# Beyond Natural Dyes: Embracing Sustainable Innovations in Industrial Textile Dyeing

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**Abstract:** The textile dyeing industry is a major contributor to environmental pollution, necessitating the development of more sustainable dyeing processes. This review examines recent advancements in eco-friendly dyeing technologies, including improvements in natural dye extraction, the development of synthetic dyeing methods, and emerging innovations such as plasma technology, digital textile printing with biodegradable inks, and microbial dyeing. While natural dyes face challenges like variability and high production costs, new technologies which use synthetic dyes yet eco-friendly offer more consistent and scalable solutions. This paper highlights the limitations and potential of these methods, emphasizing the need for further research to address cost, scalability, and environmental impact. By reviewing these advancements, this paper aims to provide a comprehensive understanding of the current state of eco-friendly dyeing technologies and suggest directions for future research to achieve broader industrial adoption and sustainability in textile dyeing.

**Keywords:** Eco-friendly dyeing; Natural dye extraction; Waterless dyeing; Dyeing process efficiency

## 1. Introduction

The textile industry is one of the most influential sectors in the global economy, producing an incredible variety of fabrics and garments that are used daily. A key part of this industry is the dyeing process, which give fabrics their vibrant colors and eye-catching patterns that consumers love. In 2023, the global market for textile dyes was valued at around USD 9.6 billion, and it is expected to keep growing as demand for textiles continue to rise [1].

However, the heavy use of dyes come with significant environmental issues. Dyeing processes consume a lot of resources and produce substantial wastewater, which could be highly polluting if not managed properly [2]. Effective management of dye waste is crucial to reduce these environmental impacts and promote sustainable practices within the textile industry.

Currently, various methods are employed to clean dye-contaminated water before it is released into the environment. These methods include adsorption, biological degradation, photocatalysis, and advanced oxidation processes. Adsorption, using materials like activated carbon and bio adsorbents, is known for being effective in removing different dyes from wastewater [3,4]. Biological methods, such as using microbes to break down complex dye molecules into less harmful substances, provide an eco-friendly alternative [5]. Photocatalysis, which involve light-activated catalysts, and advanced oxidation processes that create highly reactive species to degrade dyes, has also shown promise in both lab and pilot-scale studies [6-8].

Despite these advances, dye waste removal is not the ultimate fix. Each method has its own set of limitations when it come to the range of dyes they could effectively remove and their overall efficiency [9]. For instance, the materials used in adsorption could become saturated and require costly and time-consuming regeneration [10]. Scaling these technologies up for industrial use is another obstacle, as adsorbents which work well in the lab often lose efficiency on a larger scale [11]. Additionally, the economic costs of implementing and maintaining these technologies are significant, making it difficult for many textile manufacturers to afford [12]. As a result, while dye waste removal methods are important, they do not tackle the root cause of pollution and often add complexity and cost to textile production [13, 14]. This situation underscores the need for more sustainable dyeing processes that minimize waste right from the start.

Recently, there has been growing interest in natural dyes, which are derived from plants, insects, and minerals. Researchers had explored various methods to improve the extraction procedures and enhance the yield of these natural dyes. Techniques such as enzymatic extraction, ultrasound-assisted extraction, and the use of eco-friendly solvents has shown promise in increasing the efficiency and yield of natural dye extraction [15, 16]. For instance, enzymatic extraction uses specific enzymes to break down plant cell walls, thereby releasing more dye compounds [17]. Ultrasound-assisted extraction employ ultrasonic waves to disrupt plant tissues, enhancing the release of dye molecules [18]. Additionally, researchers experimented with different eco-friendly solvents to replace traditional toxic solvents, making the extraction process greener [19, 20]. Moreover, advancements in biotechnology had enabled the genetic modification of dye-producing plants to increase their dye content, further improving the yield [21]. Some studies also focused on optimizing extraction parameters such as temperature, pH, and extraction time to maximize dye yield and quality [22-23].

Despite these advancements, natural dye extraction still faces several significant drawbacks that hinder its widespread industrial use. The variability in dye yield and quality due to differences in raw material sources, the complexity of extraction procedures, and the higher costs associated with natural dye production are major challenges [24]. Moreover, natural dyes often had lower color fastness compared to synthetic dyes, making them less durable and limiting their application in the textile industry [25]. Consequently, while natural dye extraction had made progress, it remains insufficient for meeting the demands of large-scale textile production.

In this paper, a deeper analysis of the natural dye extraction process and its limitations will be provided. However, greater emphasis will be placed on the development and optimization of eco-friendly industrial dyeing techniques using synthetic dyes, as this approach offers a more realistic solution to the sustainability challenges faced by the textile industry.

## 2. Natural dye extraction

### *2.1 Discovery of Novel Extraction Methods of Natural Dyes*

In recent years, the extraction of natural dyes has seen significant advancements, with researchers developing innovative methods to improve yield, efficiency, and environmental impact. These novel techniques have been explored and refined to address the limitations of traditional extraction processes, such as low yield, high energy consumption, and the use of toxic solvents.

One promising method is enzymatic extraction, which utilizes specific enzymes to break down plant cell walls, releasing more dye compounds. A study by El-Dein et al. (2018) demonstrated the efficacy of enzymatic extraction from red prickly pear, achieving higher dye yields compared to conventional methods. The use of enzymes such as pectinase and cellulase not only improved yield but also reduced the extraction time significantly [17]. The main advantage of enzymatic extraction is its eco-friendliness and efficiency, but the cost and availability of specific enzymes can be a drawback.

Ultrasound-assisted extraction (UAE) has also gained attention for its ability to enhance the release of dye molecules from plant materials. Haji (2010) reported that UAE improved the extraction efficiency of natural dyes from various plant sources. The ultrasonic waves disrupt plant cell walls, facilitating the release of dye compounds and increasing the overall yield [18]. UAE is noted for its reduced extraction time and lower solvent usage, making it a more sustainable option. However, the initial investment in ultrasound equipment can be high, and the method's scalability remains a concern.

Microwave-assisted extraction (MAE) is another innovative technique that has been investigated for its effectiveness in natural dye extraction. A study by Ko et al. (2021) showed that MAE could extract anthocyanins from black rice with higher efficiency and shorter extraction times compared to traditional methods. The microwave energy rapidly heats the plant material, causing cell rupture and enhancing dye release [26]. MAE offers the benefits of reduced extraction time and energy consumption, but the high cost of microwave equipment and potential for uneven heating are challenges that need to be addressed.

Supercritical fluid extraction (SFE) has emerged as a cutting-edge method for extracting natural dyes using supercritical CO2 as a solvent. Research by Chatterjee et al. (2019) demonstrated that SFE could efficiently extract carotenoids from marigold flowers, achieving high purity and yield [27]. SFE is praised for its non-toxic and non-flammable nature, making it an environmentally friendly option. However, the high operational pressures and costs associated with supercritical CO2 equipment can be limiting factors.

Another noteworthy method is the use of eco-friendly solvents such as deep eutectic solvents (DES). Dai et al. (2020) investigated the use of DES for extracting flavonoids from lotus leaves, finding that this method enhanced extraction efficiency and yield [28]. DES are biodegradable and less toxic compared to conventional solvents, offering a greener alternative for natural dye extraction. Nevertheless, the relatively new nature of DES means that more research is needed to fully understand their long-term environmental impact and optimize their use.

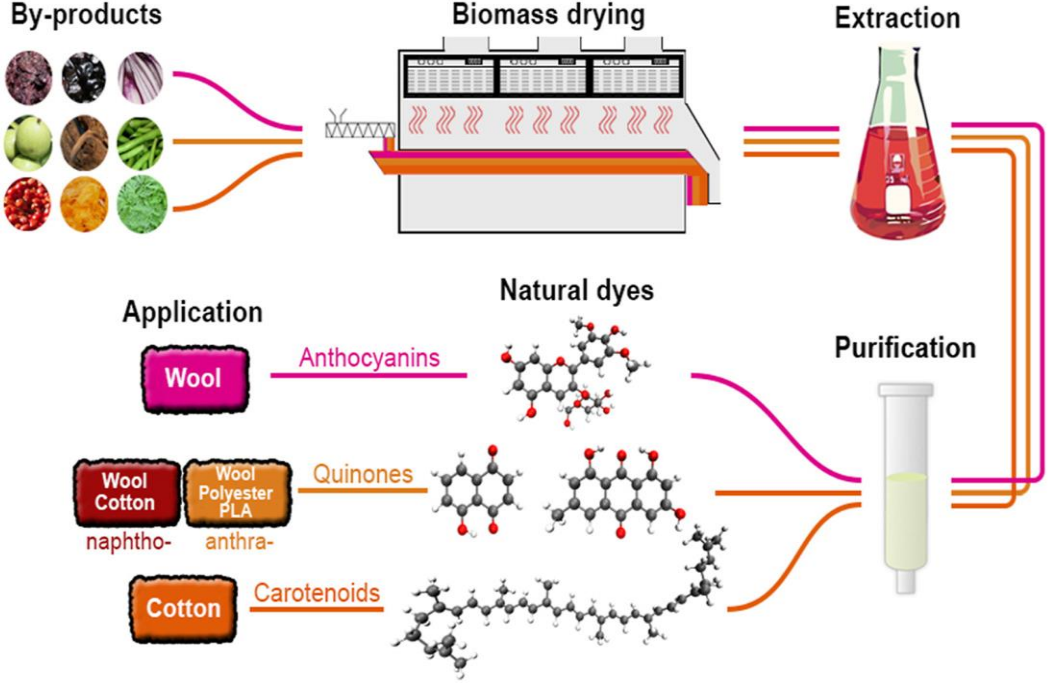


**Figure 1.** Using biomass drying and extraction methods for extracting various natural dyes.

Pressurized liquid extraction (PLE) has also shown promise in the field of natural dye extraction. A study by Mustafa et al. (2021) highlighted the effectiveness of PLE in extracting phenolic compounds from olive leaves. The method involves using high-pressure liquids at elevated temperatures to enhance extraction efficiency [29]. PLE offers the advantage of reduced solvent usage and faster extraction times, but the requirement for specialized equipment and the potential for thermal degradation of sensitive compounds are drawbacks.

Furthermore, the integration of biotechnological approaches, such as the genetic modification of dye-producing plants, has been explored to increase dye content and facilitate extraction. Zhang and Laursen (2005) reported on the development of stable natural colorants through genetic modification, which can potentially improve yield and consistency in dye quality [21]. While this approach holds great promise, ethical concerns and regulatory hurdles associated with genetically modified organisms (GMOs) must be considered.

In addition, recent studies have investigated the use of pulsed electric field (PEF) extraction, which applies short bursts of high voltage to plant cells, causing them to rupture and release dye compounds. A study by Barba et al. (2019) demonstrated that PEF could enhance the extraction of betalains from beetroot, achieving higher yields and preserving the stability of the dye compounds [30]. PEF is advantageous due to its low energy consumption and minimal solvent use, though the initial setup cost for PEF equipment is a potential limitation.

Another innovative method is subcritical water extraction (SWE), which uses water at elevated temperatures and pressures below its critical point to extract dyes. Shu et al. (2020) explored SWE for extracting polyphenolic compounds from pomegranate peels, showing that this method could achieve high extraction efficiency and purity [31]. SWE is environmentally friendly and avoids the use of organic solvents, but the high temperatures required can sometimes lead to the degradation of heat-sensitive compounds.

Lastly, ionic liquid-based extraction (ILE) has been gaining traction as an efficient method for natural dye extraction. A study by Sun et al. (2021) reported on the use of ionic liquids to extract anthocyanins from purple sweet potatoes, achieving high yields and excellent stability of the extracted dyes [32]. Ionic liquids are tunable solvents that can be designed for specific extraction tasks, but their high cost and potential environmental impact require careful consideration.

Comparing these methods, it is evident that each has its unique advantages and challenges. Enzymatic extraction and UAE offer eco-friendly and efficient alternatives but may be limited by cost and scalability. MAE and SFE provide rapid and high-purity extraction but require significant initial investment in equipment. The use of eco-friendly solvents like DES and PLE represents a move towards greener extraction technologies, although further research and optimization are needed. Biotechnological approaches, while promising, bring their own set of ethical and regulatory challenges. PEF, SWE, and ILE each offer innovative solutions with their own specific benefits and drawbacks, adding to the diverse toolkit available for natural dye extraction.

In summary, the recent advancements in natural dye extraction methods have significantly improved yield and sustainability. However, each method presents its own set of trade-offs, and further research is necessary to address these limitations. A deeper analysis of these methods and their applications will be provided in the following sections of this paper.

**Table 1.** Summary of recent enhancements in natural dye extraction

| Method | Features | Challenges | Requirements | References |
|---|---|---|---|---|
| **Enzymatic Extraction** | Utilizes specific enzymes to break down plant cell walls, releasing more dye compounds. | Cost and availability of specific enzymes can be a drawback. | Eco-friendliness and efficiency; reduce extraction time. | [17] |
| **Ultrasound-Assisted Extraction (UAE)** | Enhances the release of dye molecules from plant materials using ultrasonic waves. | High initial investment in ultrasound equipment; scalability remains a concern. | Reduced extraction time and lower solvent usage; improve scalability. | [18] |
| **Microwave-Assisted Extraction (MAE)** | Uses microwave energy to rapidly heat plant material, causing cell rupture and enhancing dye release. | High cost of microwave equipment and potential for uneven heating. | Reduce extraction time and energy consumption; address uneven heating. | [26] |
| **Supercritical Fluid Extraction (SFE)** | Uses supercritical CO2 as a solvent for high purity and yield extraction. | High operational pressures and costs associated with supercritical CO2 equipment. | Non-toxic and non-flammable; improve cost-effectiveness. | [27] |
| **Eco-Friendly Solvents (DES)** | Uses deep eutectic solvents (DES) for enhanced extraction efficiency and yield. | Relatively new; more research needed to understand long-term environmental impact. | Biodegradable and less toxic; optimize long-term use. | [28] |

| | | | | |
|---|---|---|---|---|
| **Pressurized Liquid Extraction (PLE)** | Uses high-pressure liquids at elevated temperatures to enhance extraction efficiency. | Requires specialized equipment; potential for thermal degradation of sensitive compounds. | Reduced solvent usage and faster extraction times; address equipment costs. | [29] |
| **Biotechnological Approaches** | Genetic modification of dye-producing plants to increase dye content and facilitate extraction. | Ethical concerns and regulatory hurdles associated with genetically modified organisms (GMOs). | Increase yield and consistency; address ethical and regulatory issues. | [21] |
| **Pulsed Electric Field (PEF) Extraction** | Applies short bursts of high voltage to plant cells, causing them to rupture and release dye compounds. | Initial setup cost for PEF equipment is a potential limitation. | Low energy consumption and minimal solvent use; improve cost-effectiveness. | [30] |
| **Subcritical Water Extraction (SWE)** | Uses water at elevated temperatures and pressures below its critical point to extract dyes. | High temperatures can lead to the degradation of heat-sensitive compounds. | Environmentally friendly; avoid degradation of heat-sensitive compounds. | [31] |
| **Ionic Liquid-Based Extraction (ILE)** | Uses ionic liquids to extract dyes, offering high yields and excellent stability. | High cost and potential environmental impact of ionic liquids. | High yields and excellent stability; reduce cost and environmental impact. | [32] |

### *2.2 Criticism of Natural Dye Extraction Methods in Industrial Applicability*

The pursuit of natural dye extraction methods has garnered significant attention in recent years, driven by the desire for more sustainable and eco-friendly alternatives to synthetic dyes. While numerous innovative techniques have been developed to enhance the yield and efficiency of natural dye extraction, their practical applicability in the textile industry remains fraught with challenges. This section provides a comprehensive critique of natural dye extraction methods from the perspective of industrial applicability.

One of the foremost challenges associated with natural dye extraction is the economic viability of these methods. The cost of raw materials, the complexity of extraction procedures, and the need for specialized equipment often result in higher production costs compared to synthetic dyes. Techniques such as enzymatic extraction, ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE) require significant investment in specific enzymes, ultrasonic equipment, and microwave devices, respectively [17-18, 26]. These costs can be prohibitive for large-scale industrial applications, where cost-effectiveness is a critical factor.

Natural dye extraction methods frequently suffer from variability in yield and dye quality. Factors such as the source and quality of raw materials, seasonal variations, and differences in plant species can lead to inconsistencies in the final product [17-18, 21]. For instance, enzymatic extraction and UAE may produce high yields under controlled laboratory conditions, but replicating these results on an industrial scale can be challenging due to the heterogeneity of natural sources. This variability can affect the reproducibility and standardization of dyeing processes, making it difficult to achieve consistent color quality in textile products.

The implementation of advanced extraction techniques such as supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), and pulsed electric field (PEF) extraction in industrial settings presents numerous technical and operational challenges. These methods often require high-pressure and high-temperature conditions, which can be difficult to maintain and control on a large scale [27-29]. Additionally, the need for specialized equipment and infrastructure can pose significant logistical and operational hurdles, limiting the scalability of these technologies.

While natural dyes are often perceived as more environmentally friendly than synthetic dyes, the extraction processes themselves can pose environmental and safety concerns. Some methods, such as the use of deep eutectic solvents (DES) and ionic liquids, involve chemicals that may have unknown long-term environmental impacts [28, 32]. Moreover, the disposal of waste products and by-products generated during the extraction process can create additional environmental burdens. Ensuring the safety and sustainability of these extraction methods requires comprehensive environmental assessments and the development of effective waste management strategies.

Natural dyes typically exhibit lower color fastness and durability compared to synthetic dyes. This limitation is a significant drawback for industrial applications, where textile products must meet high standards of performance and longevity. The inferior fastness properties of natural dyes can result in fading and degradation over time, reducing the aesthetic and functional value of dyed fabrics [25]. This issue necessitates additional treatments or the use of fixatives, which can further complicate the dyeing process and increase production costs.

Despite the advancements in natural dye extraction techniques, scaling these methods for industrial production remains a formidable challenge. The transition from laboratory-scale experiments to full-scale industrial operations requires extensive optimization and validation. Many natural dye extraction methods have yet to demonstrate their feasibility on an industrial scale, with issues such as process efficiency, throughput, and integration into existing manufacturing systems still unresolved [19, 30]. The scalability of these methods is crucial for their widespread adoption in the textile industry.

In conclusion, while natural dye extraction methods offer promising alternatives to synthetic dyes, their applicability in the textile industry is limited by several critical factors (Table 1). High production costs, variability in yield and quality, technical and operational challenges, environmental and safety concerns, limitations in color fastness, and scalability issues all pose significant barriers to their industrial adoption. To effectively address the sustainability challenges in the textile industry, it is imperative to focus on developing and optimizing eco-friendly synthetic dyeing processes that can deliver consistent, high-quality results at an industrial scale. This paper will further explore these alternatives and propose strategies for enhancing the sustainability of textile dyeing.

**Table 2.** Summary of problems in natural dye extraction methods

| Problem | Explanation | References |
|---|---|---|
| High Production Costs | Expensive raw materials, complex extraction procedures, and need for specialized equipment. | [17-18, 26] |
| Variability in Yield and Quality | Inconsistencies due to source, seasonal variations, and differences in plant species. | [17-18, 21] |
| Technical and Operational Challenges | High-pressure and high-temperature conditions are difficult to maintain on a large scale. | [27-29] |
| Environmental and Safety Concerns | Use of chemicals like DES and ionic liquids may have unknown long-term environmental impacts. | [28,32] |
| Lower Color Fastness and Durability | Natural dyes often fade and degrade over time, reducing fabric quality and longevity. | [25] |
| Scalability Issues | Difficulty in scaling laboratory methods to industrial production, requiring extensive optimization. | [19,30] |

## 3. Beyond natural dye extraction: eco-friendly dyeing processes with industrial dyes

### *3.1 Advancements in machinery, digital methods, and physical processes*

Technological advancements have significantly contributed to the development of more sustainable textile dyeing methods. Among these, digital printing, supercritical $CO_2$ dyeing, foam dyeing, high-efficiency dyeing machines, and air-dye technology stand out for their potential to reduce environmental impact and improve efficiency.

Digital printing has revolutionized the textile industry by applying dyes or pigments directly onto fabrics using inkjet technology. This method drastically reduces the need for water and chemicals, as the dyes are precisely deposited onto the fabric, minimizing waste. Research indicates that digital printing can significantly reduce water and chemical consumption compared to traditional dyeing methods [33-34]. Additionally, digital printing offers high design flexibility and rapid production times, achieving high print resolutions and color accuracies [34]. However, the technology must improve in terms of speed and scalability to compete with conventional dyeing methods for large-scale production. The high cost of digital inks remains a barrier, necessitating advancements to make them more affordable without compromising quality.

Supercritical $CO_2$ dyeing represents another significant innovation, using carbon dioxide in its supercritical state as a solvent for dyeing textiles. In this state, $CO_2$ effectively dissolves dyes and penetrates textile fibers, eliminating the need for water and significantly reducing chemical usage. Studies have shown that supercritical $CO_2$ dyeing can eliminate water consumption entirely and reduce energy and auxiliary chemical use, with dye exhaustion rates comparable to conventional methods [35-36]. Despite these advantages, the high initial investment costs for equipment and the need for precise control of temperature and pressure present challenges. Research into more cost-effective equipment and improved scalability is necessary for broader industrial adoption [36-37].

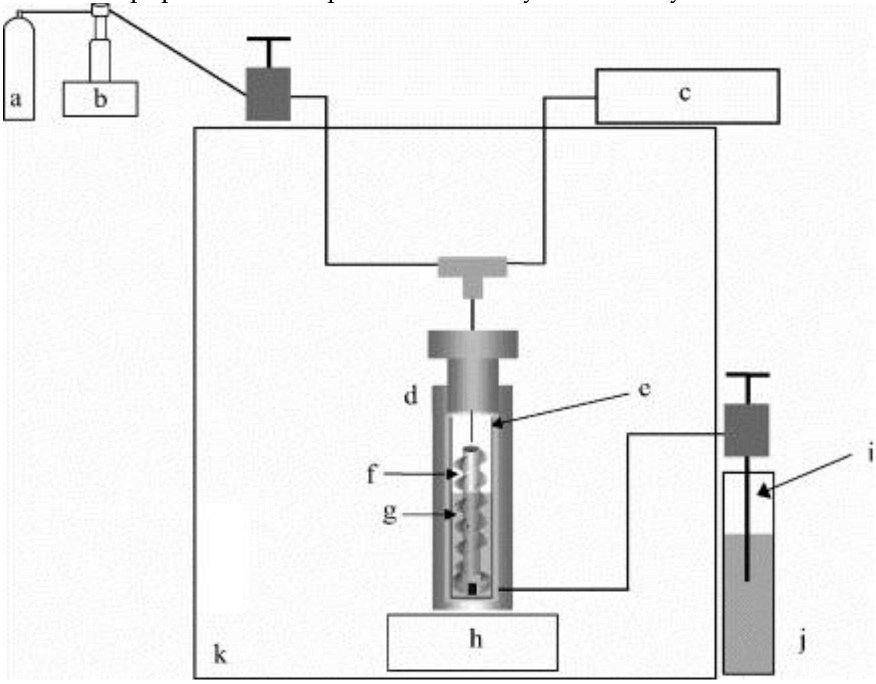


**Figure 2.** Supercritical fluid extraction apparatus: (a) $CO_2$ cylinder; (b) syringe pump; (c) pressure transducer and read-out; (d) extraction vessel; (e) quartz sample vial; (f) entraining rotor; (g) aqueous sample; (h) magnetic drive; (i) restrictor; (j) collection solvent; (k) oven [35].

Foam dyeing employs foam as a medium to apply dyes to textiles, significantly reducing water consumption. The foam is generated by mixing air with a liquid dye solution, which is then spread over the fabric. This method reduces the amount of dye and water required and minimizes energy use, as less heat is needed to dry the fabric. Foam dyeing has been successfully used for various types of textiles, including denim, demonstrating substantial reductions in water and dye usage [38]. However, the initial setup cost for foam dyeing equipment can be high, and further research is needed to improve the uniformity and consistency of dye application.

High efficiency dyeing machines have also made a significant impact on sustainable textile dyeing. These machines are designed to optimize water and energy use, reduce dye and chemical consumption, and minimize waste. Innovations include low liquor ratio machines and continuous dyeing processes, which significantly enhance the sustainability of textile production. New dyeing machines have demonstrated reductions in water consumption and energy usage compared to traditional methods. Despite these benefits, the high initial cost of these machines and the need for specialized training to operate them efficiently are challenges that need to be addressed [39].

Air-dye technology is another promising development, using air to apply dyes to textiles and thereby eliminating the need for water in the dyeing process. This technology significantly reduces water consumption and minimizes the use of chemicals [40]. Additionally, air-dye technology allows for precise control of dye application, resulting in less waste and higher efficiency. However, the scalability of air-dye technology for mass production remains a challenge, and the high cost of implementation can be a barrier for widespread adoption.

In conclusion, technological innovations in textile dyeing, such as digital printing, supercritical CO2 dyeing, foam dyeing, high-efficiency dyeing machines, and air-dye technology, offer significant environmental and efficiency benefits. These technologies reduce water and chemical usage, lower energy consumption, and minimize waste, making them crucial for the sustainable future of the textile industry. However, challenges such as high initial costs, scalability, and the need for further research and development persist. Common endeavors in this field should focus on making these technologies more cost-effective, scalable, and accessible to ensure their broader adoption and implementation in industrial settings.

**Table 3.** Summary of research in technological advancements for dyeing

| Method | Features | Challenges | Requirements | References |
|---|---|---|---|---|
| **Digital Printing** | Reduces water and chemical usage; high design flexibility, high print resolutions and color accuracies. | High cost of digital inks, needs improvement in speed and scalability for large-scale production. | Develop affordable digital inks, enhance speed and scalability. | [33-34] |
| **Supercritical CO2 Dyeing** | Eliminates water usage; reduces energy and chemical usage, high dye exhaustion rates. | High initial investment costs, requires precise control of temperature and pressure, needs cost-effective equipment. | Research cost-effective equipment, improve scalability. | [35-37] |
| **Foam Dyeing** | Significantly reduces water consumption, less heat needed to dry fabric, applicable to various textiles. | High initial setup cost, needs improvement in uniformity and consistency of dye application. | Improve uniformity and consistency, reduce setup costs. | [38] |
| **High-Efficiency Dyeing Machines** | Optimizes water and energy use; reduces dye and chemical consumption, low liquor ratio and continuous processes. | High initial cost, requires specialized training to operate efficiently. | Reduce initial costs, provide specialized training. | [39] |
| **Air-Dye Technology** | Eliminates water usage; minimizes chemical use, precise control of dye | High cost of implementation, scalability for mass | Make implementation cost-effective, | [40] |

|  |  |  |  |
|---|---|---|---|
|  | application. | production remains a challenge. | improve scalability. |

### 3.2 Chemical and Biological Innovations in Dyeing Processes

Chemical and biological innovations have made significant strides in promoting sustainable practices in textile dyeing. These advancements focus on developing new chemicals, alternative solvents, and biological processes that reduce environmental impact and enhance efficiency. This section reviews four key innovations: reactive dyes with high fixation rates, enzymatic processes, nanotechnology in dyeing, and ionic liquid-based extraction.

Reactive dyes with high fixation rates (Figure 2) represent an important chemical innovation. These dyes form strong covalent bonds with textile fibers, resulting in higher dye uptake and reduced effluent pollution. Studies have demonstrated that using reactive dyes with high fixation rates can decrease water and energy consumption during the dyeing process [41-42]. Despite their benefits, the development of reactive dyes that maintain high fixation rates across a wide range of fiber types and dyeing conditions remains a priority for ongoing research [43].

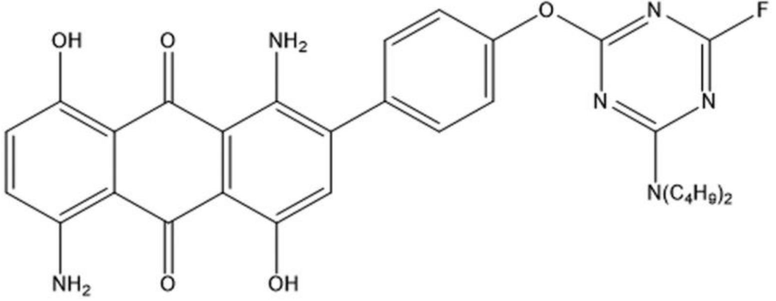


**Figure 3.** Chemical structure of the reactive disperse dye [41].

Enzymatic processes utilize natural enzymes to assist in textile dyeing, offering an eco-friendly alternative to traditional chemical treatments. Enzymes such as laccase and peroxidase can break down complex dye molecules, facilitating more efficient dyeing and reducing the need for harsh chemicals [44]. Research has shown that enzymatic processes can improve dye uptake, color fastness, and fabric quality while minimizing environmental impact [45]. However, the high cost of enzyme production and the need for optimized conditions for each enzyme type are challenges that must be overcome [46].

Nanotechnology in dyeing involves the use of nano-sized dye particles that can penetrate fibers more effectively, enhancing dye uptake and fixation. This technology not only improves the efficiency of the dyeing process but also reduces the amount of dye required, thereby minimizing waste [47]. Studies have highlighted the potential of nanotechnology to enhance the durability and color fastness of dyed textiles, making it a promising area for future development [47]. Nonetheless, concerns about the environmental and health impacts of nanoparticles need to be addressed through rigorous safety evaluations and regulatory frameworks [48].

Ionic liquid-based extraction (ILE) has emerged as an innovative method for extracting natural dyes using ionic liquids as solvents. Ionic liquids are known for their unique properties, such as low volatility and high thermal stability, making them suitable for sustainable dye extraction processes [49]. Research has demonstrated that ILE can enhance dye extraction efficiency and yield while reducing the use of toxic solvents [49]. However, the high cost of ionic liquids and the need for further studies on their long-term environmental impact are barriers to widespread adoption [50].

Chemical and biological innovations in textile dyeing offer significant potential for reducing environmental impact and enhancing process efficiency. These advancements provide promising alternatives to conventional dyeing methods, but challenges such as high costs, scalability, and safety concerns must be addressed. Collaborative efforts in research and development are essential to overcome these barriers and promote the broader adoption of these sustainable dyeing technologies.

**Table 4.** Summary of research in chemical and biological advancements for dyeing

| Method | Features | Challenges | Requirements | References |
|---|---|---|---|---|
| **Reactive Dyes with High Fixation Rates** | Form strong covalent bonds with textile fibers, resulting in higher dye uptake and reduced effluent pollution. | Development of reactive dyes that maintain high fixation rates across a wide range of fiber types and dyeing conditions remains a priority. | Decrease water and energy consumption. | [41-43] |
| **Enzymatic Processes** | Utilize natural enzymes to assist in textile dyeing, offering an eco-friendly alternative to traditional chemical treatments. | High cost of enzyme production and the need for optimized conditions for each enzyme type. | Improve dye uptake, color fastness, and fabric quality while minimizing environmental impact. | [44-46] |
| **Nanotechnology in Dyeing** | Involves the use of nano-sized dye particles that can penetrate fibers more effectively, enhancing dye uptake and fixation. | Concerns about the environmental and health impacts of nanoparticles need to be addressed through rigorous safety evaluations and regulatory frameworks. | Enhance the durability and color fastness of dyed textiles, making it a promising area for future development. | [47-48] |
| **Ionic Liquid-Based Extraction** | Innovative method for extracting natural dyes using ionic liquids as solvents. | High cost of ionic liquids and the need for further studies on their long-term environmental impact. | Enhance dye extraction efficiency and yield while reducing the use of toxic solvents. | [49-50] |

### *3.3 Process Efficiency and Water Conservation in Dyeing Methods*

Process efficiency and water conservation are critical components of sustainable textile dyeing. Innovations in these areas aim to optimize resource usage, minimize waste, and reduce the overall environmental footprint of the dyeing process. This section reviews four key advancements: low liquor ratio dyeing, waterless dyeing technologies, closed-loop systems, and advanced oxidation processes.

Low liquor ratio dyeing is an approach designed to minimize the amount of water used in the dyeing process. By using a lower volume of water relative to the weight of the fabric, this method significantly reduces water consumption and the amount of dye and chemicals required. Studies have shown that low liquor ratio dyeing can reduce water usage by up to 50% compared to traditional methods [51-52]. Furthermore, this method provides better dye deagglomeration compared to the traditional methods (Figure 3). However, achieving consistent color quality can be challenging with reduced water volumes [51].

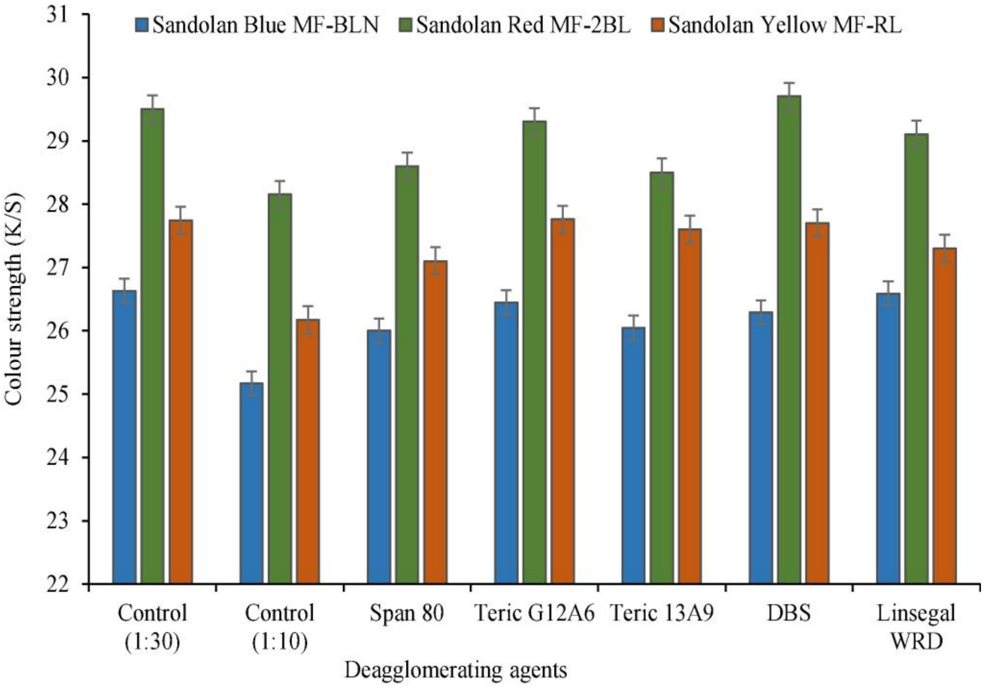
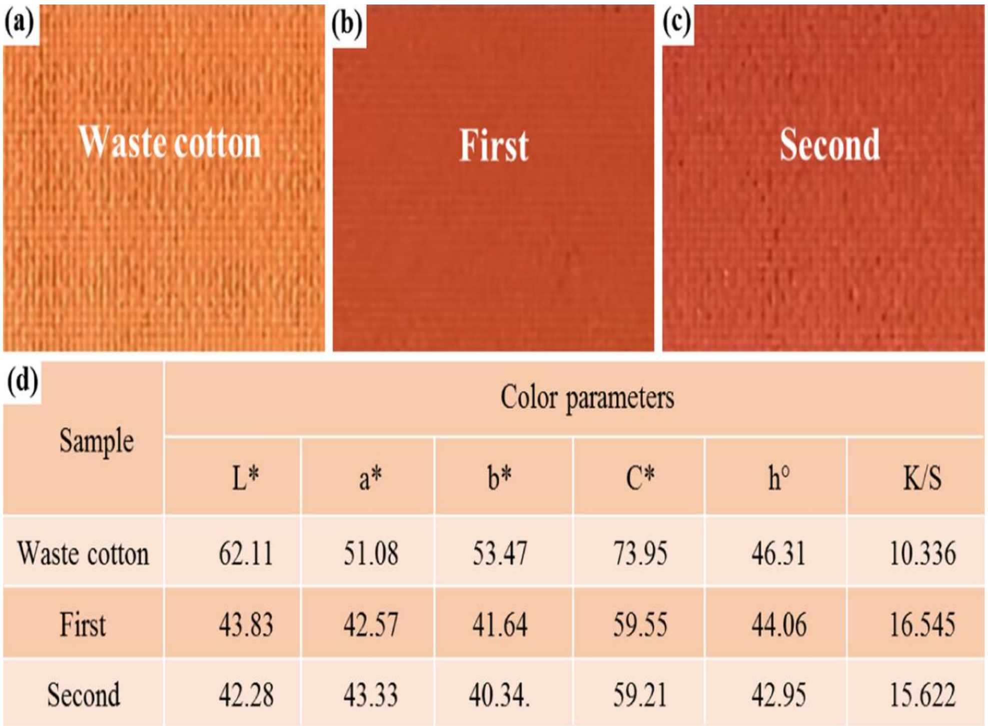


**Figure 4.** Effect of addition of various agglomeration preventing agents used together with low liquor ratio dyeing approach [51].

Waterless dyeing technologies, such as supercritical CO2 dyeing and air-dye technology, have been developed to eliminate the need for water in the dyeing process entirely. These technologies use alternative mediums, such as carbon dioxide or air, to apply dyes to textiles. Supercritical CO2 dyeing, for instance, uses CO2 in its supercritical state to dissolve dyes and penetrate textile fibers, offering a water-free and energy-efficient dyeing method [53]. Air-dye technology employs air to transfer dyes onto fabrics, significantly reducing water and chemical use [54]. While these methods offer substantial environmental benefits, high initial investment costs and the need for specialized equipment can limit their widespread adoption [53-54].

Closed-loop systems represent another significant innovation in process efficiency and water conservation. These systems are designed to recycle and reuse water and chemicals within the dyeing process, thereby reducing the overall consumption of these resources. Research indicates that closed-loop systems can recover up to 90% of the water used in dyeing, significantly reducing the environmental impact [55]. Additionally, these systems can improve process efficiency by maintaining consistent dye concentrations and minimizing waste. The main challenge associated with closed-loop systems is the need for advanced filtration and treatment technologies to ensure the quality and purity of recycled water and chemicals [56].



| Sample | Color parameters | | | | | |
|---|---|---|---|---|---|---|
| | L* | a* | b* | C* | h° | K/S |
| Waste cotton | 62.11 | 51.08 | 53.47 | 73.95 | 46.31 | 10.336 |
| First | 43.83 | 42.57 | 41.64 | 59.55 | 44.06 | 16.545 |
| Second | 42.28 | 43.33 | 40.34. | 59.21 | 42.95 | 15.622 |

**Figure 5.** Effect of addition of various agglomeration preventing agents used together with low liquor ratio dyeing approach [55].

Advanced oxidation processes (AOPs) are chemical treatments that use highly reactive species, such as hydroxyl radicals, to degrade organic pollutants in wastewater. These processes are effective in breaking down complex dye molecules, making them suitable for treating dye effluents and enhancing water conservation. AOPs, such as photocatalysis and Fenton reactions, have been shown to achieve high degradation rates of dye pollutants, improving the overall efficiency of wastewater treatment [57-58]. However, the implementation of AOPs requires careful control of reaction conditions and the management of by-products, which can add complexity to the process [58].

In conclusion, advancements in process efficiency and water conservation, such as low liquor ratio dyeing, waterless dyeing technologies, closed-loop systems, and advanced oxidation processes, play a crucial role in promoting sustainable textile dyeing. These innovations reduce water and chemical usage, minimize waste, and enhance the overall sustainability of the dyeing process. However, challenges such as high initial costs, technical complexity, and the need for advanced infrastructure must be addressed to facilitate the broader adoption of these technologies. Continued research and development efforts are essential to overcome these barriers and achieve more sustainable textile dyeing practices.

**Table 5.** Summary of research in dyeing process efficiency and water conservation

| Method | Features | Challenges | Requirements | References |
|---|---|---|---|---|
| **Low Liquor Ratio Dyeing** | Minimizes the amount of water used in the dyeing process, significantly reducing water consumption and the amount of dye and chemicals required. | Optimizing dye distribution and achieving consistent color quality can be challenging with reduced water volumes. | Enhance dye distribution and color quality with lower water volumes. | [51-52] |

| | | | | |
|---|---|---|---|---|
| **Waterless Dyeing Technologies** | Eliminates the need for water in the dyeing process entirely by using alternative mediums such as carbon dioxide or air. | High initial investment costs and the need for specialized equipment can limit their widespread adoption. | Reduce initial costs and develop more accessible equipment. | [53-54] |
| **Closed-Loop Systems** | Recycles and reuses water and chemicals within the dyeing process, reducing overall resource consumption. | Requires advanced filtration and treatment technologies to ensure the quality and purity of recycled water and chemicals. | Improve filtration and treatment technologies for consistent quality. | [55-56] |
| **Advanced Oxidation Processes (AOPs)** | Uses highly reactive species to degrade organic pollutants in wastewater, improving the efficiency of wastewater treatment. | Careful control of reaction conditions and the management of by-products add complexity to the process. | Optimize reaction conditions and manage by-products effectively. | [57-58] |

## 4. Emerging Innovative Technologies in Eco-Friendly Dyeing

As the textile industry progresses towards greater sustainability, several innovative technologies have emerged that promise to revolutionize eco-friendly dyeing processes. These advancements, thoroughly studied and showing significant potential, aim to reduce environmental impact while maintaining or enhancing dyeing efficiency. This section highlights three such promising technologies: plasma technology, digital textile printing with biodegradable inks, and microbial dyeing.

Plasma technology is gaining recognition as a sustainable method for textile surface modification. This technology uses ionized gas to alter the surface properties of textile fibers, enhancing dye uptake and fixation without the need for water or chemicals (Figure 5). By significantly reducing water and chemical consumption, plasma technology also improves dye adherence and color fastness. Plasma treatment has demonstrated substantial improvements in the hydrophilicity of polyester fabrics, leading to enhanced dye uptake and uniformity [59]. Additionally, plasma-treated cotton fibers have shown improved color fastness and reduced dye bleeding, making the process highly effective for various textile materials [60]. However, the high initial setup costs and the need for specialized equipment present significant challenges. Further research is necessary to optimize plasma parameters for different textile materials and dye types to fully realize its potential

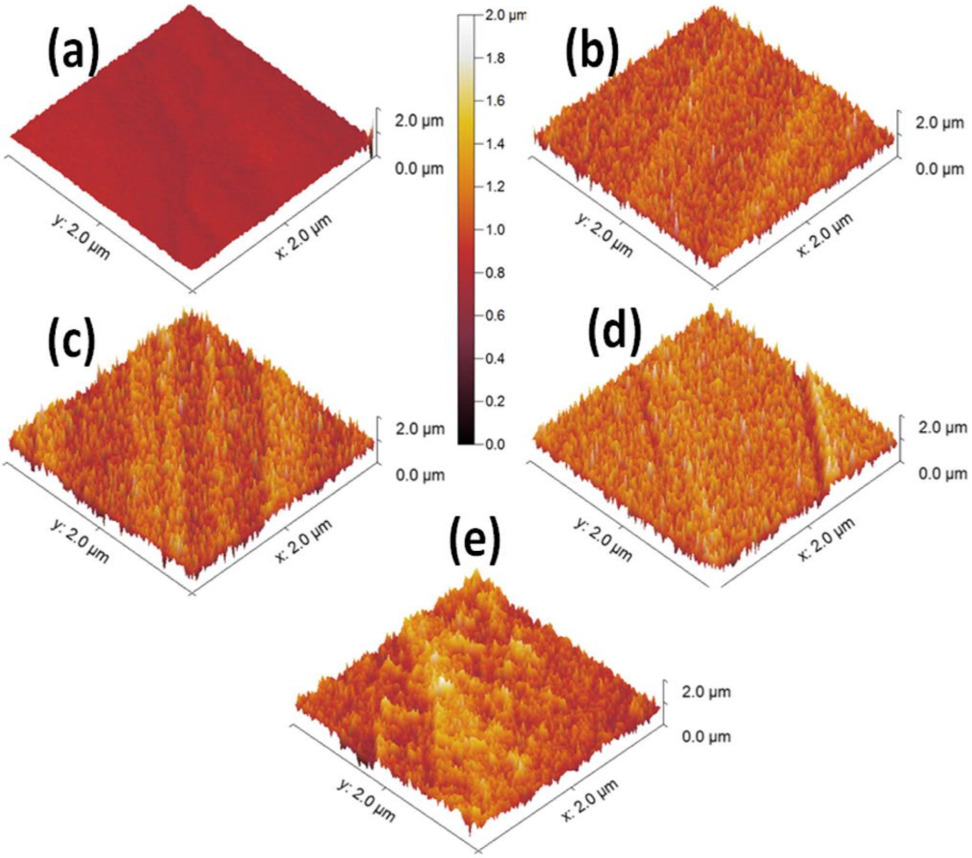


**Figure 6.** 3D view of AFM images of (a) untreated cotton fabrics (b) 5 min plasma treatment (c) 10 min plasma treatment (d) 20 min plasma treatment (e) 60 min plasma treatment. Showing rougher surface as plasma treatment indicate better dying uptake and fixation efficiency [59].

Digital textile printing, already recognized for its environmental benefits, has been further enhanced by the development of biodegradable inks. These inks, derived from natural sources, are designed to degrade harmlessly after use, thereby minimizing environmental impact. This method offers precise dye application with minimal waste, maintaining high print resolution and color accuracy. Recent developments have produced biodegradable inks using natural pigments and binders, achieving vibrant colors and excellent print quality on various fabrics [61]. Studies have also confirmed the biodegradability of these inks, showing that they decompose without leaving harmful residues [62]. The stability and performance of biodegradable inks over time need to be ensured, and efforts are required to scale up production and reduce costs to make these inks more accessible.

Microbial dyeing leverages the capabilities of microorganisms to produce natural dyes through fermentation processes. This method provides a sustainable alternative to synthetic dyes by using renewable resources. Microbial dyeing not only offers a renewable and biodegradable dyeing solution but also reduces reliance on petrochemicals. Research has demonstrated that bacteria such as *Streptomyces* and *Pseudomonas* can produce vibrant pigments suitable for textile dyeing, with good color fastness and fabric compatibility [63]. Further studies have focused on optimizing fermentation conditions to increase dye yield and reduce production time, enhancing the efficiency and cost-effectiveness of microbial dyeing [64].

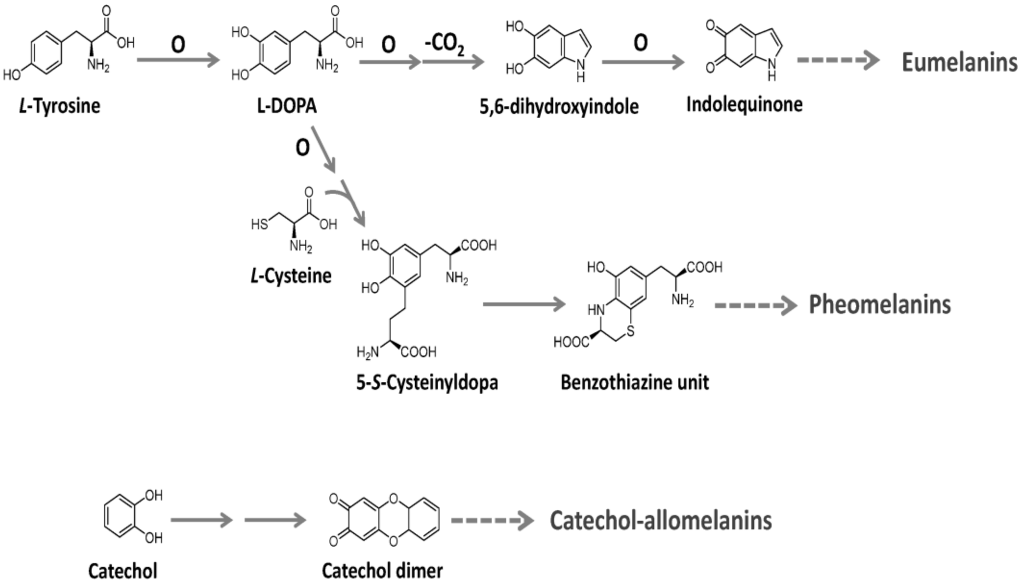


**Figure 7.** Various melanin synthesis pathways using microbial synthesis techniques[63].

Microbial dyeing offers several advantages over traditional natural dye extraction methods. One major problem with natural dye extraction is the variability in dye yield and quality due to differences in raw material sources, which can lead to inconsistencies in color and performance. Microbial dyeing, on the other hand, can produce consistent dye yields and quality by controlling fermentation conditions and using genetically stable microorganisms. Additionally, natural dye extraction often involves complex and labor-intensive processes that require large amounts of water and chemicals, leading to high production costs and environmental impact. In contrast, microbial dyeing uses fermentation, a relatively simple and scalable process that can be carried out with minimal water and chemical use. This method also allows for the production of dyes from renewable resources, such as agricultural waste and biomass, further reducing its environmental footprint.

In conclusion, innovative technologies such as plasma technology, digital textile printing with biodegradable inks, and microbial dyeing are at the forefront of eco-friendly dyeing research. These advancements hold promise for significantly reducing the environmental impact of textile dyeing processes while maintaining or enhancing dyeing efficiency. Microbial dyeing, in particular, offers solutions to the main problems of natural dye extraction by providing consistent quality, simpler processes, and the use of renewable resources. Despite their potential, challenges such as high initial costs, technical complexities, and scalability issues need to be addressed. Continued research and development are essential to overcome these barriers and facilitate the broader adoption of these sustainable dyeing technologies.

**Table 6.** Summary of emerging innovative technologies in dyeing

| Method | Features | Challenges | Requirements | References |
|---|---|---|---|---|
| **Plasma Technology** | Uses ionized gas to alter the surface properties of textile fibers, enhancing dye uptake and fixation without the need for water or chemicals. | High initial setup costs and the need for specialized equipment present significant challenges. | Optimize plasma parameters for different textile materials and dye types to fully realize its potential. | [59-60] |
| **Digital Textile Printing with Biodegradable Inks** | Uses biodegradable inks derived from natural sources, designed to degrade harmlessly after use, offering precise dye application with minimal waste. | The stability and performance of biodegradable inks over time need to be ensured, and efforts are required to scale up production and reduce costs. | Ensure stability and performance of biodegradable inks over time, scale up production, and reduce costs to make these inks more accessible. | [61-62] |
| **Microbial Dyeing** | Uses microorganisms to produce natural dyes through fermentation processes, providing a sustainable alternative to synthetic dyes using renewable resources. | Scaling up microbial dye production to meet industrial demands and ensuring consistency and stability across different batches and textile materials. | Optimize fermentation conditions to increase dye yield and reduce production time, enhancing efficiency and cost-effectiveness. | [63-64] |

## 5. Conclusions

The textile dyeing industry is undergoing a significant transformation towards sustainability, driven by the need to reduce its environmental impact. This review has examined various approaches and innovations in eco-friendly dyeing processes, highlighting both established methods and emerging technologies.

We explored advancements in natural dye extraction techniques such as enzymatic extraction, ultrasound-assisted extraction, and the use of eco-friendly solvents. Despite these improvements, natural dyes face significant industrial challenges, including variability in raw material sources, complex extraction processes, and higher production costs.

Eco-friendly industrial dyeing techniques using synthetic dyes were also discussed, including low liquor ratio dyeing, waterless dyeing technologies, closed-loop systems, and advanced oxidation processes. These methods improve process efficiency and water conservation, reducing the overall environmental footprint. However, challenges such as high initial costs and technical complexities remain.

Emerging technologies such as plasma technology, digital textile printing with biodegradable inks, and microbial dyeing offer promising solutions. Plasma technology enhances dye uptake and fixation without water or chemicals, digital textile printing with biodegradable inks minimizes environmental impact, and microbial dyeing provides consistent quality and simpler processes compared to natural dye extraction.

Despite these advancements, several blind spots and challenges persist in current research. High initial costs and technical barriers hinder the widespread adoption of these technologies. The scalability of these methods to meet industrial demands remains a critical challenge. Additionally, comprehensive life-cycle assessments are needed to evaluate the long-term environmental impacts of these technologies.

To address these challenges, further studies should focus on:

1. **Cost Reduction**: Developing more cost-effective materials and processes to lower the initial investment required for adopting new technologies.
2. **Scalability**: Enhancing the scalability of emerging technologies to ensure they can meet industrial demands efficiently.
3. **Life-Cycle Assessments**: Conducting comprehensive life-cycle assessments to understand the long-term environmental impacts and benefits of new dyeing technologies.
4. **Interdisciplinary Research**: Encouraging collaboration between materials science, chemical engineering, and environmental science to drive innovation and address complex challenges.

In conclusion, while significant progress has been made in developing eco-friendly dyeing processes, ongoing efforts are essential to overcome existing challenges and achieve broader adoption. By focusing on cost reduction, scalability, comprehensive environmental assessments, and interdisciplinary research, the textile dyeing industry can continue its transformation towards a more sustainable future.

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