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Research on the application of biological mordant dyeing with natural dyes

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Abstract. With the continuous development of society, the dyeing and finishing field is transitioning towards green sustainability and multifunctionality. The main direction is to dye fabrics using natural dyes with the aid of mordants. In recent years, the technology of biological mordant dyeing with natural dyes has become a research hotspot. This paper first discusses in detail the application of biological mordant technology with natural dyes on various types of dyed fabrics, including plant fibers, animal fibers, and synthetic fibers. It then introduces the application of biological mordant dyeing with natural dyes in fields such as antibacterial and ultraviolet protection. By comparing the environmental impact and effectiveness of metal mordants versus biological mordants on dyed fabrics, the most suitable mordant is identified. Finally, the paper provides an outlook on the optimization of the dyeing process, in-depth exploration of mechanisms, rational selection of resources, and functional application trends of biological mordant technology with natural dyes, aiming to provide a reference for research directions in this field.

Keywords: biological mordant, natural dyes, functional application, antibacterial, UV protection

1. Introduction

Since the 21st century, environmental protection has remained a critical concern, significantly impacting various domains such as the ecological environment, human health, economic development, and national security. In textile dyeing and finishing processes, the use of chemical dyes leads to severe water, air, and soil pollution [1]. As environmental protection concepts become more ingrained in people's minds, the awareness and importance of eco-friendliness and health have gradually increased. Consequently, clean dyeing and finishing technologies, which can alleviate energy crises and reduce water pollution, have garnered more attention. Natural dyes, known for their non-toxic and harmless properties, have been widely researched. However, most natural dyes exhibit low color fastness [2-3], prone to oxidation and fading due to high temperatures or environmental changes. Thus, appropriate mordants are needed in the dyeing process to improve color fixation and enhance the fabric's antioxidant properties. Common mordants in the textile industry include metal mordants and biological mordants [4-5]. Compared to metal mordants, which pose potential threats to the environment and human health, biodegradable and less harmful biological mordants have become a popular research topic.

Natural biological mordant dyeing involves using natural biological materials as mordants, transferring the color on the dye to the mordant, and then dyeing the mordant and fibers together to achieve dyeing effects [6]. This includes plant materials such as pomegranate peel [7], turmeric [8], oak [9], Terminalia chebula Retz. [10], walnut shells [11], etc., which have been widely applied in textile, paper, and leather dyeing. Natural biological mordant dyeing can avoid environmental pollution and water resource issues caused by traditional synthetic dyeing. It combines the biodegradability and biocompatibility advantages of plant dyes while addressing their low color fastness issues, offering non-toxic, eco-friendly, and excellent dyeing effects. As industrial requirements increase, the natural dye biological mordant dyeing technology, which imparts multifunctionality to fabrics, has also become an essential development direction [12].

Therefore, natural dye biological mordants, which align with green development principles, have significant advantages. In recent years, with in-depth research on natural dye biological mordant dyeing, the application of natural dyes on plant fibers, animal fibers, and synthetic fibers, as well as their functional development in antibacterial, UV-resistant, and antioxidant fields, has gained more attention.

2. Applications of natural dye biological mordant technology on different fabrics

2.1. Applications on plant fibers

Plant fibers are vital renewable resources in nature, such as hemp, which has good hygroscopicity, high strength, natural and rustic surface texture, bright colors, and novel texture. Products made from it are biodegradable and recyclable, making them eco-friendly. Plant fibers have now become important raw materials in the dyeing and finishing industry.

Yang Rong et al. [13] used acid papaya as a mordant to dye silk fabrics with madder, finding improvements in K/S value, friction color fastness, perspiration resistance, and soaping color fastness. Wang Linan et al. [14] dyed cotton fabrics using violet roots and citric acid as biological mordants, resulting in UV-resistant and antibacterial cotton fabrics. Phromphen et al. [15] used marigold as a natural dye and tannins extracted from banana peel as a biological mordant to dye cotton fabrics, which exhibited good color fastness, wash fastness, and antibacterial and UV-resistant properties. Marwa et al. [16] combined three biological mordants—oak galls, chlorophyll, and green almond shells—with jujube seed water extract to dye cotton fabrics, enhancing dye uptake and color fastness. GHAHEH et al. [17] dyed cotton fabrics with Hibiscus sabdariffa, using tannic acid, pine cones, lemon peel, and sodium alginate as mordants, effectively increasing the apparent color depth and color fastness of the dyed fabrics. Adeel et al. [18] used microwave treatment and sustainable biological mordants to isolate colorants from cinnamon, making the dyeing process more eco-friendly. Dutta et al. [19] used onion skins as a natural dye and Terminalia chebula Retz. and Eucalyptus bark as mordants to dye cotton knit fabrics with good dyeing effects.

2.2. Applications on animal fibers

Animal fibers, also known as natural protein fibers, are formed from animal hair or secretions, primarily various animal hairs and silk. Wool is a common animal fiber, which, compared to plant fibers like cotton and hemp, has good thermal insulation properties. As a protein fiber, it is acid-resistant but not alkali-resistant, so wool dyeing should be done under acidic conditions. Silk is a general term for silk fabrics, known for their luxurious appearance, smooth texture, gloss, comfort, and good tensile strength and elasticity, making it a high-end clothing material.

Hong Guoying [20] applied an environmentally friendly biological mordant, citric acid, to post-mordant dyeing of wool fabrics with natural turmeric dye, achieving color fastness to soaping that meets daily wear requirements. Wang et al. [21] used microwave extraction to isolate environmentally friendly textile dyes, melanin, from goji berry residue. Encapsulating melanin with phospholipids to create microcapsule dyes and using pomegranate peel as a biological mordant in post-mordant dyeing aligned with energy-saving and emission reduction principles. The resulting wool fabrics had high color fastness, antioxidant, and antibacterial properties, effectively increasing the added value of dyed products. Zhou et al. [22] extracted pigments from tannin-rich non-agricultural waste tallow leaves, adding chlorophyll extract as a biological mordant to dye wool fabrics, resulting in deep yellow wool fabrics with UV protection, antioxidant, and antibacterial activity, suitable for developing bioactive medical materials. Hosseinnezhad et al. [23] used wild olive, rich in tannins, as a mordant and Rhodiola extract as a natural dye to dye wool yarns. Compared to conditions without mordants, the color intensity and wash fastness of the fabrics increased. Veysian et al. [24] used ultrasonic-assisted extraction to obtain pomegranate peel pigment and walnut as a biological mordant for pre-mordant dyeing of wool yarns, achieving wash and light fastness comparable to alum mordants. Jafari et al. [25] used indigo dye with myrobalan as a biological mordant to dye wool yarns, resulting in appropriate color intensity and fastness while expanding the color gamut.

2.3. Applications on synthetic fibers

Synthetic fibers are made from polymer compounds, offering good abrasion resistance, heat resistance, and chemical stability, meeting high rigidity requirements with good impact resistance, static strength, and dynamic performance. Common synthetic fibers include polyester, nylon, acrylic, chloroprene, vinylon, and spandex.

Haji et al. [26] used dragon blood resin as a natural dye and four biological mordants (including mint, agava, gum ammoniac, and pomegranate peel) to dye nylon 6 fabrics using pre-mordant technology, achieving ISO color fastness standards. Rehman et al. [27] isolated natural colorants from saffron and safflower petals using microwave radiation and dyed nylon fabrics with turmeric and pomegranate biological mordants, enhancing the color intensity and fastness of the dyed nylon fabrics. Fatemeh et al. [28] used pomegranate peel biological mordant and Phlomis tuberosa extract dye to mordant dye nylon 6 fabrics, improving color fastness and imparting antibacterial properties. Ghaheh et al. [29] used rhubarb flower as a natural dye and four natural mordants (walnut shells, pistachio shells, pine cones, and green coffee) to mordant dye nylon 6, producing the same brown color but with varying color intensity, with the strongest color from 10% concentration walnut shells.

3. Research on functional applications of natural dye biological mordant dyeing

With the increasing global environmental awareness and demand for healthy textile performance, using biological mordants to impart multifunctionality or synergistic effects during natural dye dyeing has emerged prominently in the textile printing and

dyeing field. Therefore, the development of natural dye biological mordant dyeing techniques with multifunctionality (such as antibacterial, UV protection, and antioxidant properties) will become a significant trend in the textile industry.

3.1. Research on the antibacterial properties of natural dye bio-mordant dyeing

With the acceleration of industrialization and the improvement of living standards, consumer demand for textiles has extended beyond mere appearance to encompass health benefits. Antibacterial and antiviral properties have become key issues, garnering global attention towards the antibacterial nature of textiles. Human skin is susceptible to various microorganisms, and textiles, acting as a bridge between the body and the external environment, play a crucial role in the proliferation and transmission of pathogenic bacteria. Therefore, textiles with excellent antibacterial properties are highly sought after. Traditional fabric dyeing and antibacterial finishing are separate processes, consuming substantial amounts of dyes, auxiliaries, water, electricity, and gas, which are not in line with green production concepts. However, the bio-mordant dyeing technology of certain natural dyes not only enhances dyeing effects but also imparts unique antibacterial properties to fabrics due to the medicinal active ingredients in natural dyes or bio-mordants.

Adeel et al. [30] extracted anthocyanins from rose petals and used different chemical and bio-mordants to dye wool fabrics, resulting in antibacterial properties. Shahmoradi et al. [31] used tannic acid, pinecones, lemon peels, and sodium alginate as bio-mordants to dye cotton fabrics, which exhibited superior antibacterial properties compared to metal mordants. Indrianingsih et al. [32] extracted pigments from mango peels and used Ixora javanica leaf powder as a mordant to dye cotton fabrics, achieving antibacterial effects. This indicates that developing bio-mordant dyeing methods with good color fastness, wide antibacterial range, and long-lasting antibacterial effects will be a future trend.

3.2. Research on the UV protection of natural dye bio-mordant dyeing

Natural dyes are increasingly valued for their environmental compatibility and medicinal health benefits. Excessive ultraviolet (UV) radiation can rapidly age textiles, reducing their physical properties, strength, abrasion resistance, and service life, and can even cause various skin diseases, affecting the immune and visual systems, thereby threatening human health. Therefore, researchers are not only focusing on the coloring effects of natural dyes but also exploring their UV protection properties during the dyeing process.

Singh [33] used Kigelia Africana as a natural dye and Terminalia chebula as a bio-mordant to dye wool fabrics, achieving 99.41% antioxidant activity, 97.8% antibacterial activity, and good UV protection. Zhang's team [34] used soy protein as a mordant and ultrasonic-assisted dyeing for cotton fabrics, finding improved UV protection after bio-mordant dyeing. Yamini et al. [35] used extracts from the bark of Acacia nilotica as a natural dye and galls extract as a bio-mordant to dye cotton fabrics, achieving a UV protection factor (UPF) of 35. Chao et al. [36] extracted natural dyes from five plants (persimmon, rhubarb, Cuscuta chinensis, Acanthopanax gracilistylus, and Cuscuta reflexa), using Phyllanthus emblica as a bio-mordant to dye cotton and silk fabrics, resulting in improved UV protection after mordant dyeing with natural dyes.

It is evident that developing UV-protective natural dyeing methods in line with modern demands is an important task for the textile dyeing and finishing industry. As research progresses and dyeing technology improves, utilizing bio-mordants to develop natural dyeing technologies with good color fastness, high UV protection levels, and long-lasting UV resistance will be the direction for future development.

3.3. Other functional studies on natural dye bio-mordant dyeing

Consumers increasingly favor daily textiles that are natural, healthy, safe, protective, and of high quality, highlighting the growing value of "functionality" and "practicality" in the textile fabric market. In addition to antibacterial and UV protection functional research, the combination of natural dye bio-mordant dyeing processes with the preparation of functional textiles such as antioxidant and flame retardant textiles has also attracted widespread attention from researchers and consumers.

Kushwaha et al. [37] used Acacia nilotica bark as a bio-mordant and Nyctanthes arbor-tristis as a natural dye to dye pineapple fabrics, achieving antibacterial rates of 98.23% against Staphylococcus aureus and 97.17% against Escherichia coli, with an antioxidant activity of 99.37% against DPPH (2,2-Diphenyl-1-picrylhydrazyl) free radicals, and good UV protection. Singh et al. [38] used kapok flowers extract (KFE) and tamarind seed coats extract (TSCE) to pre-mordant wool fabrics, improving K/S values (>1.89), wash and rub fastness, with antibacterial rates above 95% and antioxidant rates between 79-95%. Siyamak et al. [39] dyed wool yarns using Melissa officinalis L. natural dye and 75% bio-mordants (Quercus infectoria and Eucalyptus bark), enhancing color fastness and imparting antibacterial, antioxidant, and UV protection properties. Kishor et al. [40] pre-mordanted wool fabrics with three different mordants (amla dye mordant (AR), Baheda mordant (BR), Harda mordant (HR)) in an infrared dyeing machine, and dyed with straw powder extract, resulting in wool fabrics with high water vapor permeability, UV shielding, and flame retardant properties exceeding 2500 g/m2/24 h, 500 UPF, and 30 LOI value.

The multifunctional research of natural dyes can not only provide new development directions for the textile industry but also offer consumers healthier and more environmentally friendly textile choices. Future research should further explore dyes suitable for various textile requirements to meet consumer demands for multifunctional and high-quality textiles. Additionally, the

development and application of natural dye bio-mordant dyeing technology should be strengthened to promote sustainable development in the textile industry.

4. Conclusion and outlook

Natural dyes, as eco-friendly, healthy, and safe coloring agents, have extensive application prospects in textiles, cosmetics, the food industry, agriculture, and other fields. The conjugate use of bio-mordants with natural colorants can effectively enhance the color fastness of natural dyes, increase or improve the functionality of dyed fabrics, and is environmentally friendly. This aligns with the industry's shift towards bio-friendly and environmentally protective production processes, as well as the transition towards green chemistry and smart manufacturing. Thus, natural dyeing holds significant research value for the future. However, the current state of natural dye bio-mordant dyeing still requires further improvement and refinement to meet the needs for quality enhancement, efficiency, and multifunctional development, as detailed below:

1. Exploring New Technologies for the Preparation and Application of Natural Dye Bio-Mordant Dyeing:** This includes methods such as media dyeing, enzyme dyeing, ultrasonic and microwave dyeing, and fiber modification dyeing. While bio-mordants can effectively avoid the pollution issues caused by metal mordants, their ability to improve color fastness needs to be further strengthened.

2. Enhancing Research on the Effectiveness, Stability, and Sustainability of Natural Dye Bio-Mordant Dyeing: There is a need to reinforce studies on dyeing processes and applications of natural dyes to improve dyeing efficiency and quality, reduce costs, and develop more products with special functions. Additionally, further in-depth research is needed into the dyeing mechanisms and processes to uncover the chemical reactions and physical changes during dyeing, thereby improving dyeing effects and stability.

3. Strengthening Research on the Safety and Environmental Friendliness of Natural Dyes:** This ensures that the dyeing process is safe and environmentally friendly for humans and nature. Using renewable resources for dye extraction, such as agricultural waste (tea leaves, fruit seeds) or fruit and vegetable peels (onion skins, pomegranate peels), can help develop and promote low-cost, eco-friendly dyeing technologies.

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