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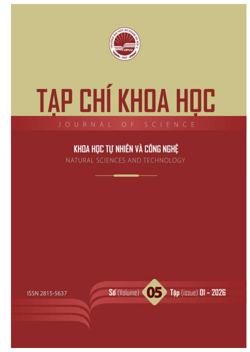

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Sustainable development of the global dyeing industry in the future

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Abstract

The dyeing stage plays an important role within the textile production chain, as it contributes significantly to the aesthetics and commercial value of the product. Moreover, it is the step that can detect mistakes from previous stages and find an appropriate solution. However, the dyeing sector in Vietnam remains a weak stage compared to other segments of the textile chain. Additionally, dyeing is characterized by high consumption of energy, chemicals, and water, leading to environmental pollution. In the context of a global shift towards sustainable development, the dyeing industry must change to meet environmental protection standards, conserve resources, and ensure labor safety.

This article introduces new sustainable development directions of the dyeing industry, such as the adoption of eco-friendly dyeing technologies, the use of natural dyes, the reuse of wastewater, and the optimization of production processes. These are also emerging research directions that have attracted considerable attention in recent years.

Keywords: dyeing industry, sustainable development, eco-friendly dyeing technologies, natural dyes, digital management

1. Introduction

In the textile and garment production chain, the dyeing stage holds a critical role in enhancing the value of the product. However, it consumes a lot of energy, chemicals, water and causes huge environmental pollution problems, especially creating a huge source of wastewater. In pre-treatment processes such as washing, scouring, bleaching, dyeing and finishing, a large amount of water is used. On average, processing 1 kg of textile material requires 100–150 liters of water, of which the dyeing process consumes 61% of the total water used. Depending on the type of dye, the amount of water required for

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dyeing fabric ranges from 30 to 50 liters per kilogram of fabric. In some cases, dyeing one kilogram of cotton fabric may require up to 100 liters of water. For yarn dyeing, the water usage is approximately 60 liters per kilogram [1], [2]. Each year, the dyeing industry discharges about 15–20% of the total water used into the environment as wastewater [3]. Textile dyeing wastewater contains various pollutants such as dyes, heavy metals, salts, and auxiliary chemicals from wet processing. These substances contribute to high BOD and COD levels, leading to oxygen depletion in water bodies. Toxic compounds, including azo dyes, may break down into carcinogenic substances, posing risks to human health. In aquatic environments, wastewater reduces light penetration and inhibits photosynthesis. It can also cause eutrophication, resulting in loss of aquatic life. Overall, untreated dyeing wastewater has severe and long-term environmental impacts [1].

Additionally, the dyeing industry consumes a considerable amount of energy. Therefore, reducing the input of energy, water, and chemicals is essential to mitigate the environmental impacts associated with textile dyeing processes [4].

According to a survey conducted during 2017–2018 by VECEA (Vietnam Energy Conservation and Efficiency Association), the technologies of dyeing and finishing enterprises in Vietnam have considerable limitations. Specifically, 12.8% of dyeing equipment in textile enterprises was over 17 years old, while 34% of the equipment was less than 10 years old, and 36.2% were under 7 years old. This indicates that numerous outdated machines characterized by low productivity, poor energy efficiency, and severe environmental impact remain in operation. The study also revealed that the dyeing and finishing processes include all three types: batch, semi-continuous, and continuous. Among batch dyeing systems, machines with liquor ratios ranging from 1:10 to 1:15 accounted for approximately 70%, while low liquor ratio machines (1:2.5 to 1:8) represented 16%, and high liquor ratio machines (1:20) occupied 14%. With 70% of equipment having liquor ratios between 1:10 and 1:15, water consumption and wastewater from the dyeing and finishing process remain substantial [5]. According to the survey results from the research project, the majority of dyeing equipment used in dyeing enterprises was manufactured before 2019. Most dyeing enterprises have only partially automated their operations [6].

Statistical data indicate that the textile dyeing industry is the second-largest contributor to global water pollution, accounting for approximately 20% of total industrial wastewater. Various production stages in textile processing, such as desizing, scouring, bleaching, and dyeing consume large volumes of water, resulting in huge wastewater generation [7]. In addition, the dyeing stage also consumes a lot of energy. Therefore, research into the application of scientific and technological advancements to develop the dyeing industry is necessary.

2. Recent Developments in the Dyeing Industry

In recent years, the textile dyeing industry has increasingly shifted toward sustainable development due to environmental pressures. Key advancements include water-saving and waterless dyeing technologies, as well as the use of eco-friendly and bio-based dyes. The adoption of new technology, particularly in recycling water and chemicals, is also gaining importance. Additionally, automation and digital control systems are improving process efficiency and consistency. Together, these innovations support a transition toward a more sustainable and environmentally responsible textile industry.

2.1. Application of Natural Colorants and Dyeing Agents

The dyeing and finishing stages involve the use of chemicals and synthetic dyes, which consequently result in the discharge of hazardous substances into the environment and affect human health. Although many synthetic dyes have been banned due to their toxicity, they still affect the environment and human health. Therefore, research and adoption of natural colorants as alternatives to synthetic dyes, and natural mordants replacing synthetic agents, represent a sustainable direction for the dyeing industry.

In 2020, Neetu Radi and associates used natural dyes and natural mordants for textile dyeing, aiming to produce environmentally friendly fabrics such as papaya extract and natural mordants extracted from pomegranate peel and orange peel for wool and silk. The fabric has an antibacterial ability of over 90% against both S. aureus and E. coli. UV protection is greatly increased, shown by the UPF index from 79 to 704 [8].

In 2024, Md. Reazuddin Repon and his research team published a study on the use of natural dyes and natural mordants as alternatives to synthetic dyes and chemical mordants. The study investigated the dyeing of cotton, wool, and silk fabrics using natural colorants such as anthocyanins, flavonoids, tannins, carotenoids, and indigoids extracted from plants. Natural mordants, including tannins, plant resins, chitosan, and enzymes were employed in place of conventional metallic salts. The results demonstrated that the natural dyes produced vibrant colors on the fabrics with relatively high color fastness. However, to enable large-scale industrial application and fully replace synthetic dyes, further experimental research, technological improvements, and the development of application standardized procedures for mass production are required [9].

Table 1. Some natural dyes [10].

Type of natural dye	Source	Typical colors	Fiber application	Advantages
Indigoids	Plants	Blue, purple	Cotton, wool, silk	Excellent light fastness, natural origin, eco-friendly
Carotenoids	Plants (turmeric, saffron, annatto)	Yellow, orange, red	Cotton, silk, wool	Non-toxic, biodegradable, safe for skin and environment
Quinonoids	Plants and insects	Yellow to red	Wool, silk	Antimicrobial and functional properties
Flavonoids	Plants	yellow to red/blue	Cotton and wool	UV protection potential
Tannins	Plants	Yellow, brown, black	Cotton, wool	Improve dye affinity, eco-friendly
Anthocyanins	Plants	Red, purple, violet	Wool, silk	Natural, non-toxic

Hue Trinh Thi Kim and Huong Mai Bui investigated the sustainable dyeing of 100% cotton fabrics using natural colorants extracted from avocado seeds, a common agricultural waste in Vietnam. Dye extraction was performed by boiling minced avocado seeds in distilled water at 60°C for 60 minutes with an extraction ratio of 1:10. The optimal dyeing conditions were identified as follows: liquor ratio of 1:30, dyeing temperature of 60°C, dyeing time of 60 minutes, dye solution concentration of 75% v/v, and pH 7. Mordanting with tannin and $CuSO_4.5H_2O$ significantly improved color strength and color fastness, creating a diverse range of hues. Color durability tests showed washing fastness at grade 3–4 and rubbing fastness at grade 4–5 according to ISO standards (International Organization for Standardization). The findings demonstrate that avocado seed-based natural dyes can produce attractive and eco-friendly colors for cotton fabrics, though their fastness remains lower than that of synthetic dyes, indicating the need for further optimization for industrial applications [11].

2.2. Emerging Technologies

2.2.1. Low-Water Dyeing Technologies

Air drying is an environmentally friendly process. The fabrics are dyed in a tank under high pressure, using air as a transporting fabric. This dyeing method decreases wastewater caused by low liquor. The dyeing liquor is automized and fixed with high-pressure airflow and then sprayed on the fabric. This dyeing technology is highly efficient and can dye two colors on opposite sides. However, this dyeing method is only suitable for synthetic fabrics [12].

Foam dying use gases are dispersed within a liquid state of equilibrium or disequilibrium. Foam technology is considered a potential process that uses less water compared to traditional dyeing methods. It requires low liquid content so that it can discharge wastewater. In foam dyeing, the bubbles containing the dye particles are applied mechanically, transferring the dye liquor to the substrate and fixing it. Foam dyeing can be carried out in batches and on a continuous process. It continuously applies the necessary components in foam and prevents unnecessary consumption of dye liquor. This saves water, chemicals, and dyes [13], [14].

2.2.2. Waterless Dyeing Technology

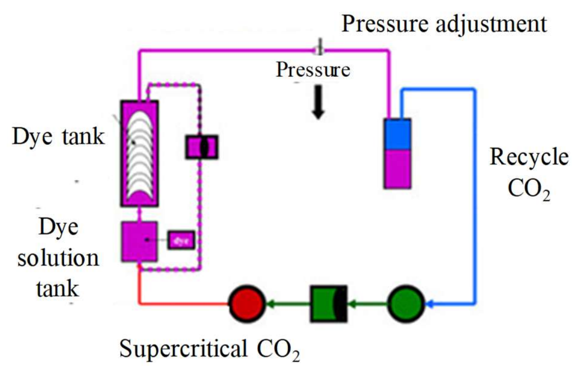

Figure 1. Dyeing scheme using supercritical solution [3].

Waterless dyeing technology using supercritical carbon dioxide (CO_2). When CO_2 reaches a temperature of 31°C and a pressure of 74 bar, it enters a supercritical state with properties of both liquid and gas. In this state, supercritical CO_2 has a molecular density similar to that of a liquid and high diffusivity like a gas; therefore, the dyeing process is faster than conventional dyeing. At the end of the dyeing process, drying is not required. Moreover, CO_2 can be easily recycled up to 90% through separation equipment [3], [15], [16]. This technology does not use water, significantly reducing wastewater pollution and energy consumption. It is environmentally friendly and supports sustainable development goals. However, supercritical CO_2 dyeing has only been applied to synthetic fibers such as polyester, acetate, and nylon [3].

Je Hong Textile Co., Ltd. is establishing a new Waterless Dyeing Textile Factory in Aurora Textile Industrial Park, aiming to build the most reliable waterless dyeing base in Vietnam, with environmentally friendly and innovative textile dyeing and finishing technology. This factory is under construction in 2024 in Nam Dinh province. However, the application of these new technologies in Vietnam faces several challenges, including high investment costs, technical complexity, and limited fiber availability; therefore, they have not yet been widely adopted.

2.3. New Equipment

The Airflow dyeing machine uses airflow to transport fabric instead of water, reducing water usage to only 20–30% compared to traditional dyeing processes. Moreover, this machine automatically adjusts temperature, pressure, and time, thereby minimizing errors during the dyeing process. In addition, it saves chemicals and energy, and helps reduce fabric wrinkling [12], [17].

Supercritical CO_2 Dyeing Machine: This machine uses supercritical carbon dioxide instead of water, eliminating salt and auxiliary chemicals. The process generates no wastewater, requires no drying, and achieves shorter dyeing times compared to traditional methods. The process generates no wastewater, requires no drying, and achieves shorter dyeing times than traditional methods [16].

This machine is designed for a low liquor ratio (1:1 to 1:5), therefore reducing water consumption. It features automated controls for temperature, pressure, and fabric winding speed, which help decrease wrinkling and color unevenness, while improving the overall quality of dyed products [15].

2.4. Automate production processes

One of the most important steps in the dyeing process is the preparation of chemicals and dyes. In the past, dyeing relied on manual mixing of chemicals, which often led to uneven color quality. Nowadays, this step is gradually being automated from calculating and weighing to mixing, thereby enhancing the consistency and overall quality of the final product [18].

Figure 2. Automated dye mixing system at laboratory scale.

Research on an automation system based on a Programmable Logic Controller for dye dosing machines and environmental system design. The device automatically prepares dye solutions according to the machine and monitors solution levels using sensors, making real-time adjustments as needed [19].

Figure 3. Automated dye mixing system at industrial scale.

2.5. Digital Management Solutions

In addition to production lines with modern equipment to save energy, chemicals, and water, many factories are also investing in smart management software to streamline production management.

Smart management systems in dyeing factories include data collection, transmission, and storage. These smart management systems automatically collect real-time data from dyeing machines and auxiliary equipment such as dye mixing, dyeing time, environmental conditions, and energy usage. This data is managed and shared across relevant departments.

Smart management systems include functions such as online equipment monitoring, energy and environment, order and quality management. Based on sensor technology, big data, and IoT (Internet of Things), the system proposes early warnings and machine operational adjustments.

To implement a smart management system, machinery must also be intelligent with sensors, internet connectivity, and inter-device communication to ensure continuous data flow.

Several studies have introduced smart dyeing factory management software, such as Certon software (Benninger) to collect and process data. The technology integrates RFID (Radio Frequency Identification) sensors into the dyeing and finishing stages. It enables product counting, classification by color and weight, the detection of production errors, and the evaluation of worker performance [20], [21].

Santex Rimar Group has introduced the ATHENA software, using sensors to collect data such as machine speed, temperature, fabric tension, moisture, and fabric width. This data supports big data analytics for predictive maintenance and automatic parameter settings across machine levels [21].

A software application has been developed to monitor and collect data from color control systems during the dyeing process. It enables managers to monitor and adjust color charts for new orders. This software has been implemented at Phong Phu International Joint Stock Company [22].

Figure 4. Color control software interface during dyeing process [22].

The dyeing industry in Vietnam is undergoing a gradual transformation driven by the adoption of natural colorants, advanced technologies, modern equipment, automation, and digital management systems. The use of natural dyes derived from plants, minerals, and other renewable sources has gained increasing attention due to their biodegradability, low toxicity, and potential to reduce environmental pollution. At the same time, new dyeing technologies such as low-liquor-ratio dyeing and supercritical CO_2 dyeing have significantly improved resource efficiency by reducing water, energy, and chemical consumption. The introduction of modern dyeing equipment with enhanced control systems enables more uniform dyeing quality, shorter processing times, and fewer defects. Furthermore, automation in dyeing operations, including automatic dosing, real-time monitoring, and process optimization, helps minimize human error and improve productivity. Digital management systems, supported by the Internet of Things (IoT) and data analytics, allow enterprises to monitor production processes, manage resources effectively, and ensure traceability and compliance with environmental standards.

Despite these notable advances, several challenges remain in implementing these solutions in Vietnam. Natural dyes, although environmentally friendly, often face limitations related to color consistency, scalability, and compatibility with different types of fibers. Advanced technologies and modern equipment require high initial investment and sophisticated technical expertise, which are significant barriers for many small and medium-sized enterprises. In addition, the level of automation and digitalization in the Vietnamese dyeing industry is still relatively low, with limited integration between production systems and management platforms. The lack of skilled human resources, insufficient research and development capacity, and dependence on imported technologies further constrain the effective implementation of these innovations. Moreover, supporting infrastructure, such as standardized supply chains for natural dyes and efficient wastewater treatment systems, is not yet fully developed. Therefore, while these solutions offer promising directions for enhancing sustainability and productivity, addressing financial, technical, and institutional challenges is essential to accelerate the sustainable development of the dyeing industry in Vietnam.

3. Conclusions

In the context of increasing environmental pressures and the demand for sustainable development in the textile dyeing industry, innovation in both technology and management has become essential. Advanced dyeing technologies such as supercritical CO_2 dyeing and low liquor ratio dyeing help reduce water usage, gas emissions, and energy consumption. The use of modern equipment that can control temperature, pressure, and processing time enhances production efficiency and product quality.

In addition, the growing trend of using natural dyes and mordants as alternatives to synthetic chemicals contributes to reducing environmental pollution, improving safety, and promoting the greener practices within the textile industry.

Moreover, smart management systems, such as raw material management, production processes, and waste treatment play a crucial role in maintaining competitiveness and protecting the environment. The integration of technological innovation, equipment upgrades, safe chemical selection, and smart management ensures sustainable development in the textile industry.

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