

## Chapter

# Introduction to Dyes

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## Abstract

Dyes are chromatic chemicals that chemically adhere to substrates, bestowing vivid and long-lasting hues to things including fabrics, plastics, leather, and food. This chapter examines the historical development of dyes, tracing their ancient origins from natural sources such as plants, insects, and minerals to the groundbreaking invention of synthetic colors during the Industrial Revolution. The categorization of dyes into natural and synthetic types is examined along with their unique qualities, applications, and interactions with various fabrics. The importance of dyes encompasses various sectors, including textiles, art, and advanced technology applications. Dyes are essential in leather tanning, food and cosmetics, pharmaceuticals, and sustainable energy technologies such as dye-sensitized solar cells. The dye business plays a crucial role in worldwide economies, propelled by the demand for sustainable and high-performance colorants. Nonetheless, problems include environmental degradation, fluctuations in raw material prices, and the conservation of traditional dyeing methods.

**Keywords:** chemical compound, natural and synthetic dyes, ecofriendly, textile fabric, color fastness

## 1. Introduction

### 1.1 Definition of dye

A dye is a colored substance that possesses a unique ability to bind to a substrate and impart color to it. In other words, dyes are chromatic compounds typically used in a solvent to color materials such as textiles, plastics, leather, and food [1, 2]. They differ from pigments in that they are soluble and bind chemically to the substrate, requiring mordants (chemical fixatives) to enhance colorfastness and durability [3].

### 1.2 Historical overview of dyes

The history of dyes is a complex and fascinating narrative that intertwines with the development of human civilization. From the earliest use of natural pigments to the revolutionary discovery of synthetic dyes, the story of dyes reflects humanity's ingenuity, cultural practices, and scientific progress. Here we discuss in detail.

### *1.2.1 Ancient origins (prehistoric era to early civilizations—3000 BCE)*

As early as the prehistoric era, there was a foundational era in human history where dyeing emerged as a critical cultural and technological innovation. Early humans, driven by the desire to express identity, status, and creativity, began harnessing natural resources to color textiles and artifacts [4]. Dyes derived from plants, insects, and minerals were extracted through rudimentary chemical processes, such as boiling, fermentation, and reduction. Archeological evidence indicates that natural pigments were used as early as 36,000 years ago with dyed flax fibers found in Georgia's Dzudzuana cave (30,000 years old) and indigo-dyed Peruvian textiles (6000 years old) [5–7]. In ancient Egypt, natural dyes like indigo, saffron, and madder were used to color linen, symbolizing spirituality and social status in Mesopotamia and China [8]. For example, yellow represented divinity while green signified rebirth. By 2600 BCE, China had advanced silk-dyeing techniques using cochineal and madder for vibrant hues [9]. The Silk Road (6400 km) facilitated the exchange of dyestuffs like indigo and saffron between east and west spreading dyeing knowledge globally. This era laid the groundwork for modern dye chemistry, blending artistry with empirical knowledge to transform raw materials into culturally significant colors [10].

### *1.2.2 Classical antiquity (golden age of dyes: 3000 BCE–500 CE)*

In the classical antiquity period, the art of dyeing reached new heights with specific dyes becoming symbols of wealth, power, technological implication, and cultural identity [11]. Civilizations including the Egyptians, Greeks, Romans, Phoenicians, Indians, and Chinese mastered dyeing techniques from early chemical concepts such as solubility and coordination chemistry, oxidation–reduction processes. To get preferred colors like Tyrian purple from Murex Snails, the Phoenicians used sophisticated biochemical procedures that consisted of oxidation and reduction reactions. This bright color shows authority and riches. Woad, in the meanwhile, gave European cultures like the Celts beautiful blue tones, and madder roots gave Egypt and Persia rich reds. Saffron produced golden-yellow tints in the Mediterranean [12]. Alums, mainly used as a mordant, exposed an early understanding of coordination chemistry, which upgraded colorfastness and dye attachment. The combination of indigo from *Indigofera* plants and red dyes from lac insects in India demonstrated a profound understanding of organic chemistry and solubility [13]. These developments draw attention to the substantial degree of chemical expertise incorporated in conventional dye-making processes. The Chinese possessed advanced methods for dyeing silk, employing tannins and iron salts to achieve black hues through precipitation. This progress not only enhanced the value of textiles but also reflected social hierarchies, cultural identities, and economic power. The chemical understanding of this period explains how ancient painters were, in many aspects, the first practical chemists. Hence, this classical period opens the evolution of dye chemistry and its durable impact on human society.

### *1.2.3 Medieval and renaissance periods (500–1600 CE)*

During the Middle Ages and Renaissance era, dye chemistry flourished, where painters created colorful fabrics that reflected religion, culture, and social status. While trade routes like the Silk Road and Hanseatic League extended access to exotic

materials like indigo and saffron, natural dyes like madder, woad, and cochineal ruled [14]. For the production of deeper and long-lasting colors, artists develop different methods such as resist dyeing, overdyeing, and the use of mordant application. The red color represented monarchy, while blue color the Virgin Mary. Cochineal's arrival from the Americas transformed European dyeing during the Renaissance [15, 16]. Beyond their surface appearance, these colors created cultural identity and economic power. Hence, the modern artificial dyes were founded in this era by a mix of artistic creativity, global commerce, and pragmatic experimentation.

#### *1.2.4 Industrial revolution (1760–1840)*

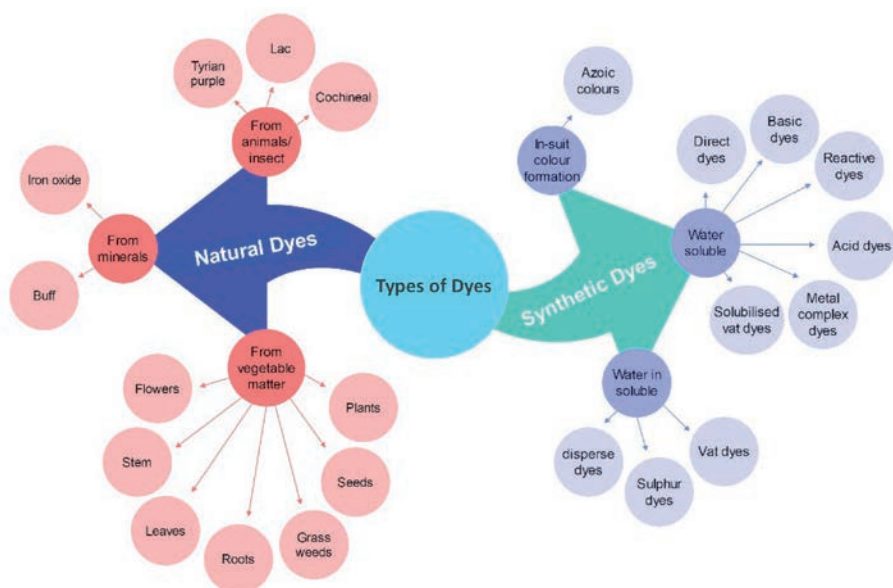
In this period, the Industrial Revolution changed the textile sector from initially labor-intensive natural colors to other mass-producing synthetic dyes. The first time was in 1856, when William Henry Perkin unintentionally discovered Mauveine, which produced coal tar-based synthetic dyes and produced bright and reliable colors formerly unreachable with natural sources like cochineal or indigo [17, 18]. Steam-powered dyeing machines and the mechanization of large-scale textile production quickly lower prices and improve accessibility. Factories with automated dyeing procedures thrived at this time. Hence, guaranteeing color stability in application and raising the need for reasonably priced colored fabrics. Furthermore, in this evolution, synthetic hues sometimes included hazardous chemicals that endangered the environment and impacted workers' well-being. The move to synthetic dyes affected the local economic and cultural legacy as fewer traditional craft dyeing techniques were needed.

#### *1.2.5 Modern period (1900–Present) and beyond*

The modern period has revolutionized dye chemistry obtained from industrial innovation, environmental challenges, sustainability, and a regeneration of traditional practices. Further, developments like digital printing and supercritical CO<sub>2</sub> dyeing reduce resource use and pollution [19]. In the meantime, natural dyes like cochineal and madder have been used again for sustainable practices and historical authenticity. Furthermore, in this period, plant-based extraction and safer mordants were used for the improvement of colorfastness and the reduction of toxicity. Furthermore, in the nineteenth century, many companies, like Winsor and Newton (founded in 1832), strongly focused on madder dye, emphasizing ongoing refinement of old pigments. In return, the late twentieth and early twenty-first centuries committed to reducing ecological impact through sustainable actions, including the development of eco-friendly dyes, biodegradable pigments, and closed-loop dyeing systems to reduce the waste [1]. Moreover, biotechnology plays an important role in the manufacturing of dyes with microorganisms, reducing reliance on petrochemicals. Hence, the rehabilitation of natural dyes and traditional dyeing techniques reflects a rising appreciation for cultural heritage and sustainability. This modern period has explored the opportunities of dye chemistry and emphasized the significance of balancing innovation with environmental applications.

## **2. Classification of dyes**

The dyes are mainly classified into two main types. These are natural dyes and synthetic dyes [6]. These natural and synthetic dyes can be further classified according to



**Figure 1.**  
*Classification of dyes.*

their source of origin, chemical structure, solubility, and application method. **Figure 1** explains the types of dyes. Each type has distinct characteristics and applications.

### 2.1 Natural dyes

Natural dyes are pigments derived from nature through organic and inorganic materials or sources such as plants, animals, and minerals [12, 20]. Natural dyes are mostly used due to their eco-friendly nature and a variety of colors through compounds like indigo, alizarin, and curcumin.

### 2.2 Synthetic dyes

Synthetic dyes are man-made colorants. Chemical synthesis adds different chemicals to natural colors to create these dyes [21]. The synthetic dyes provide an incredible range of vivid and stable hues. These dyes are further categorized as in-situ color creation, water-insoluble dyes, and water-soluble dyes. Synthetic dyes are mostly used in industries like textiles, printing inks, plastics, leather, pharmaceuticals, and food coloring because of their great behavior, including colorfastness, lightfastness, and cost efficiency [2, 22, 23].

## 3. Importance of dyes (textiles, art, and industry)

### 3.1 Textiles (the backbone of the dye industry)

Textiles form the foundation of the dye industry, acting as the primary material for applying dyes and significantly shaping its development [24]. Archeologically, mostly natural dyes were used to color fabrics. Nowadays, due to the wide variety

of textile fibers available, such as cotton, wool, polyester, etc., the demand for specialized dyes and cutting-edge dyeing techniques has increased [25]. The textile industry's requirement for vibrant, long-lasting, and sustainable colors has spurred modernizations in dye chemistry, such as reactive, disperse, acid, and vat dyes, as well as cutting-edge technologies like digital textile printing and waterless dyeing [26]. But challenges like environmental pollution from dye effluents have pressed the industry toward sustainable solutions, consisting of biodegradable dyes and eco-friendly processes [27]. In the Asia Pacific region, the global textile dye market is projected to grow gradually, driven by major textile manufacturing pivots and also enhanced by the value of sustainable practices. This mutual relationship between textiles and dyes fuels progress in both fields, with developments in smart and functional textiles further expanding the role of dyes. The relationship between these industries underscores the importance of chemistry in shaping the future of color, design, and sustainability while meeting the evolving needs of consumers and the environment.

### *3.1.1 Role of dyes in textile*

Dyes are a key component of the textile sector since they help to provide materials used in technical textiles, home furnishings, and garments with different hues [28]. This not only satisfies the many aesthetic, functional, and cultural needs of consumers but also greatly improves the visual appeal, utility, and market competitiveness of these textile products over a wide range of uses [29]. Dyes are used in the garment sector to provide bright and long-lasting colors that fit customer tastes and fashion trends. Applied to a variety of natural and synthetic textiles like cotton, wool, polyester, and nylon, it creates garments with various hues and designs. Dyes are necessary in the home furnishings industry for coloring products like bed linens, upholstery, carpets, and curtains, hence enabling creative freedom and personalization. They assist in designing attractive and pleasant living areas. Dyes serve functional goals for technical textiles such industrial fabrics, where they provide not only color but also particular functional qualities such as UV resistance and flame retardancy, medical textiles, vehicle interiors, and antimicrobial characteristics. Factors like the material being dyed, desired color, durability criteria, and legal issues influence the selection of dye type and formulation [30]. All things considered, dyes are essential in changing fabrics into flexible, useful, and aesthetically pleasing products that fit various industrial and consumer needs [31].

### *3.1.2 Dye-fiber interactions*

The dye-fiber interactions are essential for the dyeing process, as the efficiency of a dye depends on its compatibility with the specific type of fiber being colored [24]. Each fiber, whether natural, synthetic, or blended, has exclusive chemical and physical properties that determine how it relates to dyes [32]. For example, cotton and other cellulosic fibers like cotton [33], linen, and rayon are best dyed with reactive or direct dyes, which form strong covalent bonds with the fiber, ensuring excellent wash fastness and also vibrant colors. Direct dyes, which depend on van der Waals forces and hydrogen bonding, are mostly used for cellulosic but are less colorfast unless treated with after-treatments. Protein fibers like wool and silk contain amino and carboxyl groups, making them perfect for acid dyes [34]. These dyes form ionic bonds with the positively charged amino groups in the fiber under acidic conditions, resulting in rich, durable colors. Metal-complex dyes are a subclass of acid dyes, mostly

used for wool to increase its lightfastness and wash fastness. Synthetic fibers such as polyester fibers have less affinity for most dyes and require disperse dyes, which are non-ionic and penetrate the hydrophobic fibers under high temperature and pressure. Similarly, nylon fiber has a high affinity for acid dyes, which form ionic bonds with the amino acids in the nylon. Disperse dyes and reactive dyes are mostly used for nylon, while acrylic fibers have a high affinity for acid dyes and disperse dyes and are typically colored with basic (cationic) dyes due to their negatively charged sites. Hence, matching dyes to fiber types is a crucial aspect of textile dyeing, as it ensures optimal dye-fiber interaction and colorfastness. The choice of dye and dyeing process focuses on the type of fibers, the desired colors, and the required colorfastness. By understanding the dye-fiber interactions, textile manufacturers can produce high-quality and durable dyed fabrics.

### *3.1.3 Properties of textile dye*

Textile dyes are particular chemical compounds designed to impart color to fabrics. Their effectiveness depends on different properties that confirm optimal performance, durability, and sustainability [35, 36]. Here are some properties of textile dyes explained in detail.

#### *3.1.3.1 Colorfastness*

Colorfastness is the capacity of a dye to keep its hue under various external influences like washing, light, heat, and friction. Consumer pleasure depends on high colorfastness since it guarantees the fabric keeps its look over time. Primarily, three varieties of colorfastness exist.

- a. Lightfastness is the ability of the dye to resist fading under light exposure. Outdoor textiles and clothes that will be exposed to the sun rely on this.
- b. Wash fastness is the ability of the color to resist fading during washing. This is important for home textiles as well as for clothes that will be washed often.
- c. Rub fastness refers to a dye's ability to withstand fading when it is abraded or rubbed. This is especially important for items under friction, such as clothing and furniture.

#### *3.1.3.2 Affinity for fiber*

The affinity for fiber is an important property of textile dyes, describing their ability to interact with and adhere to specific types of fibers. This affinity has two types, i.e., chemical affinity and physical affinity.

##### *3.1.3.2.1 Chemical affinity*

Chemical affinity is the dye's ability to create notable chemical links with fiber, which is crucial for achieving long-lasting and permanent color. For example, reactive dyes have high chemical affinity for cotton fabric and form covalent connections that confirm strong color fixing. While the acid dyes are mostly drawn to wool and silk, bonding with ionic interactions.

### *3.1.3.2.2 Physical affinity*

Physical affinity defines the ability of dye to bond with a fabric surface, which depends on its molecular structure. Smaller dye molecules easily penetrate the fabric surface, but large molecules cannot react with fibers easily. Hence, the color sticking is influenced by the fiber's porosity and surface texture.

### *3.1.3.3 Stability*

Dye's stability is its capacity to resist fading, discoloration, and breakdown under different physical and chemical conditions. The stability of dye directly affects the lifetime and anti-aging look of coloring materials, including paper, leather, and textiles. Various parameters are used to assess dye stability. Thermal stability, chemical stability, light stability, pH stability, and eco-friendly surroundings are among these criteria.

#### *3.1.3.3.1 Thermal stability*

The thermal stability is a crucial factor affecting the type of textile dye. Dyes may compromise their structural integrity and diminish or deteriorate at elevated temperatures. High-performance dyes are ideal for industrial processes and applications demanding repeated exposure to elevated temperatures, as they preserve their color integrity even under extreme heat. Their exceptional thermal stability ensures uniform luminosity and reliable functionality even in challenging conditions.

#### *3.1.3.3.2 Chemical stability*

A significant factor is chemical stability. Chemical stability means a dye's ability to resist breaking down when it comes into contact with strong textile processing chemicals, like bleach or alkaline solutions used in mercerizing. This attribute ensures fabric quality and prevents undesirable fading throughout the manufacturing process. A chemically stable pigment in an acidic solution preserves its luminosity. The pigments employed in mercerizing also withstand the corrosive effects of sodium hydroxide. Ensuring colorfastness in demanding industrial processes requires significant endurance, as inferior dyes will degrade and undermine the outcome [37].

#### *3.1.3.3.3 Light stability*

A primary element is light stability. High-quality dyes will maintain their color in sunlight, ensuring the fabric preserves its natural hue. This attribute most significantly benefits outdoor textiles. A high light stability dye exhibits reduced susceptibility to fading. Therefore, they are perfect for goods needing long-term color maintenance under bright circumstances.

#### *3.1.3.3.4 pH stability*

The pH of the medium influenced the stability of a dye. Though some colors do better in neutral or alkaline settings, relatively few are stable in acidic ones. Keeping the right pH will help to ensure the longevity of the dye and its capacity to reach nice coloration. If the pH varies from the ideal range, it could cause a change in hue or color loss due to alterations in the dye's chemical structure.

#### *3.1.3.3.5 Eco-friendliness*

Low toxicity is emphasized by eco-friendly textile dyes to protect the health of consumers and employees, and their biodegradability allows for environmental breakdown, thereby reducing pollution [38, 39]. Additionally, by reducing pollution and degradation, these colors have a minor effect on the environment and contribute to the sustainability of the textile sector. Through the incorporation of characteristics like low toxicity, biodegradability, and reduced environmental effect, eco-friendly dyes enable safer production processes and align with international efforts to promote sustainable manufacturing practices.

#### *3.1.3.4 Solubility*

A dye's solubility means the dye is easily dispersed and forms a homogeneous solution in water or other solvents. Dye solubility mainly consists of two types. These are water solubility and solvent solubility.

##### *3.1.3.4.1 Water solubility*

If a dye is easily dissolved in water, then it is called water-soluble dye. Mostly during the dyeing process, the fabric is permitted to absorb the dye uniformly. For example, direct dyes need a constant color guarantee and suitable penetration of cellulose fibers so that the dye can be easily absorbed in water. Reactive dyes too rely on water solubility to enable their diffusion into the fiber and later chemical bonding. Too little solubility would cause the dye to clump or precipitate, hence producing uneven coloring and low colorfastness. Therefore, a major element is water solubility, which defines consistent and high-quality dyeing outcomes.

##### *3.1.3.4.2 Solvent solubility*

Solvent solubility is the capacity of dye to dissolve in organic solvents such as ionic liquids or supercritical CO<sub>2</sub> rather than water. Specialized dyeing methods such as solvent dyeing and supercritical CO<sub>2</sub> dyeing rely on non-aqueous solvents to deliver certain coloring effects or environmental advantages, so this characteristic is quite crucial. A dye's solubility in a solvent is affected by many elements, including the dye and solvent's polarity, the solvent's dielectric constant, temperature, and additive presence. Though supercritical CO<sub>2</sub> provides a sustainable alternative to water-based dyeing techniques, ionic liquids and deep eutectic solvents can greatly boost the solubility of natural dyes.

#### *3.1.3.5 Compatibility*

Dye compatibility is the capacity of a dye to interact with other dyes or chemicals in a dyeing system without producing negative effects. Two main factors are dye-to-dye compatibility and chemical compatibility [40].

##### *3.1.3.5.1 Dye-to-dye compatibility*

Compatibility of a dye is the ability of a dye to combine with other dyes without producing negative effects like uneven dyeing, color separation, or low colorfastness. This characteristic is important for making a broad spectrum of colors and tones. For

example, mostly cotton dyes mixed with other dyes smoothly make rich, fast, and bright colors. This characteristic helps the textile to achieve consistent, good quality results, expanding their color opportunities for different designs.

#### *3.1.3.5.2 Chemical compatibility*

The compatibility with other chemicals guarantees a dye's capacity to be utilized together with numerous chemicals usually used in the dyeing process, including salt, alkali, reducing agents, and other auxiliaries, without creating negative reactions. This quality is essential since the dye's interaction with these elements directly affects successful dyeing and colorfastness. Reactive dyeing, e.g., requires the dye to react with alkali chemicals, disrupting fiber connections. The color should also not degrade or produce undesired byproducts when applied with reducing agents.

#### *3.1.3.6 Shade and color range*

Important characteristics of textile dyes that directly affect their appropriateness for certain uses in the textile industry include color spectrum and shade constancy. The dye's broadest color spectrum lets it create a variety of hues, therefore sustaining the various color needs of the textile sector. This flexibility might allow the construction of vivid, diverse patterns that suit a range of consumer preferences and fashion trends. Conversely, regular shade declares that the dye produces a uniform hue across multiple applications and batches. This consistency guarantees the quality and homogeneity of the final product, thereby avoiding color fluctuations that can create dissatisfied consumers and inconsistent brand messages. Moreover, these features enable fabric manufacturers to create both creative and premium results.

#### *3.1.4 Innovations in textile dyeing*

Innovations in textile dyeing will be a remarkable convergence of science, technology, and sustainability, and will progress the industry, especially in the fields of digital printing and eco-friendly dyeing procedures. Digital textile printing is a method that has changed the way materials are dyed and designed. Utilizing inkjet technology to directly apply dyes onto fabrics presents a refined alternative to traditional dyeing methods, enabling unparalleled personalization, rapidity, and resource efficiency. This method is ideal for fast fashion and small-batch production, as it reduces waste by utilizing only the necessary dye, conserves water, and facilitates intricate designs and rapid color alterations. Eco-friendly dyeing techniques prioritize the utilization of natural, non-toxic, and biodegradable substances to mitigate their adverse effects on the environment [41]. Traditionally, textile dyeing is infamous for its high water use, chemical contamination, and production of hazardous wastewater. Business leaders and scholars are developing sustainable alternatives to help mitigate these issues. The remarkable advancement of natural dyes derived from plants, minerals, and microorganisms such as bacteria and fungi yields vibrant colors, requires minimal energy and water, is non-toxic, and exerts a negligible environmental impact [24].

Advancements in biotechnology have resulted in enzyme-based dyes and eco-friendly and more efficient auxiliary components [42]. The use of supercritical carbon dioxide as a solvent in waterless dyeing is a highly innovative approach. This approach involves subjecting CO<sub>2</sub> to a supercritical state, enabling it to function

as both a liquid and a gas, hence facilitating the penetration of colors into fabrics without the use of water. This technology conserves water and inhibits the discharge of toxic substances into ecosystems. Moreover, nanotechnology in textile dyeing has created new opportunities for enhancing dye fixation, color fastness, and fabric performance. Augmenting the utilization of colored materials further facilitates the incorporation of nanoparticles to produce consistent antimicrobial surfaces, UV-protective textiles, and self-cleaning fabrics. These advancements are not only theoretically intriguing but also significantly pertinent due to their fulfillment of the pressing demand for sustainable practices in the textile sector. Ultimately, digital printing and sustainable dyeing methods indicate a fundamental transformation in textile chemistry. The industry is progressing toward a future where modern technology and sustainable concepts can produce vibrant, high-quality textiles with minimal environmental impact. As academics, we must persist in scrutinizing these technologies, instruct the forthcoming generation of scientists, and propel the transition toward a more sustainable and efficient textile sector.

### **3.2 Art (dyes as a medium of creative expression)**

Artists have used dyes as a medium of creative expression for generations, so offering a different spectrum of possibilities to create bright and important works [43]. Here is a look at dyes from different perspectives as a medium of artistic creative expression.

#### *3.2.1 Historical use of dyes in art*

Dyes have been a basis of human creativity, expressing both cultural expression and chemical innovation from prehistoric cave paintings to modern textile arts [44]. Early painters utilized certain biological materials such as iron oxides and charcoal to create earthy tones [45]. Narrative and symbolic ceremonies utilized these paints. As society changed, dyeing methods developed. For instance, whereas in Mesopotamia, Tyrian purple dye made from sea snails became a status symbol [46], the Egyptians created synthetic Egyptian blue for sacred pictures. China's mastery of indigo cultivation around 2400 BCE led to the evolution of silk-dyeing methods [32]. While ancient world arts give importance to West African mud cloth, Japanese shibori, Asian batik, and Indian bandhani, they investigated chemical ideas such as metal-ion complexes and solubility [47]. Europe during the Middle Ages saw colors like lead white and ultramarine, which were not synthetic but rather derived from natural sources. Perkin's invention of mauveine in the nineteenth century was a turning point, allowing bright, mass-produced color. Even now, dyes link art and chemistry by combining historical methods with modern materials science. This legacy emphasizes how, over tens of thousands of years, artistic vision and scientific developments have molded human.

#### *3.2.2 Painting, printing, and fabric art*

In painting, printing, and fabric art, dye is a medium that penetrates and chemically bonds with materials to produce bright, long-lasting, often translucent effects. Artists in painting can apply dyes on many surfaces like paper, fabric, or canvas using brushes or other instruments, much like they do paints. From transparent washes to opaque hues, dyes can be layered or diluted to produce various effects. Watercolor

dyes, for instance, dissolve in water and connect with cellulose fibers using hydrogen bonds, allowing them to produce fragile, translucent paintings with gentle color changes. Historically, oil painting used dyes like carmine. It includes combining dyes or pigments with drying oils that polymerize by oxidation, generating permanent, cross-linked films. For lightfastness, modern oil painting gives priority to synthetic pigments, e.g., cadmium red. Acrylics guarantee color permanence by using dyes spread in acrylic polymer emulsions, which create water-resistant films upon evaporation. Among the most noteworthy are quinacridone reds, synthetic dyes with planar aromatic structures that resist fading and produce strong chroma, and indigo, a vat dye needing reduction to leuco-indigo before oxidation to blue. These methods and materials show how chemistry from hydrogen bonding to polymerization influences the creative process as well as the lifetime of artworks. We also use dyes for printing and dyeing. Fabric art methods use dyes to color textiles by means of dip-dyeing, in which the fabric is submerged in a dye bath to obtain an equal hue or batik, which uses wax to resist the dye and produce detailed patterns. Common ways to transfer graphics onto fabric include dye block printing and screen printing. Techniques include screen printing, utilizing reactive dyes which create covalent connections with cellulose or disperse dyes which penetrate synthetics using hydrophobic interactions in printing. Block printing often uses mordants to increase dye-fiber affinity and sends dye pastes onto cloth. Under heat, digital printing uses sublimation dyes that bond with polyester fibers. In mixed media art, dyes can be used with other materials and methods. Used to stain or color metal, wood, or clay, they provide a splash of color and improve the general texture and visual appeal of the piece; e.g., dyes could be applied to a collage to produce a certain atmosphere or to blend various elements [48].

### *3.2.3 Importance of dyes in traditional art*

Natural dyes have been absolutely crucial for the growth of cultural identity, customs, and artistic expression in a great spectrum of societies [43]. A UNESCO-recognized art form from Indonesia, batik uses natural colors like indigo in conjunction with wax-resist dyeing. More than only ornamental qualities, colors and designs have great cultural relevance; they visually explain stories. While elaborate decorations preserve local history and spiritual beliefs, blues are often connected with stability and our connection to nature. India's textile history provides beautiful examples. Rich in religious symbolism, the natural dyes used in Madhubani and Kalamkari paintings are made from indigenous plants using age-old traditions. During Hindu festivals, vivid reds and yellows are more than just decorative; they symbolize wealth, life, and divine favors. These constant color customs show how dyes connect cultural memory, identity, and religion, as well as being more than simply a source of color [7]. Cochineal represented power and divine favor in ceremonies and textiles made from insects important to Mesoamerican trade. Every design carries some cultural relevance. The dye used to color Malian African mud cloth, for example, is created from fermented mud and conjures ancestral stories and shared aspirations [49]. While the Japanese used indigo dyeing for confirmations of patience and tranquility, Chinese silk dyeing emphasizes meticulous craftsmanship using natural colors like madder and gardenia, which are basic to imperial art. Beyond looks, these hues express environmental balance, spiritual connectedness, and social hierarchy. Ancient Egyptians valued malachite and indigo for their mystical relevance in tomb decorations and ceremonies [50]. Natural dyes' comeback in artisan crafts and sustainable design

emphasizes their ongoing function in maintaining cultural legacy by linking contemporary efforts to old traditions, honoring the environment and human creativity.

#### *3.2.4 Modern artistic evolutions*

Changes in artificial and practical colors have had a major impact on modern art. By combining chemical innovation with artistic expression, these colors upsurge visual potential. Industrial synthetic dyes offer artists unmatched brilliance and longevity. Developed in 1907 and popularized in the 1930s, phthalocyanine blue gave Max Ernst a powerful lightfast replacement for conventional Prussian blue. Artists like Paul Cezanne and Seraphine Louis used synthetic alizarin as early as 1895 for its constant, strong hues. The strong molecular structures of these pigments absorb particular light wavelengths, hence generating bright hues that resist fading. Functional dyes such as thermochromic and photochromic pigments add dynamic interactive components to art. Some hues, e.g., exhibit reversible chemical interactions. Leuco dyes in thermochromic systems change between vibrant and colorless conditions, hence enabling artworks to react to environmental signals. Nanotechnology increases this interaction even more the structural color produced by nanostructured surfaces creates iridescent changes without pigments. Like Vant black, it absorbs 99.96% of light, therefore creating void-like images that change spatial awareness. Driven by environmentally friendly technologies, sustainability is getting more attention. Plant waste and low-impact synthetic-based bio pigments lower the need for hazardous heavy metals. Digital printing (inkjet-based) reduces waste by applying dyes pixel-by-pixel, while supercritical CO<sub>2</sub> fluid dyeing and other waterless dyeing techniques remove water pollution. Though they preserve creative diversity, these techniques tackle environmental issues. In the end, synthetic and functional dyes provide tools for bright, participatory, sustainable creation, exposing the harmony between chemistry and art. Although problems like degradation still exist, constant developments in analytical chemistry, bio-dyeing, and nanotechnology keep pushing creative boundaries and guarantee that the interaction between science and beauty stays dynamic and changing.

### **3.3 Industry (beyond textiles and art)**

The applications of dyes go far beyond traditional sectors like textiles and art. Their optical, chemical, and interactive features inspire creativity in many other domains. Here is a brief overview of the use of dyes in different fields.

#### *3.3.1 Printing and paper*

The paper industry carefully selects dyes based on their chemical characteristics to impart specific aesthetic and functional qualities. By dissolving in water, direct dyes and sulfonated aromatic chemicals included in paper pulp during manufacture ensure a consistent color in products such as newsprint and office paper. Their capacity to engage with cellulose via hydrogen bonds produces long-lasting and vivid hues. Acid dyes in premium coated papers, greeting cards, and stationery need acidic conditions to attach to fibers, thus providing exact color control. Though they might show lower lightfastness, basic dyes are well-known for their strong pigmentation capacity, which lets them create bright colors for labels and ornamental materials, including gift wrapping. Fluorescent pigments absorb ultraviolet light and release visible wavelengths to brighten high-visibility items like neon sticky notes and security papers (banknotes). Apart from hue, functional additives improve paper

performance. Optical brighteners, which absorb UV radiation and re-emit blue light, help printing paper to look “whiter-than-white.” Embedded in specialist papers, pH indicators change color depending on acidity, therefore functioning analytically like litmus strips or industrial pH testing. These dyes and additives help papers meet many goals, from daily use to specialized ones. These dyes and additives demonstrate the connection between chemistry and design, thereby balancing sustainability, safety, and durability. Using dyes, printing produces high-quality images for packaging, newspapers, and magazines. Pigments in ink and paper coloring improve the look and functional qualities of paper products, enhancing their appeal and lifetime. Dyes in carriers such as solvents or resins impart color to materials, including paper, plastic, or textiles. Dissolving in organic solvents, solvent-based dyes are major dye types that generate high-intensity colors in conventional printing methods, often used in packaging. While they usually require fixatives to ensure durability, water-based dyes offer environmentally suitable substitutes for digital printing and food packaging with low volatile organic compounds (VOCs).

By forming covalent connections with cellulose, reactive dyes offer colorfastness in textile printing. UV-curable dyes cross-link under UV light to produce images resistant to scratches. Recent developments in ink technology have helped enhance performance and sustainability. For premium digital printing, nanoparticle dyes improve color depth and dispersion stability. E-readers utilize thermochromic and electrochromic inks, while smart inks combine biodegradable inks and plant-based dyes to create environmentally friendly packaging that supports the circular economy. These changes indicate a trend toward beneficial eco-friendly materials that nevertheless generate wonderful outcomes. The paper industry, therefore, relies on dyes to color paper products and manufacture high-quality inks. By enhancing its functional performance and visual appeal, its use increases the lifespan of the paper and its aesthetic appeal for many uses.

### *3.3.2 Leather tanning*

Raw hides are converted into functional and visually appealing products through the complex interplay of chemical principles, craftsmanship, and innovative design referred to as leather dyeing. Contemporary advancements in dye chemistry prioritize sustainability and performance, aligning with stringent environmental regulations and evolving consumer preferences for eco-friendly products. To ensure that leather remains a durable, versatile, and eco-friendly material, the industry is increasingly using green energy methods such as biodegradable dyes and low-waste processes. There are different methods for leather dyeing and tanning. These are described below.

#### *3.3.2.1 Leather dyeing*

There are five basic leather coloring methods. These are the aniline, pigment, drum, hand, and spray methods. Emphasizing natural textures by deep penetration into the leather’s fibers, the aniline dyeing procedure first preserves elasticity. Pigment dyeing is the second method, which consistently colors the surface and so provides longevity and fade resistance. The third method is drum dyeing which is perfect for large-scale manufacturing since it reaches thorough saturation using spinning drums. The fourth method is hand dyeing; it creates unique artisanal finishes by means of manual application. The fifth method is spray dyeing; it offers quick, uniform coverage for large surfaces, usually in industrial environments.

### *3.3.2.2 Leather tanning methods*

The choice of dye and method depends on the leather's tanning process, which determines its structural properties and dye affinity. There are several leather tanning methods, such as vegetable tanning, chrome tanning, chrome-free tanning, synthetic tanning, aldehyde tanning, oil tanning, brain tanning, mineral tanning, and combination tanning.

#### *3.3.2.2.1 Vegetable tanning*

Vegetable tanning is a traditional leather-making process that uses natural tannins derived from plants such as oak bark, quebracho, and chestnut. These tannins chemically bond with the collagen fibers in the hide, stabilizing and cross-linking them to convert raw hide into durable leather. The process involves soaking the hide in water for cleaning, followed by immersion in vats with progressively stronger vegetable tanning solutions, a method that can take weeks or even months. The resulting leather has a natural, warm appearance, excellent breathability, and high durability, though it starts off stiff and softens over time while developing a rich patina. Still, as compared to other tanning techniques, it is more prone to water damage. Vegetable-tanned leather is often used in high-end items, including shoes, belts, handbags, and furniture upholstery, since it is attractive and durable.

#### *3.3.2.2.2 Chrome tanning*

Chromium (III) sulphate is utilized in chrome tanning, a modern and efficient leather manufacturing method, to maintain and strengthen the collagen fibers in the hide. The first phase of the process is regular hide preparation; next, immersion in a chromium salt solution with exactly controlled pH and temperature. Its flexible, permeable nature allows for dyeing, which leads to durable absorption and bright colors. Usually requiring just a few hours to many days, depending on the hide's thickness, chrome tanning is far faster than vegetable tanning. The resulting leather is quite strong, supple, and flexible. Its aptitude for bright dyeing and exceptional resilience to water and mildew are remarkable. The disposal of chromium-contaminated wastewater raises environmental issues, though. Apart from fashion items like purses, gloves, and outerwear, chrome-tanned leather makes up more than 85% of world production and is widely used in industrial uses requiring resilience and flexibility.

#### *3.3.2.2.3 Chrome-free tanning*

Ecologically conscious leather production, chrome-free tanning, uses safer substitutes like vegetable tannins, aldehydes, or synthetic chemicals in place of toxic chromium salts. This method lowers environmental and health concerns connected with conventional chrome tanning while producing soft, usable leather. Though usually slower and perhaps less water-resistant than chrome-tanned leather, chrome-free alternatives offer comparable flexibility and dyeability, with certain techniques producing biodegradable outcomes. In sustainable fashion, vehicle interiors, and luxury products, the leather is especially prized where eco-friendliness is a top priority. Although they might not be similar to chrome tanning in all performance criteria because of continuous developments in alternative tanning chemicals, businesses dedicated to balancing quality and environmental responsibility are finding

chrome-free tanning techniques more and more reasonable. Hence, this method is considered a greener method with an eco-friendly environment.

#### *3.3.2.2.4 Synthetic tanning*

Synthetic tanning, often known as artificial tanning, employs laboratory-produced organic compounds to replicate the advantages of traditional vegetable or chrome tanning while mitigating their disadvantages. Depending on the chemicals used, the method calls for processing hides under measured conditions with certain synthetic tanning agents. Usually more efficient than vegetable tanning, this technique yields more consistent outcomes. While sustaining the suppleness and elasticity natural in chrome-tanned leather, the resulting leather can be changed to increase chemical or water resistance. Many synthetic tanning chemicals have also been formulated to be more environmentally benign than conventional methods. Reducing toxicity and enhancing biodegradability help to achieve this. From daily needs to specialty items with particular performance criteria, synthetic tanning is also found in a great range of leather goods because of its flexibility and environmental friendliness.

#### *3.3.2.2.5 Aldehyde tanning*

Aldehyde tanning is a leather manufacturing technique that cross-links collagen fibers with reactive chemicals such as formaldehyde or glutaraldehyde, stabilizing the skin. This procedure processes the hide under controlled pH and temperature using an aldehyde solution, which accelerates the tanning process. As compared to vegetable-tanned leather, the resulting leather shows improved water resistance, better dimensional stability, and higher strength. The formaldehyde-based tanning technique is harmful and risks health and the environment. Its structural qualities are especially beneficial for industrial uses calling for robust leather, like specialist belts and industrial gloves.

#### *3.3.2.2.6 Oil tanning*

Oil tanning, an old leather-processing method also known as brain tanning, uses natural oils and fats, usually from animal brains, to soften and preserve hides. This method consists of soaking the hide and then lightly pressing oils into it. Smoking is typically used to define the therapy and improve preservation as well as to impart a certain color and earthy aroma. The resulting leather has an amazing natural feel and is incredibly soft, flexible, and breathable. On the other hand, its stain sensitivity and ongoing maintenance requirements are drawbacks. In Native American crafts and specialty leather goods like handbags and moccasins, where a soft and natural look is desired, this age-old technique is still highly prized. Hence, the oil tanning method is distinguished by its handmade quality and its association with traditional leather-working methods.

#### *3.3.2.2.7 Combination tanning*

By integrating the benefits of each approach, combination tanning creates leather with improved and tailored qualities using two or more tanning methods. For example, combining chrome and vegetable tanning produces leather that balances the hardness and natural look of vegetable-tanned hides with the softness of

chrome-tanned hides. A range of tanning chemicals are used in successive treatments during the process. Customized methods deliver the desired traits. While preserving a more natural appearance than chrome tanning by itself, this hybrid combined tanning approach offers higher water resistance than pure vegetable tanning. The outcome is a premium, flexible leather that may be exactly customized to fit certain requirements. Occasionally, combination tanning is utilized to obtain the extraordinary softness and polished natural appearance absolutely for high-end leather products such as luxury bags, shoes, and accessories. By maximizing both use and design, this technique demonstrates inventiveness in leather manufacture.

### *3.3.3 Food and cosmetics*

Dyes play a multifaceted role in food, cosmetic, and personal care products, enhancing their visual appeal, aiding in brand identification, creating a sense of luxury, indicating specific functions, providing camouflage and correction, and influencing psychological and emotional well-being [38]. Their strategic use ensures that these products not only meet aesthetic standards but also cater to the diverse needs and preferences of consumers. Food dyes play a significant role in the food industry, enhancing the visual appeal, maintaining color consistency across batches, and marketability of various products. They play a key role in consumer perception, as color influences taste expectations and purchasing decisions. In food, both natural and synthetic dyes are used. They are particularly important in processed foods, i.e., ice cream, canned fruits, breakfast cereals, processed vegetables, beverages such as soft drinks, energy drinks, sports drinks, and flavored juices, baked goods, condiments, and candies. For example, the bright red dyes in candies mostly attract children, while natural-looking dyes in ready-to-eat meals make them more appetizing. The dyes are also essential in the cosmetic and personal care industry for enhancing visual appeal, providing color variety, offering functional benefits, aiding in brand identification, and influencing consumer psychology. Cosmetic goods, including lipsticks, eyeshadows, blushes, and nail polishes, use dyes in a variety of shades and colors. This allows consumers to choose colors that match their personal style, skin tone, and the occasion. High-quality vibrant dyes can give the impression of a luxurious and premium-quality product. Bright and intense colors in products like high-end lipsticks or eyeshadows can make consumers feel that they are using a top-of-the-line item. Furthermore, in hair coloring products, different colors may represent different levels of lightening or the specific shade of the final result. For skin base products like concealers and foundations, dyes are used to help hide flaws, dark circles, and other skin imperfections. They can also help the skin tone to change, making it more even and smooth. In psychological and emotional effects, hues have the ability to affect feelings and moods. The correct hue in cosmetics, for instance, can increase a person's confidence and make them feel more attractive; using a preferred shade of lipstick or eyeshadow can also have a good psychological impact, therefore enhancing the user's sense of self-assurance and organization.

### *3.3.4 Pharmaceuticals*

In pharmaceuticals, dyes are quite important and diverse since they go well beyond basic coloring. Their uses range from medication formulation to patient safety to diagnostics to regulatory compliance; hence, they are absolutely vital in contemporary medicine. For example, as hospitals and pharmacies offer a large number

of drugs, dyes are used to color-code tablets, capsules, and liquid pills, allowing healthcare personnel to quickly identify several drugs. A frequent but major problem in healthcare environments, this lowers the likelihood of pharmaceutical mistakes. Dyes are also used to indicate medicinal strengths; for example, a lesser strength pill might be light colored, but a greater strength version of the same medication could be darker. This visual cue guarantees the right dose is given, hence supporting efficient treatment for patients as well as medical personnel. Dyes also have quite significant effects in enhancing the visual attractiveness of pharmaceutical items. The look of drugs can affect some adults as well as children and influence their desire to use them. Moreover, some dyes can show a drug's durability. Environmental variables, including pH, temperature, and humidity, can promote drug deterioration and cause them to change color. Dyes are also useful in medical diagnosis, for example, to stain pathological biological material. A straightforward method is hematoxylin and eosin (H&E) staining. While eosin colors the cytoplasm and extracellular matrix pink, hematoxylin colors the cell nuclei blue-purple. Pathologists can find various cell kinds, spot aberrant cell architectures, and diagnose cancers with this staining. Choosing the right antibiotic treatment depends on bacterial classification, which is done using other specialist stains such as Gram stains.

Fluorescent dyes are used in advanced diagnostic techniques such as flow cytometry and fluorescence microscopy. Fluorescence microscopy links these hues to particular chemicals or cells. Excited by a certain wavelength of light, they emit fluorescence, which allows researchers to examine the distribution and function of proteins within cells. Flow cytometry sorts and analyzes cells using fluorescent-tagged antibodies depending on their physical and chemical traits. Moreover, fluorescence is another technique. Often, guided surgery emphasizes tumors or other problematic regions using colors. This strategy allows doctors to precisely remove the sick area while maintaining healthy tissue. This process benefits patients by increasing the accuracy and success rate of treatments. Medical imaging also makes use of dyes as contrast agents. The digestive tract is X-rayed using barium sulfate. Coating the surfaces of the digestive organs allows medical personnel to identify issues like ulcers, polyps, or obstructions and enhances their appearance. Magnetic resonance imaging (MRI) increases the contrast between healthy and ill tissues by means of gadolinium-based contrast agents. This allows for precise diagnosis of conditions such as brain tumors and multiple sclerosis.

### *3.3.5 High-tech application*

Functional dyes have transformed modern technology by means of advances in data storage, renewable energy, and biological imaging [51]. Modern uses depend on these molecularly designed, complex dyes since they are light-responsive, biocompatible, and conductive.

#### *3.3.5.1 Optical data storage system*

Functional dyes are mostly used due to their fast speed and maximum data storage density. CDs and DVDs, like other traditional optical discs, use dyes to produce a pattern of pits and lands that represent digital data. Conversely, new functional dyes permit more precise control over the recording and reading of data since they can absorb and emit light at particular wavelengths. This allows for the production of next-generation optical storage media, Blu-Ray discs that can hold far more data in

a smaller physical area. The employment of functional dyes in optical data storage is absolutely necessary to satisfy the rising need for large-capacity, quick-access storage options given the exponential increase of digital information. Moreover, functional dyes are meant to be quite durable under various environmental circumstances, hence guaranteeing long-term data storage. They withstand deterioration from elements like heat, light, and humidity that could finally lead to data loss. Archiving essential digital data, including historical records, scientific research, and cultural legacy artifacts, calls for these attributes.

### *3.3.5.2 Renewable energy*

Functional dyes in solar cells boost the absorption of sunlight over a greater spectrum. Focusing on organic dyes, dye-sensitized solar cells (DSSCs) generate an electric current by means of photon collection and electron mobility. Tuning these dyes to absorb light at different wavelengths will assist in increasing their efficiency in converting solar energy into electrical power. By increasing the capacity of solar cells to collect light, functional dyes allow the creation of cheaper and more efficient solar energy systems. This depends on us reducing our reliance on fossil fuels and switching to a more sustainable energy future. Dyes are also a very inexpensive replacement for traditional silicon-based solar cells. The manufacture of DSSCs utilizing functional dyes is often less costly. Considering their low energy consumption and simple manufacturing process, DSSCs could be a sensible option for large-scale solar energy production. Therefore, the overall cost of solar cells is decreased by producing effective dyes from inexpensive and plentiful ingredients.

## **3.4 Dyes' economic and cultural impact**

The dye industry has profoundly influenced human civilization and has been a foundation stone of global economic and cultural development. The evolution from the initial extraction of natural dyes in prehistoric eras to the extensive production of synthetic dyes in contemporary times has significantly influenced fashion trends, trade networks, and technological progress. A long time ago, dyeing was more than just a pragmatic need; it became a cultural symbol reflecting beliefs, identities, and history. This analysis will address the pressing challenges confronting the sector and the transformative potential that exists, while also exploring the multifaceted role of dyes in global economies and cultural heritage.

### *3.4.1 Financial benefits of the worldwide dye industry*

International economies mostly focused on the dye sector because it produces employment and economic development. Expected to be worth USD 12.68 billion in 2024, the worldwide textile dye market is projected to upsurge at a compound annual growth rate (CAGR) of 6.1% to USD 21.61 billion by 2033 [52]. This expansion is fueled by various elements, including the increasing need for textiles caused by rapid urbanization, population increase, and greater discretionary money, particularly in developing nations [53]. Market revenue expansion is also being driven by the need for sustainable, eco-friendly, and long-lasting colors. Improvements in digital printing technology and the rising demand for specialty textiles, particularly technical and smart textiles, help the textile dye sector as well.

### *3.4.2 Cultural legacy*

Many societies all throughout the world depend on traditional dyeing techniques, which are culturally important. Often handed down through time, these techniques are employed to produce conventional textiles, garments, and artifacts. Changed civilizations have employed natural dyes derived from plants, minerals, and insects for millennia to create unique and important colors. Keeping ethnic identity and traditional skills benefits local artisans and endorses environmentally responsible behavior. Projects are underway to document and bring back fading traditional skills to save this cultural legacy from industrialization and modernity.

### *3.4.3 Significance of dyes on consumer choice and fashion trends*

By offering a broad variety of colors and tones that fit changing tastes and cultural expressions, dyes greatly affect customer choices and fashion trends. Often set by organizations like the Pantone Color Institute, color trends affect a wide range of goods consisting of cosmetics, accessories, and clothing [54]. Colors may be a strong weapon for designers to produce intended moods and stories in their collections since they can inspire certain feelings and interpretations. It is crucial to comprehend the psychological and cultural significance of colors, as different hues are associated with specific emotions or cultural implications. For instance, many link red with zeal and vitality, while blue is usually considered soothing and reliable. The growth of social media and digital media has also had a major influence on color preferences among fashion customers. Should it gain popularity among celebrities and influencers, the need for a certain type can be rapidly increased. Sustainability is becoming a pressing problem; hence, eco-friendly colors and materials are in more demand.

### *3.4.4 In global dye market challenges and prospects*

Tight environmental rules, raw material price fluctuation, and supply chain interruptions are among the many issues the worldwide dye business confronts. Resource-demanding and waste-producing traditional dyeing methods drive more strict environmental rules and greater compliance expenses. Market income growth is hampered by the increasing availability of alternatives, including natural dyes and pigments, and the greater cost of dyes. Still, the business offers many possibilities. Advancements in dyeing technology, such as digital printing and waterless dyeing, are helping to increase the efficiency and sustainability of dyeing processes. Increased focus on sustainability is driving more interest in natural and eco-friendly dyes. Rising consumer knowledge of sustainable goods and the textile industry's growth in rising countries are driving the market.

## **4. Challenges and future directions**

Many important problems in the dyeing sector need quick fixes and creative ideas. Dyeing's effects mostly include land degradation, water pollution, and worker health hazards; therefore, environmental concerns take first priority [55]. Dyeing operations' significant water use and use of chemicals call for strict environmental rules in places including China, North America, and Europe. Supply chain disruptions and



**Figure 2.**  
*Challenges and future directions.*

changes in the prices of raw materials, including benzene, could affect the costs of textile dye production and price stability. As industrialization and the widespread use of synthetic dyes threaten the profitability of conventional dyeing techniques, cultural preservation becomes a major issue. The future of the dye industry lies in blending invention with history while also considering environmental concerns and sustainability. Emphasizing the development of affordable, scalable skills and sustainable production practices, technological innovation is absolutely vital. Implementing automation and digitalization methods, including machine learning, artificial intelligence, and the internet of things, is very vital if dyeing operations are to be more efficient and productive. Sustainable practices are essential; bio-based colors derived from bacteria, algae, and food waste, along with waterless dyeing techniques utilizing supercritical CO<sub>2</sub>, are increasingly gaining popularity. Encouraging and supporting traditional dyeing methods facilitates cultural preservation and safeguards generations of cultural heritage. The dynamics of the global market will be significant; owing to rapid industrialization and rapidly increasing demand from countries such as China and India, the Asia-Pacific region is expected to command the biggest proportion of the dyes sector. The increasing demand for sustainable and eco-friendly dyes in North America and Europe offers new economic opportunities for creative and environmentally conscious dye makers. **Figure 2** explains challenges and future direction.

## 5. Conclusions

The dye business, encompassing natural pigments and synthetic dyes, has significantly influenced human civilization by addressing both practical and cultural needs. While it has catalyzed innovation in industry, art, and textiles, it presently encounters challenges related to cultural preservation and environmental sustainability. The industry can achieve sustainable solutions by reclaiming natural dyes and integrating

traditional techniques with technological advancements such as digital printing, waterless dyeing, and biotechnology. Hence, the dye industry, a cornerstone of global economic and cultural heritage, remains vital and contributes to a sustainable future by harmonizing innovation with tradition.

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