textile with alkaline agents or surfactants or organic solvents [24]. This process removes the fatty matter, which mainly consists of waxes, proteins, pectin substances, and mineral materials, adhered and/or added to the textile substrate [1,8,22].	20,000–45,000 [26]
Mercerizing	A treatment applied to the textile substrate, in which it is immersed under tension in a cold solution of sodium hydroxide (22.5%) and later neutralized in an acid medium, with the objective of improving its appearance and its physical and chemical compounds, as well as increasing the brightness and affinity for dyes [1,27,28].	17,000–32,000 [26]
Bleaching	A chemical process that eliminates unwanted colored matter from fibers, yarns, or cloth. In this process, the natural coloration matter is removed by means of reducing or oxidizing agents, such as hydrogen peroxide, chlorine bleaching, and sodium hypochlorite. After washing and chemical bleaching, a natural permanent whiteness is obtained, which can be further enhanced by the application of optical brighteners [1,25,28].	2500–25,000 [26]



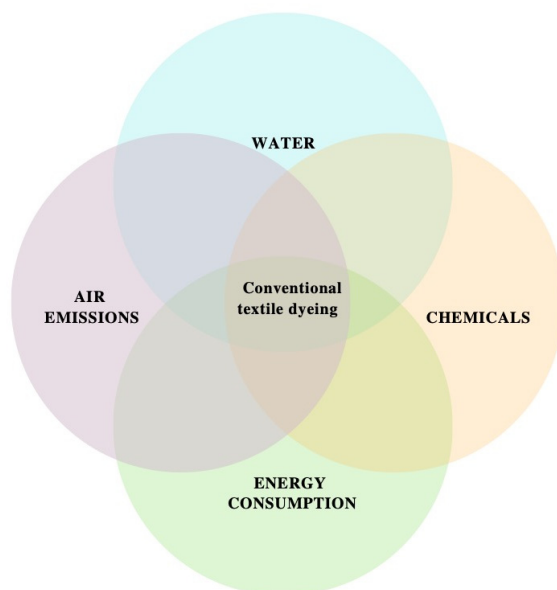
**Figure 3.** Steps of the textile dyeing process: (a) migration is the transfer of the dye molecules from the dye bath to the surface of the textile substrate and subsequent adsorption onto the fiber surface. This stage is influenced by the solubility of the dye and the flow rates of the dye liquor through the fiber, yarn, or fabric in the dyeing machine [30]; (b) adsorption is this step in which the surface molecule is incorporated into the fiber interior. The factors that influence this step are the nature of the textile substrate, the nature of dye/fiber interactions, temperature, pH, the presence of auxiliary chemicals, and dye concentration [30]; (c) diffusion is the fixation of dye molecules on the surface of the textile substrate and inside the fiber. This phase depends on factors such as the molecular size and shape of the dye, the fiber structure, and the process temperature [30].

In general, to obtain uniform colors with good fastness properties, the dyeing steps must satisfy the ideal conditions of temperature, pH, bath ratio, and processing time, which are essential for the addition of auxiliary chemical products during the process. In addition, in conventional dyeing, water is used at all stages, resulting in the consumption of a large

amount of water and the production of a very complex and polluting effluent, due to the addition of chemicals.

### 3.1. Environmental Issues of the Conventional Textile Dyeing

The steps of the coloration process have a great environmental impact, mainly in relation to water, chemical, energy consumption and air emissions, as shown in Figure 4. These impacts are interconnected, and in each step of the process water and chemical products are used, resulting in an effluent that is highly polluting. In addition, the machinery of the process requires high energy consumption, often from the burning of fossil fuels, which results in atmospheric emissions and contributes to climate change and greenhouse gases.



**Figure 4.** Environmental issues of conventional textile dyeing.

The textile dyeing process is responsible for 17% to 20% of the world's water pollution [2]. Water pollution is caused by the addition of unwanted substances or foreign matter that significantly alter the original characteristics of water [31]. In the dyeing processes, water pollution comes from the high concentrations of chemicals, such as salt, dye, soap agents, surfactants, acid, peroxides, and softeners that are present in the textile effluent [3,4,32].

Salts account for close to 50% of the effluent and contribute to the high total of dissolved solids, biological oxygen demand (BOD) (which is the oxygen demand of microorganisms needed to oxidize organic matter in water under aerobic conditions [13]) and chemical oxygen demand (COD) (which is the oxygen demand needed to chemically oxidize all pollutants in water and the most common way of measuring water quality [22,23]) [13]. In addition, the presence of unfixed dyes contributes to increases in the levels of COD and BOD of water sources [32,33].

Textile effluents contain many chemicals. When these are mixed with other chemicals, they are highly polluting and dangerous [2]. A hazardous chemical is one for which statistically significant evidence has indicated that acute (short term) or chronic (long term) effects can occur for humans and the environment when they are exposed to specific substances. In addition, some chemicals are corrosive, can cause severe burns, and can react dangerously with other chemicals. Another issue is fire hazards, which can arise from the use of easily flammable liquids [2]. If effluents are not properly treated before being released into the environment, they can enter the food chain and be transferred to humans and animals via bioaccumulation [22].

The implementation of cleaner technologies for the treatment of effluents is essential to the recovery and improvement of water resources. Conventional wastewater treatment technologies involve physical, chemical, and biological methods that have certain disadvan-

tages, such as high capital investment and maintenance costs [34]. However, the currently available conventional treatment methods do not fully remove pollutants [35]. There is an urgent need to develop cost-effective and efficient processes for properly treating wastewater [17]. Another issue related to the impact of the dyeing process is the energy consumption required for heating water and drying textile materials. The energy required in textile processing depends on the machine type, the operations, and the dyeing conditions. This energy is mainly derived from burning fossil fuels, thereby contributing to increasing the carbon footprint [16,36]. The carbon footprint is measured by the impact of greenhouse gases that are produced by burning fossil fuels for electricity, heating, etc. [37].

The United Nations' Intergovernmental Panel on Climate Change stated that 10% of global greenhouse gas (GHG) emissions are caused by the textile industry [38]. Air emissions resulting from heating processes, such as acetic acid, formaldehyde, nitrogen, and sulfur oxides from boilers, were identified as the second biggest pollution problem for the textile industry [2]. Therefore, to minimize energy consumption and atmospheric emissions resulting from textile dyeing, variables that directly influence the process, such as temperature, pH, bath ratio, and equipment, must be carefully evaluated.

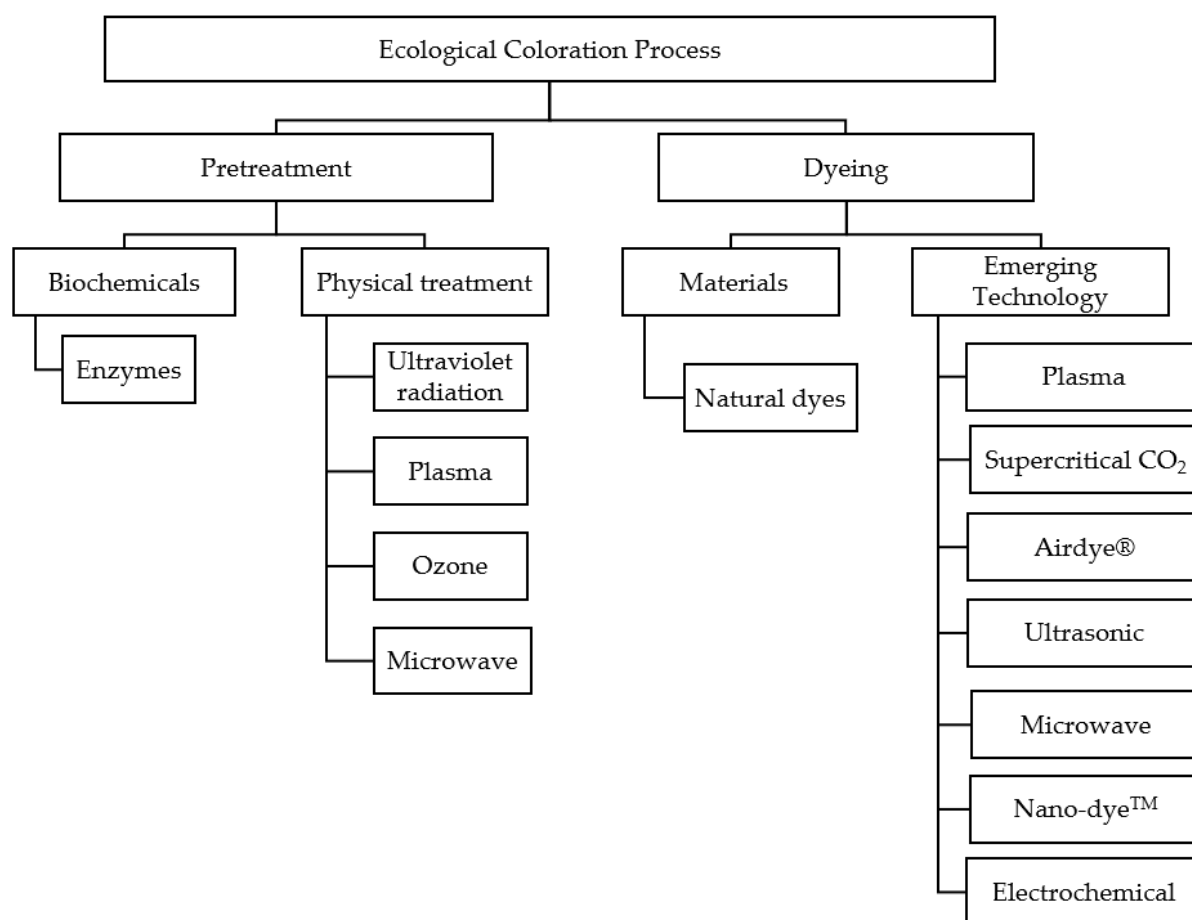
#### 4. Mapping of Alternatives for Ecological Coloration Processes

Legislative requirements and global environmental restrictions demand changes in the methods and in the chemicals used in textile processing. Some systems, such as Zero Discharge of Hazardous Chemicals (ZDHC) (a multi-stakeholder organisation comprising over 170 contributors from across the industry including Brands, Suppliers, Chemical Suppliers, and Solution Providers available online at <https://www.roadmapprozero.com/> accessed on 29 April 2022) and Bluesign® (a holistic system that provides solutions in sustainable processing and manufacturing to industries and brands based on strict criteria, auxiliary material, and services that are developed to support sustainable development, available online at <https://www.bluesign.com/en>, accessed on 29 April 2022) provide services and tools for the implementation of safe practices within companies, such as the correct use of chemical products. The ZDHC Manufacturing Restricted Substances List (ZDHC MRSL) identified prohibited chemicals and processes in the textile, apparel, and footwear (including leather and rubber) supply chains. The Bluesign® System Substance List (BSSL, Consumer Safety Limits) specifies consumer safety limits for chemicals in articles, and the Bluesign® System Black Limits (BSBL) specifies limits for finished chemicals, such as auxiliaries or dyes. These systems provide a comprehensive, full-package service solution for chemical suppliers, textile manufacturers, and brands, driving innovation and best practices to protect consumers, workers, and the environment.

Rethinking conventional dyeing to achieve a sustainable dyeing system is critical in establishing an environmentally friendly, socially responsible, and economically viable process. The sustainability of the dyeing process can be evaluated by the quality, economy, and efficiency of the process and, in addition to environmental issues, involves the reproducible quality of the process, the minimization of costs, and maximization of profits [37].

Materials scientists and textile researchers are working to find ecological alternatives for the textile and apparel industry [39]. A major challenge for the textile industry is to improve the wet processing of textiles, as that process relates to the reduction or exclusion of water, the substitution of harmful chemical products, the minimization of energy consumption, and a reduction in the emissions of toxic and polluting gases [37].

The main ecological alternatives for the pretreatment and dyeing processes are mapped in Figure 5. It is worth noting that the ecological coloration process comprises the combination of these alternatives and that considerable effort is required for it to be effectively implemented in the textile industry. These efforts require specific studies to validate the combination of these alternatives in relation to the four major areas of environmental impact that are related to conventional textile dyeing processes (as shown in Figure 4).



**Figure 5.** Alternatives for an ecological coloration process.

The textile dyeing process starts with the pretreatment of the textile substrate. It is essential to know the ecological alternatives available for the pretreatment stages. In this way, the replacement of toxic chemical processes by ecological chemicals, such as enzymes, or physical processes, such as ultraviolet radiation, plasma, or ozone technology, are some of the viable options.

The development of enzymes is important for the ecology of textile dyeing processes [40]. Enzymes function as catalysts in chemical reactions; at the end of the process, the enzymes are released unchanged and biodegraded [41]. The use of enzymes in different processes is effective and safe [1]. In the ecological dyeing process, different enzymes can be used in different stages, and they present the advantages shown in Table 2.

**Table 2.** Enzymes used at wet processes.

Process	Enzyme	Advantages
Bioresizing	Amylase, lipase, pectinase, Polygalacturonase [24,42].	Generation of a lower volume of wastewater, with lower amounts of toxic chemicals compared to the traditional desizing [42].
Bioscouring	Pectinase, cellulase, cutinase, lipase [24,42].	The biosourcing process is carried out at neutral pH; it reduces water consumption by 30% to 50% compared with traditional cleaning processes. In the biosourcing of cotton fibers, there is a small loss of weight and strength, maintaining the natural softness of the substrate [42].
Biobleaching	Oxidoreductase, xylanase, laccase [24,42].	Textile substrates that are subjected to a combination of pretreatment steps with biobleaching show good results in terms of whiteness, absorbency, dyeability, and tensile properties [42].



Physical treatments are another ecological alternative for the surface modification of textile fibers in the absence of an aqueous system. The main physical treatments are presented in Table 3.

**Table 3.** Physical pretreatments for textile substrates.

Pretreatment	Objective
Ultraviolet radiation (UV)	UV treatment improves the coloration process of textile products due to surface modification of the textile substrate. UV technology can be used for bleaching and surface modification processes prior to coloration processes, such as dyeing and printing. UV also increases the wettability of hydrophobic fibers in the printing process and prevents the formation of pilling problems [43].
Plasma	Plasma, the “fourth state of matter”, is an electrically neutral ionized gas with a significant number of charged particles that are not bound to an atom or molecule. Plasma technology can assist in desizing, removing natural or synthetic grease and wax from textile fibers, increasing the dyeing rates of textile polymers, and improving the diffusion of dye molecules into fibers to increase color intensity and wash fastness [44].
Ozone	Ozone is excellent for oxidizing organic or inorganic impurities that are present in textile substrates [22]. The ozone process promotes the oxidation of the textile fiber surface to improve its dyeability [1]. The ozone process can be used for bleaching under low temperature conditions, replacing the use of hydrogen peroxide and less water [22].
Microwave	Microwave technology involves electromagnetic radiation and interacting electric and magnetic fields, which oscillate in directions that are perpendicular to each other. The use of microwaves is a heating source for desizing, scouring, bleaching processes, dyeing, and drying processes [39].

Chemicals that contain restricted or prohibited substances and that cause serious problems for the environment, aquatic life, and human health must be subjected to the removal of hazardous substances through the implementation of smarter chemistry [21]. Many researchers and research centers focus their studies on the search for alternatives to replace synthetic dyes, mainly due to the fact that some natural dyes offer functional benefits for the user and other advantages for the environment [13]:

- Ecological: natural dyes come from renewable materials; they are less toxic, less pollution-causing, less harmful to health, and non-carcinogenic;
- Biodegradable and renewable: natural dyes from plants come from agro-renewable and biodegradable sources;
- Color palette: the use of different mordants or different concentrations with the same dye can be explored to obtain different colors;
- Functional benefits and properties: some natural dyes have antibacterial, antimicrobial, insect repellent, antioxidant, and UV protection properties.

Given the importance of natural dyes in replacing toxic dyes, we considered the classes of natural dyes that originate from plants and microbes. Natural dyes can be obtained from parts of plants, such as roots, leaves, branches, stems, heartwood, bark, flowers, fruits, and seeds, as shown in Table 4. However, for ecological coloration practices with the use of plants dyes, it is necessary to enhance scientific and technological knowledge to optimize some variables in the dyeing process, such as the addition of biomordants.

The use of natural dyes and pigments from microorganisms for textile application is expanding. Many studies on the coloration of textile materials with pigments obtained from bacteria, mushrooms, and fungi have been carried out, as shown in Table 5. The latest advances in molecular biology in the production of bacterial pigments have proved to be economically viable, because the production of these pigments can be increased through the cloning of the genes responsible for the biosynthesis of a large number of pigments, e.g., in the production of indigo on an industrial scale using *Escherichia coli* bacteria in fermentation tanks [46].

**Table 4.** Examples of dyes obtained from plants.

Origin	Plant	Scientific Name	Color	Source
Bark	Onion	<i>Allium cepa</i>	Brown	[20]
Flower	Lavender	<i>Lavandula</i> sp.	Grey	[45]
Leaf	Eucalyptus	<i>Eucalyptus</i> sp.	Brown/yellow	[45]
	Spinach	<i>Spinacea oleracea</i>	Green	[45]
	Thyme Bela Luz	<i>Thymus mastichina</i>	Yellow	[45]
	Pepper mint	<i>Mentha piperita</i>	Green	[45]
	Artichoke	<i>Cynara scolymus</i>	Green	[45]
	Boldo	<i>Peumus boldus</i>	Pink	[45]
	Blueberry	<i>Vaccinium myrtillus</i>	Purple/blue	[45]
	Green tea	<i>Camellia sinensis</i>	Brown	[45]
Rhizome	Saffron	<i>Curcuma longa</i>	Brown/red	[20]
Seed	Urucum	<i>Bixa orellana</i> L.	Orange/red	[20]
	Coffee	<i>Coffea arabica</i>	Brown	[20]

**Table 5.** Examples of dyes obtained from bacteria, mushrooms, and fungi.

Microbes	Name	Color	Source
Bacteria	<i>Chryseobacterium shigense</i>	Yellow	[47]
	<i>Pseudomonas</i> sp.	Brown	[47]
	<i>Serratia plymuthica</i>	Pink	[47]
	<i>Vibrio</i> sp.	Red	[48]
	<i>Serratia marcescens</i>	Red	[49]
	<i>Chromobacterium violaceum</i>	Violet	[50]
	<i>Serratia marcescens</i>	Red	[51]
	<i>Escherichia coli</i>	Blue	[47]
Mushrooms	<i>Rugamonas rubra</i>	Red	[50]
	<i>Sarcodon imbricatus</i>	Blue/green	[47]
	<i>Hydnellum peckii</i>	Beige/blue	[47]
	<i>Cortinarius semisanguineus</i>	Red/orange	[47]
	<i>Phaeolus shcweinitzii</i>	Green	[47]
Fungi	<i>Pisolithus tinctorius</i>	Brown	[47]
	<i>Fusarium oxysporum</i>	Pink/purple	[52]
	<i>Monascus purpureus</i>	Red	[52]
	<i>Emericellanidulans</i>	Red/brown	[52]
	<i>Fusariumverticillioides</i>	Red	[52]

Some bacteria can produce pigments that can be used successfully as textile dyes and can provide many unusual colors, including black, white, brown, gold, silver, fluorescent green, gemstone, and blue [53]. Overall, the pigments obtained from microbial sources have many important advantages [11,53]:

- Production in the desired quantity, regardless of climate fluctuations, geographic conditions, and the whims of nature.
- Versatility and ease of production, compared with other sources.
- Ability to obtain different colors and tones, without interference with genes.

- Easy propagation and low cost for industrial production, with easy growth on substrates under controlled conditions.

In this sense, industrial biotechnology has contributed to the development of processes with improved efficiency to replace fossil fuels and petroleum-based materials and to provide a closed-loop system with the potential to eliminate waste. Such a production system depends on biological processes and natural ecosystems that use natural inputs and minimal amounts of energy and do not produce waste, as products that are discarded are reused as inputs for other processes [54].

Colorifix Limited was the first company to use a biological process to promote the coloring of textiles on an industrial scale. Its dye development process begins with a search for color based on an organism (animal, plant, insect, or microbe) in nature. After identification, DNA sequencing of the organism is carried out to identify the genes that lead to the production of the dye, and thus to translate this DNA code in creating a microorganism. This established microorganism has the ability to produce the pigment in the same way that it is produced in nature [55].

The isolated use of natural dyes is not sufficient to establish the process as sustainable. It is necessary to consider the process in a global way, taking into account all the products that will be added during each stage, as well as the amounts of water. In addition, the availability of natural raw materials to meet the demand of the current textile industry is a relevant issue. Efforts to develop environmentally friendly chemical processes must be combined with the development of new technologies for dyeing processes. Many studies are being carried out to develop technologies, such as plasma, supercritical CO<sub>2</sub>, AirDye, ultrasonic, microwave, electrochemical dyeing, and nano-dye technologies, which are briefly described in Table 6.

**Table 6.** Emerging technologies for the coloration process.

Technology	Description
Plasma	This treatment promotes surface modification of polymeric/textile substrates, improves hydrophilic properties (chemical changes) and increases the surface properties (physical changes) of fibers/textile substrates. This surface modification increases the dyeability of the fiber and is an effluent-free and environmentally friendly process [56]. There are several benefits in applying plasma technology that are vital for sustainability, such as reducing the use of water, chemicals, and energy (compared with the conventional wet method), minimal consumption of chemicals, and no required drying process [57,58].
Supercritical CO <sub>2</sub>	Supercritical carbon dioxide dyeing is a revolutionary and attractive ecological alternative to conventional wet methods in the textile industry [39]. The supercritical CO <sub>2</sub> process involves using less energy than conventional processes. The principle of the process is based on heating carbon dioxide (CO <sub>2</sub> ) above 31 °C, pressurized above 74 bar, where it becomes supercritical, a state of matter that is an expanded liquid or a strongly compressed gas [1,59]. For supercritical carbon dioxide dyeing, the CO <sub>2</sub> is heated to 120 °C and pressurized at 250 bar; the CO <sub>2</sub> penetrates the fibers, thus acting as a swelling agent during dyeing, i.e., increasing the diffusion of dyes in the fibers [59].
AirDye®	AirDye® technology is a sustainable solution for printing and dyeing. AirDye® uses the process of sublimation, i.e., transferring inks to fabrics using transfer paper combined with heat and pressure. All used paper is recycled, and the dyes are inert, which means they can return to their original state and be reused. Therefore, the AirDye® process has no harmful byproducts, which provides a significant reduction in energy and costs, as there is no need for screens, boilers, dryers, or chemicals [60]. The process uses up to 95% less water and up to 86% less energy, and reduces emissions by 84%, compared with conventional dyeing methods [60].
Ultrasonic	Dyeing with ultrasound technology causes dispersion, degassing, and acceleration of the diffusion rate of the dye or finishing chemicals inside the fiber [61]. In this process, the dispersion of dye molecules occurs individually, increasing the activation energy of the molecules and causing a rapid diffusion within the fiber structure to increase the dyeing rate [62]. The ultrasonic process can be applied in almost all preparatory wet processing operations, such as desizing, scouring, bleaching, and washing [63].

Table 6. Cont.

Technology	Description
Microwave	The microwave frequencies are between the radio wave bands and the infrared radiation of the electromagnetic spectrum, corresponding to the frequency band between 300 MHz to 300 GHz with a wavelength of 1 m to 1 mm (MAITI). Microwave technology offers uniform, rapid, and effective heating, which increases the dye molecules' diffusion in the polymers, resulting in a high exhaustion rate, high dye diffusion, and excellent color fastness properties [64–66].
Nano-dye™	The dyeing process called Nano-Dye, which is a continuous dyeing system in which reactive dye molecules are kept in individual nano stages to incorporate to cellulose, has the following advantages compared with the conventional dyeing process: no salt, use of up to 75% less water, use of up to 75% less energy, and up to 97% exhaustion [67]. The studies carried out by Nano-Dye Technologies Inc demonstrate that the indirect electrochemical reduction dyeing method with indigo dye has a low economic cost and excellent cyclical performance, which can significantly contribute to increasing the sustainability of dyeing in the production of denim [67].
Electrochemical	Electrochemical dyeing is an efficient process for the reduction and oxidation of vat and sulfur dyes, which are normally used for cellulosic fibers [5]. The studies carried out by Li et al. [68] demonstrated that the indirect electrochemical reduction dyeing method with indigo dye has a low economic cost and excellent cyclical performance, which can significantly contribute to increasing the sustainability of dyeing in the production of denim.

The sustainable growth of society is in direct proportion to the development of new methods and technologies for managing its environmental quality [25]. The use of emerging technologies for the dyeing process still has little expression in the textile industrial context. Many questions regarding this can be raised, such as limitations in relation to some textile fibers, the need for investments to implement new equipment, economic viability, and the knowledge of professionals in regard to materials and processes. In addition, it is worth mentioning that the variables related to the costs of the processes, such as energy consumption and equipment, are parameters that must be evaluated so that the dyeing process is environmentally and economically sustainable. Therefore, further investigation is necessary.

Emerging technologies are important for the development of ecological dyeing systems, as well as for wastewater treatment. Conventional effluent treatment systems are characterized by high energy consumption, lack of infrastructure maintenance, and an unsatisfactory pollutant removal rate [69]. The replacement of conventional methods of effluent treatment is great challenge, due to the need for investments in industrial plants and the challenge of developing methods of easy production and application. In addition, studies are needed on the integration of high-performance processes, the efficient removal of polluting chemicals, and sludge degradation [4,69].

Treatment for recycling and the reuse of wastewater is essential in addressing water pollution and water scarcity [70]. Recent studies on the treatment of textile effluents highlighted the use of hybrid processes that combine emerging technologies (ozone treatment, electrochemical processes, and plasma) with traditional techniques (fenton, ozonation, and electrocoagulation) [4]. Although the combination of technologies for the treatment of effluents is quite effective in the recycling and reuse of water, such processes come with challenges of economic and commercial viability [24,70].

## 5. Discussion

The environmental issues of conventional dyeing methods are widely known and discussed, although ecological dyeing practices have little implementation in the textile industry context. Thus, it is necessary to clarify and synthesize information about how to achieve sustainable practices in textile coloration, with a focus on the following:

1. Use of ecological materials and/or processes for pretreatment and dyeing;
2. Minimization of water use, reuse of wastewater, and treatment of effluents;
3. Incorporation of efficient and economically viable technologies;

4. Development of partnerships between the textile fiber production industry, chemistry experts, and professionals in textile design and processing; and
5. Dissemination of information to all textile professionals, especially those professionals who are involved in the design process.

Each of these points contributes to minimizing the impact of coloration processes. When these strategies are used together, better results are obtained in relation to the required volume and pollution of water, energy consumption, the use of toxic chemicals, and atmospheric emissions, thus achieving greater sustainability. In this context, it is important to explore studies that are mainly related to the use of biochemicals, natural dyes, and emerging technologies, which are pertinent in evaluating in detail the perspectives of each of these approaches.

During the steps in the textile coloration process, it is estimated that about 3600 dyes and 8000 different chemicals are used [22]. The use of biochemicals, such as enzymes, is an ecological alternative for the pretreatment process and the effluent treatment processes. The use of enzymes in pretreatment demonstrates advantages over conventional processes [71]. In the scouring process, the enzymes can be used to replace highly toxic chemicals, such as caustic soda [72]. In the bleaching processes, biochemicals reduce water consumption and enhance water recycling [73]. In addition, the use of enzymes allows some pre-treatments, such as desizing and bleaching, to be performed together (combined), reducing the number of steps and consequently the volume of water and energy consumption [73]. Despite the advantages of using enzymes, some barriers need to be resolved for the mass usage of these biochemicals, especially in terms of economic viability [74].

In addition to the problem related to the volume of chemicals, issues related to pollution resulting from the synthesis, production, and use of colorants deserve great attention [74], as do the difficulties related to the production, extraction, and use of natural dyes. The absorption rate of dyes to the textile substrate is up to 40% to 50%; therefore, most of these chemicals are eliminated in the effluents [22]. The replacement of synthetic dyes by natural dyes is a sustainable option, but it should be widely discussed to offset the paradigms that prevent the mass usage of dyeing practices with natural dyes. In practice, this includes the association of natural dyes with toxic chemicals, such as mordants. In this case, the process totally overlooks the ecological essentials, as it results in polluting wastewater and is harmful to human health. However, these toxic chemicals can be replaced with biodegradable materials, such as biomordants, or by processes that improve the affinity of the textile substrate and colorant. In addition, the difficulties related to the volume of dye, which reflects the intense production of raw materials, should be discussed to enhance studies on natural dyes that originate from microorganisms.

There is little doubt that toxic chemicals must be replaced. However, this replacement is not enough for the dyeing process to be ecological. The amount of water needed for the steps of conventional dyeing processes must be reconsidered, with a focus on emerging technologies with dry processes or circular processes. It is estimated that 18% to 42% of the total water used during textile dyeing is used in the pretreatment steps [22]. There are several physical processes that can be used to replace the use of chemicals and water in the pretreatment processes, such as using plasma and ozone. The plasma treatment can also improve the absorption of the dye to the fiber, resulting in a lower dye consumption and a lower amount, or elimination, of residual chemicals in water [74]. The pretreatment of the textile substrate with ozone is a viable alternative for bleaching processes; this technology has the advantages of not using hydrogen peroxide, using less water, and requiring a lower temperature than conventional processes [73,74]. In addition, emerging technologies for effluent treatment should be explored to develop processes in which the effluent is reused in dyeing processes, making the process circular without influencing the quality of textile substrates.

The search for new technologies is essential in making investments in equipment profitable and in promoting studies in this area, as well as in the development of knowledge. In addition, it is essential that there is a partnership between companies that produce

textile fibers, chemicals, and emerging technologies. There is also a need for thorough investigation of the advantages of these technologies in comparison with conventional methods, and to disseminate knowledge to professionals and academics in the textile sector.

Designers are responsible for choosing raw materials, colors, trims, and even product packaging. Therefore, all choices made during the design process impact the textile chain, from the beginning to the end of a product's life. Design education focused on ecological coloration practices is essential in the transition to a sustainable textile industry. The content of design courses must be prepared to answer questions related to the sustainability of the processes. The gaps in these contents can be filled with educational programs aimed at textile students' training, as well as at fashion and textile professionals, providing technical and updated knowledge about the processes of textile technology. If designers have knowledge about the nature of textile fibers and coloration processes, they will be able to develop critical thinking about their choices and seek information and dialogue with the industry in favor of the developing ecological dyeing practices.

## 6. Conclusions and Future Trends

The issues addressed in this study contribute to the development of actions within the United Nations' 17 Sustainable Development Goals and the 169 targets of those goals [6]. The introduction of environmental regulations and legislation in several countries and the awareness of consumers have stimulated the research and development of new and ecologically sound methods and chemical products. New materials, equipment, and methods are constantly being developed to present sustainable solutions for the textile processing sector. However, to what extent is the information about materials and ecological processes being assimilated by fashion and textile professionals, including designers? The designers can and should contribute to the construction of a sustainable textile system. These professionals must be properly prepared and provided with sufficient knowledge to make choices that meet the goals of sustainable development. Therefore, this paper highlighted the importance of training designers so that they develop critical thinking that will enable them to align creativity with technical knowledge about sustainable materials, processes, and chromatic possibilities. Given the relevance of the color theme, textile dyeing processes, and the education of designers, we intend to develop this study by creating and evaluating practical educational actions to promote sustainable coloration practices.

**Author Contributions:** Conceptualization, methodology, investigation, writing—original draft preparation, and writing—review and editing, L.L.; visualization and supervision, I.C. and J.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was financed by Project UID/CTM/00264/2021 of 2C2T (the Centre for Textile Science and Technology), which is funded by national funds through FCT (Foundation for Science and Technology).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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