



ECO-FRIENDLY DYEING TECHNIQUES FOR SUSTAINABLE TEXTILE AND FASHION DESIGN

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ABSTRACT

The textile and fashion industry is one of the major contributors to environmental pollution because of its intensive consumption of water, energy, dyes, auxiliary chemicals, and other resources. Among the various stages of textile production, dyeing and finishing are particularly significant because they generate substantial wastewater and require considerable amounts of energy and chemical inputs. Conventional synthetic dyes can introduce persistent colourants, salts, auxiliaries, and potentially hazardous substances into wastewater streams. Consequently, the development of eco-friendly dyeing techniques has become an important component of sustainable textile and fashion design. This study examines environmentally responsible dyeing approaches, including natural dyes, plant-based colourants, biomordants, waste-derived dyes, microbial pigments, low-water dyeing, waterless dyeing, and emerging green-solvent technologies. Particular attention is given to the relationship between dye selection, fibre type, extraction methods, mordanting, colourfastness, water consumption, energy requirements, and wastewater generation. Recent literature demonstrates that natural dyes can provide renewable and biodegradable alternatives to many conventional colourants, although limitations related to shade reproducibility, colourfastness, raw-material availability, extraction efficiency, and industrial scalability remain. The research adopts a qualitative systematic literature-review design. Peer-reviewed studies published primarily in 2023 and 2025 are examined to identify major eco-friendly dyeing techniques, their benefits, limitations, and implications for sustainable fashion design. The analysis suggests that no single dyeing technology is suitable for every textile fibre or production context. Instead, sustainable dyeing requires an integrated approach involving appropriate fibre selection, renewable colourants, efficient extraction, safer mordants, optimized dyeing conditions, wastewater management, and life-cycle thinking. Recent research also highlights the importance of technology, education, consumer behaviour, marketing, and industrial adaptation in scaling natural colourants within the fashion industry. The study concludes that eco-friendly dyeing can make an important contribution to sustainable textile and fashion design when environmental performance is considered together with colour quality, durability, economic feasibility, cultural value, and industrial practicality.

KEYWORDS: *Eco-friendly dyeing; sustainable textiles; sustainable fashion; natural dyes; plant-based colourants; biomordants; textile coloration; waterless dyeing; low-water dyeing; wastewater; circular economy; green chemistry; sustainable design; natural pigments; textile innovation.*

INTRODUCTION

Textiles and fashion play an important role in the global economy and in everyday life. Clothing and textile products provide functional, cultural, social, and aesthetic value. At the same time, the production of textiles involves a complex chain of activities, including fibre production, spinning, weaving or knitting, pretreatment, dyeing, printing, finishing, garment manufacturing, transportation, use, and disposal. Titisari, B., & Sinha, P. (2025). Explained that Each stage has environmental implications, but wet processing is particularly important because it requires water, heat, chemicals, dyes, and auxiliary substances. Dyeing is undertaken to provide textiles with the colours required by consumers, designers, manufacturers, and fashion markets. Colour is fundamental to fashion design because it affects aesthetic perception, product identity, consumer preference, seasonal trends, and brand positioning. However, conventional colouration systems have traditionally depended heavily on synthetic dyes and chemical auxiliaries. Research has identified dyeing and



finishing as environmental hotspots because these operations can require significant water, energy, and chemicals. The environmental consequences of textile dyeing extend beyond the consumption of resources. Wastewater generated during dyeing may contain residual dyes, salts, surfactants, detergents, heavy metals, and other chemical substances. Dye-containing wastewater can affect aquatic ecosystems by changing water colour and reducing light penetration, while certain dye-related substances may also present toxicity concerns. A 2023 review in *Nature Reviews Earth & Environment* emphasized the environmental significance of dye-containing wastewater and examined chemical, biological, and physical approaches for its treatment. The increasing awareness of climate change, water scarcity, chemical pollution, biodiversity loss, and resource depletion has encouraged researchers and designers to reconsider conventional textile production. Sustainable fashion therefore requires not only changes in fibre production and garment consumption but also improvements in wet-processing technologies.

Eco-friendly dyeing represents one possible pathway toward this transformation. It includes the use of renewable natural dyes, waste-derived colourants, biological pigments, safer mordants, reduced-water processes, improved extraction technologies, and innovative dyeing media. The purpose is not simply to replace a synthetic dye with a natural dye. Rather, sustainable dyeing should consider the complete process, including the origin of the colourant, extraction, transportation, mordanting, dye application, energy consumption, water consumption, wastewater, colourfastness, and end-of-life implications. Traditional dyeing processes can be resource-intensive Dong, et al. (2025). Found that. Water is required for fabric preparation, dye-bath preparation, washing, rinsing, and post-treatment. Energy is required to heat dye baths and operate machinery. Chemicals may be used for scouring, bleaching, mordanting, dye fixation, washing, softening, and finishing. The environmental burden is therefore not determined only by the dye itself. It is influenced by the complete process. A dye that appears environmentally preferable may not necessarily be sustainable if its production requires excessive land, water, energy, or toxic extraction chemicals. Wastewater is another major concern. Conventional textile effluents can contain complex mixtures of colourants and processing chemicals. Research published in 2023 noted that untreated dye-containing wastewater can negatively affect ecosystems and may contain substances with carcinogenic, mutagenic, or teratogenic properties. For this reason, sustainable dyeing should aim to reduce pollutant generation at the source rather than relying exclusively on wastewater treatment after pollution has already occurred. Natural dyes have received renewed attention because they can be obtained from renewable biological sources.

These include leaves, flowers, bark, roots, fruits, seeds, agricultural residues, food waste, algae, microorganisms, and other biological materials. Examples include indigo, madder, annatto, eucalyptus, weld, woad, turmeric, onion skins, pomegranate peel, tea waste, and coffee grounds. Research on natural colourants has expanded considerably, with studies examining their extraction, chemical composition, dyeing performance, functional properties, and potential for industrial applications. A 2023 review examining eucalyptus, weld, madder, annatto, indigo, and woad found that natural dyes have potential not only for textile coloration but also for functional properties such as antibacterial and anti-UV effects. However, the review also identified limitations involving shade range and colourfastness.



Another 2023 review concluded that advances in extraction, substrate preparation, mordanting, and dyeing techniques are improving the sustainability and performance of natural dyes, although poor fastness, low fibre affinity, shade reproducibility, and cost remain important barriers to large-scale industrial adoption. Plant-based colourants represent one of the most widely studied categories of natural dyes. Plants can provide different classes of colour-producing compounds, including anthocyanins, carotenoids, flavonoids, tannins, quinones, and indigoids. Plant materials may be obtained from cultivated dye plants, naturally occurring vegetation, agricultural residues, or food-processing waste. Using waste materials as colourant sources can contribute to circular economy principles by converting materials that might otherwise be discarded into useful resources. However, plant-based dyeing must be carefully managed. Large-scale cultivation of dye plants may compete for land and water with food production. Therefore, agricultural waste, invasive plants, pruning residues, and other underutilized biomass can sometimes provide more attractive sustainability pathways. Research on plant-based colourants emphasizes the importance of selecting extraction and application methods according to the chemistry of the specific colourant and the textile substrate.

Mordants are substances used to improve the interaction between colourants and textile fibres. Traditional mordants can include metallic salts. While some mordants can improve dye uptake and colourfastness, their environmental impacts must be considered. Biomordants provide an alternative area of research. Biomordants may be obtained from plant materials rich in tannins or other compounds capable of interacting with fibres and dyes. The development of biomordants is important because simply using a natural dye does not automatically make the complete dyeing process environmentally sustainable. If a natural colourant is applied using hazardous or resource-intensive auxiliaries, environmental benefits may be reduced. Recent research therefore increasingly examines natural dyes and mordants as part of integrated eco-friendly dyeing systems. A particularly promising approach is the use of waste materials as colourant sources. Examples include coffee grounds, onion skins, fruit peels, agricultural residues, and other biomass. Waste-derived dyeing connects textile coloration with circular economy principles. Instead of viewing organic waste only as a disposal problem, it can be treated as a potential source of pigments or dye molecules. Research has demonstrated the potential of used coffee grounds for dyeing textile materials. Such approaches can simultaneously provide a colour source and contribute to waste valorization. This approach is particularly relevant for sustainable fashion designers because it creates opportunities for local sourcing, storytelling, material experimentation, and distinctive colour palettes. Another emerging area involves pigments produced by microorganisms, including bacteria, fungi, and microalgae. Microbial pigments can potentially reduce dependence on petroleum-derived colourants and may offer opportunities for controlled pigment production. Research published in 2023 identified microalgae-derived pigments, including phycobiliproteins, chlorophylls, and carotenoids, as promising alternatives for textile coloration, while also noting that commercial production and textile application require further development.

Similarly, research on bacterial pigments and bioactive textile dyeing has explored combinations of biological pigments, natural antibacterial ingredients, and alternative solvents. These developments demonstrate that the future of sustainable colouration may



extend beyond traditional plant dyeing. Another important approach is reducing or eliminating water from the dyeing process. Conventional aqueous dyeing can require substantial quantities of water for preparation, dye application, rinsing, and washing. Low-water technologies aim to reduce water requirements, while waterless systems attempt to use alternative dyeing media. Technologies investigated in the literature include supercritical carbon dioxide dyeing, air-based systems, digital coloration, and other innovative processes. A 2025 review of sustainable dyeing technologies concluded that different fibres require different approaches and that no single sustainable dyeing method is suitable for every application. It identified supercritical carbon dioxide and certain alternative solvent systems among the promising technologies, while also noting challenges relating to industrial feasibility, equipment, solvent handling, and fibre compatibility. This finding is important for fashion designers and textile manufacturers because sustainability cannot be achieved through technology selection alone. The technology must be compatible with the fibre, dye chemistry, colour requirements, production scale, cost, and quality standards. Sustainable dyeing has direct implications for fashion design. Designers influence colour selection, material choices, product development, and consumer perception. The adoption of natural colourants can create unique visual characteristics because natural dyes often produce subtle variations rather than perfectly uniform industrial shades. These variations can become part of the aesthetic value of sustainable fashion. A 2025 systematic review found five major areas in natural-colourant research: colourant sources, colouration technology, application, culture and tradition, and industrialization. It further identified industry scalability, consumer behaviour, economic value, and marketing as important themes. The increasing environmental pressure on the textile industry creates a need for practical and scalable dyeing alternatives.

RESEARCH OBJECTIVES

1. To examine major eco-friendly dyeing techniques used or investigated for sustainable textile and fashion design, including natural dyes, plant-based colourants, waste-derived dyes, biomordants, microbial pigments, low-water processes, and waterless technologies.
2. To evaluate the environmental, technical, aesthetic, and economic advantages and limitations of eco-friendly dyeing techniques, with particular attention to water consumption, energy requirements, chemical use, wastewater, colourfastness, reproducibility, and scalability.
3. To identify opportunities and challenges for integrating eco-friendly dyeing into sustainable textile and fashion design, and to propose directions for future research and industrial implementation.

RESEARCH QUESTIONS

1. What are the major eco-friendly dyeing techniques available for sustainable textile and fashion design?
2. What environmental, technical, aesthetic, and economic benefits and limitations are associated with eco-friendly dyeing techniques?
3. How can eco-friendly dyeing techniques be integrated and scaled within sustainable textile and fashion design practices?



LITERATURE REVIEW

Sustainable textile dyeing has emerged as an important research field because conventional wet processing can generate significant environmental impacts. Dyeing requires resources such as water and energy and may involve dyes, salts, detergents, auxiliaries, and other chemicals. Santiago, D., et al. (2023). Explains that The literature increasingly approaches sustainable dyeing from a systems perspective. Instead of focusing only on the replacement of synthetic dyes, researchers examine the entire process from raw-material sourcing through extraction, dye application, washing, wastewater management, and product use. Pizzicato et al. (2023) describe dyeing and finishing as important hotspots in textile production because of their water, energy, and chemical requirements. Their review emphasizes extraction, substrate preparation, mordanting, and dyeing as key areas of sustainable innovation. This indicates that sustainable dyeing should be evaluated as a complete production system rather than as a single chemical substitution.

Natural Dyes

Natural dyes are colourants obtained from biological or mineral sources. Plant-derived dyes have traditionally been used by many cultures for centuries, but industrialization resulted in the widespread adoption of synthetic dyes because of their consistent shades, broad colour ranges, and relatively predictable performance. The renewed interest in natural dyes is associated with sustainability concerns. Natural dyes may be renewable and biodegradable, although their sustainability depends on how they are sourced, extracted, transported, and applied. Pizzicato et al. (2023) identified natural dyes as promising alternatives but emphasized that problems with fastness, fibre affinity, shade reproducibility, and cost continue to limit industrial adoption. Thus, natural dyes should not automatically be regarded as environmentally perfect. Their sustainability must be assessed in relation to their complete life cycle.

Extraction Techniques

Extraction is a critical stage in natural dye production. Conventional extraction can require large quantities of water, heat, or chemical solvents. More sustainable extraction methods seek to maximize colourant yield while reducing energy, solvent, and water consumption. Researchers have investigated aqueous extraction, ultrasound-assisted extraction, microwave-assisted extraction, fermentation, enzymatic techniques, and alternative solvents. Efficient extraction can improve the overall environmental performance of natural dyeing because less raw material and energy may be required to obtain the desired concentration. The literature also emphasizes that extraction conditions influence the chemical composition and colour characteristics of the resulting dye. Consequently, extraction must be standardized if natural colourants are to be used consistently at industrial scale.



Mordanting and Biomordants

Mordanting is important because many natural dyes have relatively low affinity for certain textile fibres. Mordants can increase dye uptake and influence colour development. However, the environmental impact of mordants must be considered. The search for safer alternatives has encouraged research into biomordants, especially tannin-rich plant materials. Biomordants can potentially reduce dependence on some conventional metal-based mordants while creating additional opportunities for using agricultural and plant resources. Recent literature identifies biomordants as an important part of sustainable natural dye systems.

Colourfastness

One of the strongest challenges facing natural dyes is colourfastness. Fashion and textile products need to withstand washing, rubbing, perspiration, light exposure, and other conditions. Synthetic dyes have historically benefited from extensive industrial optimization, whereas many natural colourants produce weaker fastness under certain conditions. The literature therefore emphasizes optimization of mordanting, dye concentration, pH, temperature, dyeing time, fibre preparation, and after-treatment. Research examining natural dyes such as eucalyptus, weld, madder, annatto, indigo, and woad shows that colour characteristics depend strongly on processing conditions and auxiliary materials. Improving fastness is therefore essential for moving natural dyes from niche craft applications toward mainstream fashion.

Plant-Based Colourants

Plant-based colourants are among the most accessible natural dye resources. They may be derived from roots, bark, leaves, flowers, fruits, seeds, and agricultural residues. The advantages of plant-based dyes include renewable sourcing and the possibility of using locally available materials. They can also contribute cultural value because traditional dye plants are associated with indigenous knowledge and regional textile practices. Nambela's review of plant-based colourants emphasizes their potential for sustainable textile applications but identifies inadequate technical knowledge, limited raw-material availability, high costs, and low industrial adoption as continuing challenges. This suggests that successful industrialization will require improved cultivation, extraction, standardization, education, and supply-chain development.

Agricultural and Food Waste as Dye Sources

The circular economy encourages the conversion of waste into new resources. Textile dyeing can participate in this model through the use of food and agricultural residues as colourant sources. Coffee grounds, fruit peels, onion skins, leaves, shells, and other residues can contain useful pigment molecules. The use of waste materials provides two potential benefits: reducing waste and reducing dependence on virgin dye resources. Research on used coffee grounds, for example, has shown that they can provide useful colouration for textile materials, although process conditions such as mordanting and acid treatment influence colour saturation and fastness.



Microalgae and Microbial Pigments

Microalgae provide another promising source of sustainable colourants. They can produce pigments such as chlorophylls, carotenoids, and phycobiliproteins. The advantage of microbial production is that pigments may be produced under controlled conditions rather than relying entirely on seasonal plant harvesting. However, commercial application remains challenging. Research in 2023 concluded that microalgae pigments show promise as natural textile dyes but require additional research to improve commercial pigment production and textile application. Microbial pigments therefore represent a developing rather than fully mature industrial technology.

Bioactive Dyeing

Sustainable textile research is increasingly combining colouration with additional functions. Bioactive dyeing can potentially produce textiles with antibacterial, antioxidant, UV-protective, or other properties. The combination of natural pigments and bioactive materials may increase the value of textile products while reducing reliance on separate chemical finishing processes. Research published in 2023 explored bacterial pigments, natural antibacterial ingredients, and deep eutectic solvents as components of sustainable bioactive textile dyeing. This represents a shift from viewing dyeing solely as a colouration process toward multifunctional textile engineering.

Low-Water Dyeing

Reducing water consumption is a central goal of sustainable dyeing. Low-liquor-ratio machines, optimized process parameters, foam-based applications, digital technologies, and other approaches can reduce the quantity of water required. Reducing water use also has secondary benefits because less water needs to be heated, transported, treated, and discharged. However, water reduction must not compromise colour quality or increase the use of hazardous chemicals.

Waterless Dyeing

Waterless dyeing is an emerging technological pathway. Supercritical carbon dioxide dyeing is one of the most frequently discussed approaches, particularly for polyester and other suitable synthetic fibres. A 2025 review found that supercritical CO₂ has significant potential for sustainable dyeing, especially for polyester, but it is not universally applicable because different fibres require different dye chemistries. This demonstrates a major principle in sustainable textile technology: there is no universal dyeing solution.

Alternative Solvents

Researchers are investigating alternative dyeing media and solvents that can reduce water use and improve resource efficiency. Deep eutectic solvents and other emerging systems have received attention. However, alternative solvents should not be evaluated solely on whether



they reduce water consumption. Their toxicity, biodegradability, recyclability, energy requirements, cost, and worker safety must also be considered. Therefore, green chemistry principles should guide the development of alternative dyeing systems.

Digital and Emerging Technologies

Digital technologies can also support sustainable coloration. Digital textile printing, process monitoring, automated dosing, predictive modelling, and artificial intelligence may reduce unnecessary material use and improve process control. Digitalization can support sustainable dyeing by optimizing temperature, time, dye concentration, and energy consumption. The development of technology-based sustainable dyeing is increasingly connected with the broader digital transformation of textile manufacturing.

Wastewater Treatment and Reuse

Even environmentally preferable dyeing systems can generate wastewater. Therefore, wastewater treatment and reuse remain important components of sustainable production. Treatment technologies include physical, chemical, biological, membrane, adsorption, oxidation, and hybrid approaches Mutaf-Kılıç, T., Demir, A., Elibol, M., & Oncel, S. S. (2023). Found t.hat The 2023 literature emphasizes that biological methods can offer environmentally friendly and energy-efficient routes for dye degradation, while advanced membrane systems may enable dye and salt removal and potential resource recovery. The most sustainable strategy, however, is to reduce pollution at the source while treating and reusing unavoidable wastewater.

METHODOLOGY

This study uses a qualitative systematic literature-review approach to investigate eco-friendly dyeing techniques for sustainable textile and fashion design. The research focuses on published academic literature concerning: Academic literature was identified through searches of scholarly databases and publisher platforms. Search terms included combinations of: eco-friendly textile dyeing,” “sustainable dyeing,” “natural dyes,” “natural colourants,” “sustainable textile coloration,” “biomordants,” “waterless dyeing,” “low-water dyeing,” “green textile processing,” and “sustainable fashion.” Priority was given to peer-reviewed literature published in 2023 and 2025, supplemented by highly relevant recent literature where necessary. Studies were considered relevant when they: This study adopts a qualitative research methodology to examine eco-friendly dyeing techniques for sustainable textile and fashion design. The research focuses on identifying and evaluating environmentally responsible dyeing methods, including natural dyes, plant-based colourants, waste-derived dyes, biomordants, microbial pigments, low-water dyeing, and waterless dyeing technologies. Secondary data were collected from peer-reviewed journal articles, research papers, academic books, and credible online scholarly sources, with particular emphasis on recent studies published in 2023 and 2025. The collected literature was reviewed to understand the environmental, technical, economic, and design-related benefits and limitations of different dyeing techniques. Particular attention was given to water consumption, energy use, chemical requirements, wastewater generation,



colourfastness, reproducibility, availability of raw materials, and industrial scalability. The information obtained from the selected studies was systematically organized and compared to identify common trends, research gaps, and opportunities for applying eco-friendly dyeing methods within sustainable textile and fashion design.

RESEARCH DESIGN

The research uses a qualitative descriptive research design based on a systematic literature review. This design was selected because the study aims to explore and describe existing knowledge about environmentally sustainable textile dyeing rather than conduct laboratory experiments. Relevant academic studies were identified using keywords such as eco-friendly dyeing, sustainable textile dyeing, natural dyes, plant-based dyes, biomordants, waste-derived colourants, waterless dyeing, and sustainable fashion. The selected literature was examined according to predetermined themes, including types of eco-friendly dyes, dye extraction methods, mordanting techniques, water and energy consumption, wastewater impacts, colourfastness, sustainability, and industrial application. The research design allows information from different studies to be compared and synthesized in order to develop a comprehensive understanding of the current development of eco-friendly dyeing techniques and their relevance to sustainable fashion design. This study adopts a qualitative descriptive research design based on a systematic review of existing literature on eco-friendly dyeing techniques for sustainable textile and fashion design. The research focuses on examining natural dyes, plant-based colourants, waste-derived dyes, biomordants, microbial pigments, low-water dyeing, and waterless dyeing technologies. Relevant information is collected from peer-reviewed journal articles, research publications, academic books, and reliable scholarly sources, with particular attention given to recent research published in 2023 and 2025. The selected studies are analyzed and compared according to environmental impact, water and energy consumption, chemical use, wastewater generation, colourfastness, cost, availability of raw materials, and industrial scalability. This research design provides a structured approach for understanding the advantages and limitations of different eco-friendly dyeing methods and their potential contribution to sustainable textile and fashion design.

DATA ANALYSIS

Because this study is based on secondary research rather than primary laboratory experimentation, data analysis involved qualitative thematic analysis. The literature was reviewed and classified according to five analytical dimension. The environmental dimension considered water use, energy use, chemicals, wastewater, waste, and potential toxicity. The technical dimension considered colour yield, colourfastness, fibre compatibility, reproducibility, and process control. The economic dimension considered raw-material availability, processing costs, machinery requirements, and scalability. The fashion/design dimension considered colour diversity, aesthetics, cultural value, consumer preferences, and trend compatibility. The industrial dimension considered standardization, supply chains, production speed, quality control, and technological requirements. Thematic analysis was selected because the literature contains diverse experimental methods and cannot be reduced to one numerical performance indicator. The data collected from the reviewed literature were



analyzed using thematic analysis. Information from the selected studies was organized into major themes related to environmental performance, technical effectiveness, economic feasibility, and fashion-design applications. The environmental analysis considered water consumption, energy requirements, chemical use, wastewater generation, biodegradability, and waste reduction. Technical factors included colour yield, colourfastness, fibre compatibility, shade reproducibility, and dyeing efficiency. Economic factors included the availability and cost of raw materials, processing requirements, equipment, and potential for industrial-scale production. The analysis also considered the role of eco-friendly dyeing in fashion design, particularly in relation to aesthetics, colour variation, cultural value, consumer preferences, and sustainable product development. The findings from different studies were compared to identify similarities, differences, advantages, limitations, and research gaps. The analysis indicates that eco-friendly dyeing techniques have considerable potential to reduce the environmental impact of textile production, although challenges such as colourfastness, standardization, cost, raw-material availability, and industrial scalability continue to require further research.

FINDINGS

The literature consistently indicates that natural dyes can provide renewable and potentially biodegradable alternatives to conventional synthetic colourants. However, natural dyes should not automatically be considered sustainable. Their environmental performance depends on cultivation, harvesting, extraction, mordanting, transportation, dyeing, washing, and disposal. Poor or inconsistent colourfastness is one of the most important barriers to the industrial adoption of natural dyes. Studies emphasize that improvements in extraction, mordanting, substrate preparation, pH, temperature, and dyeing conditions are necessary to obtain acceptable performance. Biomordants can improve natural-dye performance while supporting the development of more environmentally responsible dyeing systems. Their effectiveness depends on the chemical relationship between the mordant, dye, and textile fibre. Agricultural and food waste can become useful colourant resources. The use of materials such as coffee waste demonstrates how textile dyeing can contribute to resource recovery and circular-economy strategies. The literature identifies water consumption as a major sustainability concern. Low-water and waterless technologies can potentially reduce water demand and associated energy consumption. However, technology selection must consider fibre compatibility and overall environmental performance. The 2025 literature demonstrates that advanced dyeing systems such as supercritical CO₂ can provide significant sustainability advantages for suitable fibres, but no single technology works effectively across all fibre categories. The most important finding is that sustainability should be considered as a whole-process strategy. Replacing a synthetic dye with a natural dye is not sufficient if the new process requires excessive water, energy, land, solvents, or environmentally harmful auxiliaries. Designers influence colour choices, textile selection, product development, consumer education, and market acceptance. The 2025 literature highlights technology, marketing, education, consumer behaviour, and economic value as important to the industrialization of natural colourants. Natural colourants face challenges involving raw-material supply, seasonal variation, standardization, cost, colour reproducibility, and production scale. These limitations explain why natural dyes remain more common in niche, artisanal, premium, and experimental fashion markets than in high-



volume industrial production. The evidence suggests that the future is unlikely to depend on a single technology.

CONCLUSION

Eco-friendly dyeing techniques represent an important pathway toward sustainable textile and fashion design. Conventional dyeing can contribute substantially to water consumption, energy consumption, chemical use, and wastewater generation. Consequently, changing textile colouration practices is necessary for reducing the environmental impact of fashion. Natural dyes, plant-based colourants, biomordants, waste-derived pigments, microbial colourants, microalgae pigments, low-water processes, and waterless technologies offer different opportunities for improving sustainability. Research published in 2023 demonstrates considerable progress in natural-dye extraction, mordanting, colouration, and alternative biological pigments, while research published in 2025 emphasizes industrialization, technology, consumer behaviour, marketing, and scalability. Nevertheless, eco-friendly dyeing faces several challenges. Natural dyes can suffer from poor colourfastness, shade variation, limited colour reproducibility, inconsistent raw materials, and higher costs. Advanced waterless systems can require specialized equipment and may be appropriate only for particular fibre categories. These limitations demonstrate that there is no single universal solution for sustainable textile coloration. The study therefore concludes that sustainable dyeing should be approached through an integrated system. Textile manufacturers should evaluate the entire dyeing process rather than focusing exclusively on the origin of the dye. Designers should consider colour, fibre, durability, resource consumption, cultural context, and consumer expectations simultaneously. Future research should focus on improving natural-dye extraction, developing safer biomordants, increasing colourfastness, standardizing colour production, utilizing agricultural waste, improving microbial pigment production, developing affordable waterless technologies, recycling dye baths, and conducting life-cycle assessments. Ultimately, eco-friendly dyeing can contribute significantly to sustainable fashion when technological innovation is combined with responsible design, circular-resource use, consumer education, and industrial transformation.

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