INNOVATIONS IN THE DYEING AND FUNCTIONAL FINISHING OF MULBERRY SILK

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Abstract. Mulberry silk, prized for its luxury and comfort, faces limitations in its natural state, such as photoyellowing, poor resistance to abrasion and wrinkling, and a lack of functional properties. The modern textile market demands not only aesthetic appeal but also enhanced performance and functionality. This scientific-analytical article explores the latest innovations in the dyeing and functional finishing of mulberry silk fabrics. It provides a critical examination of sustainable dyeing practices, including the use of natural dyes with eco-friendly mordants, low-liquor ratio dyeing, and the application of supercritical CO2 fluid technology. Furthermore, the article delves into advanced functional finishing techniques, such as nano-finishing for UV protection, antimicrobial activity, and flame retardancy, as well as polymer grafting and cross-linking for improved crease recovery and durability. The analysis synthesizes recent research findings, evaluating the effectiveness of these treatments, their durability to washing, and their impact on the inherent desirable properties of silk. The conclusion emphasizes that the integration of novel dyeing and finishing technologies is pivotal for transforming traditional silk into a high-performance, multifunctional, and sustainable textile, thereby expanding its applications in technical, medical, and smart textile sectors.

Keywords: Mulberry Silk, Sustainable Dyeing, Natural Dyes, Supercritical CO2 Dyeing, Nano-Finishing, Antimicrobial, UV Protection, Flame Retardancy, Smart Textiles, Functional Finishes.

Annotatsiya. Tut ipagi hashamat va qulayligi bilan qadrlanadi, ammo tabiiy holatida u fotosarg'ayish, ishqalanish va g’ijimlanishga chidamsizlik va funktsional xususiyatlarning yetishmasligi kabi cheklovlarga ega. Zamonaviy to'qimachilik bozori nafaqat estetik jozibadorlik, balki yaxshilangan ishlash va funktsionallikni talab qiladi. Ushbu ilmiy-tahliliy maqola tut ipak matolarini bo'yash va funktsional yakunlash sohasidagi so'nggi yangiliklarni o'rganadi. Maqolada ekologik toza bo'yagichlar bilan tabiiy bo'yoqlardan foydalanish, past suyuqlik nisbatida bo'yash va superkritik CO2 suyuqlik texnologiyasini qo'llashni o'z ichiga olgan barqaror bo'yash amaliyotlari muhokama qilinadi. Bundan tashqari, maqola UV himoyasi, antimikrob faollik va olovga chidamlilik uchun nano-ishlov berish, kabi ilg'or funktsional tugatish usullarini o'rganadi. Tahlil so'nggi tadqiqot natijalarini umumlashtiradi, ushbu ishlovlarning samaradorligi, ularni yuvishga chidamliligi va ipakning tabiiy istalgan xususiyatlariga ta'sirini baholaydi. Xulosa shuni ta'kidlaydiki, an'anaviy ipakni yuqori samarali, ko'p funktsional va barqaror to'qimachilikka aylantirishda yangi bo'yash va yakunlash texnologiyalarini

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integratsiyalash muhim ahamiyatga ega bo'lib, bu uning texnik, tibbiy va aqlli to'qimachilik sohalaridagi qo'llanilishini kengaytiradi.

Kalit so'zlar: Tut ipagi, barqaror bo'yash, tabiiy bo'yoqlar, superkritik CO2 bo'yash, nano-ishlov berish, antimikrob, UV himoyasi, olovga chidamlilik, aqlli matolar, funktsional qoplamalar.

Аннотация. Шелк тутового шелкопряда, ценимый за свою роскошь и комфорт, имеет ограничения в своем естественном состоянии, такие как фото-пожелтение, плохая устойчивость к истиранию и сминанию, а также отсутствие функциональных свойств. Современный текстильный рынок требует не только эстетической привлекательности, но и улучшенных эксплуатационных характеристик и функциональности. Данная научно-аналитическая статья исследует последние инновации в области крашения и функциональной отделки шелковых тканей тутового шелкопряда. В статье представлено критическое изучение устойчивых методов крашения, включая использование натуральных красителей с экологичными протравами, крашение с низким коэффициентом ванны и применение технологии сверхкритического флюида CO2. Кроме того, статья углубляется в передовые методы функциональной отделки, такие как нано-отделка для УФ-защиты, антимикробной активности и огнестойкости, а также прививка полимеров и сшивание для улучшенного восстановления от сминания и долговечности. Анализ синтезирует результаты последних исследований, оценивая эффективность этих обработок, их устойчивость к стирке и их влияние на присущие шелку желательные свойства. В заключении подчеркивается, что интеграция новых технологий крашения и отделки имеет ключевое значение для преобразования традиционного шелка в высокопроизводительный, многофункциональный и устойчивый текстиль, тем самым расширяя сферу его применения в техническом, медицинском и smart-текстиле.

Ключевые слова: Шелк тутового шелкопряда, устойчивое крашение, натуральные красители, крашение в сверхкритическом CO2, нано-отделка, антимикробная, УФ-защита, огнестойкость, умные текстильные материалы, функциональные отделки.

Introduction

Once degummed, mulberry silk fabric possesses a brilliant white appearance, high affinity for dyes, and a sublime handle. However, to meet the evolving demands of global consumers and industrial applications, mere coloration is insufficient. Contemporary textile processes aim to imbue silk with durable functional properties while simultaneously addressing the environmental concerns associated with traditional textile wet processing [1-2].

The conventional dyeing of silk often involves acid, metal-complex, or reactive dyes in aqueous baths, requiring substantial amounts of water, salt, and energy, and generating colored effluent. Similarly, traditional finishing with

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formaldehyde-based resins, while effective for crease resistance, raises ecological and health concerns. This creates a compelling need for innovative approaches that minimize environmental impact while maximizing the value and performance of the final silk product [3].

This article provides a systematic analysis of cutting-edge developments in two key areas: (1) Sustainable and efficient dyeing technologies, and (2) Advanced functional finishing processes designed to extend the application scope of mulberry silk.

SUSTAINABLE DYEING INNOVATIONS FOR SILK

There is a resurgence of interest in natural dyes derived from plants, insects, and minerals due to their non-toxic, biodegradable, and renewable nature.

Challenges with Natural Dyes on Silk: Poor color fastness (especially light and wash), limited color range, and reproducibility issues. Mordants (metal salts like alum, ferrous sulfate, tin chloride) are essential to fix the dye, but some heavy metal mordants are ecologically harmful [4-5].

Innovations:

Bio-Mordants: The use of natural extracts rich in tannins (e.g., pomegranate rind, myrobalan) as substitutes for metal mordants. These act as eco-friendly bridging agents between the dye and the fiber.

Pre-Mordanting with Chitosan: Chitosan, a biopolymer derived from crustacean shells, can be applied to silk as a primary coating. It enhances dye uptake and fastness due to its cationic nature and ability to form complexes with dyes.

Ultrasound and Microwave Assistance: These technologies enhance the extraction of dyes from natural sources and improve the dyeing kinetics, leading to deeper shades, better uniformity, and reduced dyeing time and temperature.

Reducing the volume of dye bath is a direct route to saving water and energy.

Foam Dyeing: The dye solution is converted into a foam, which is then applied to the fabric. This technology can reduce water consumption by over 80% compared to conventional exhaust dyeing.

Supercritical CO_2 Dyeing: As discussed in degumming, supercritical CO2 is an excellent solvent for disperse dyes. In this waterless process, CO2 carries the dye into the fiber pores, and upon depressurization, the CO2 gasifies, leaving a dry, dyed fabric. This process offers unparalleled advantages:

- ❖ Zero Water Consumption and Wastewater.
- ❖ No Need for Auxiliaries like dispersing agents or salt.
- ❖ Faster Dyeing Cycles and reduced energy consumption (no drying needed).
- ❖ While primarily for synthetic fibers, research is advancing to adapt this technology for protein fibers like silk using modified dyes.

ADVANCED FUNCTIONAL FINISHING FOR DURABILITY AND COMFORT

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Silk is prone to wrinkling. Modern finishes aim to overcome this without using harmful chemicals [6-8].

Citric Acid as a Cross-linker: Citric acid (CA) is a non-toxic, polycarboxylic acid that can act as a cross-linking agent for silk. Under catalytic conditions (e.g., with sodium hypophosphite), it forms ester bonds with the hydroxyl groups of serine and tyrosine residues in silk, creating intra-fiber cross-links that improve crease recovery angle.

Silane-Based Finishes: Organofunctional silanes can form durable, flexible, and hydrophobic networks on the silk surface, improving both wrinkle resistance and water repellency.

Although silk is more flame-resistant than cotton, it still burns. For applications in protective clothing and home textiles, enhanced flame retardancy is desired.

Phosphorous-Based Finishes: Compounds like dimethylphosphonopropionamide (DMPA) can be grafted onto silk. They work through a condensed-phase mechanism, promoting char formation and reducing the release of flammable volatiles.

Bio-Based Solutions: Phytic acid, a naturally occurring phosphorus-rich compound found in plants, has shown promising results as an eco-friendly flame retardant for silk.

NANO-FINISHING FOR MULTIFUNCTIONAL PERFORMANCE

Nanotechnology involves the application of particles in the size range of 1-100 nm to impart functions without affecting the fabric's breathability or hand feel.

UV Protective Finishing: Silk has moderate UV resistance. The application of nanoparticles like Zinc Oxide (ZnO) or Titanium Dioxide (TiO_2) can significantly enhance the Ultraviolet Protection Factor (UPF). These nanoparticles act as physical blockers, scattering and absorbing harmful UV radiation [9-10].

Antimicrobial Finishing: To prevent odor, staining, and degradation caused by microbes, silver nanoparticles (AgNPs) are extensively used. They offer broad-spectrum antimicrobial activity through the release of silver ions. Other options include copper nanoparticles and chitosan-based finishes, which are also biocompatible.

Application Methods: Exhaustion, pad-dry-cure, and layer-by-layer (LbL) assembly are common techniques for applying nano-finishes. The key challenge is ensuring the durability of nanoparticles to repeated laundering.

COMPARATIVE ANALYSIS

A critical aspect of any finishing treatment is its effect on the inherent properties of silk. The following table summarizes the performance of different advanced finishes.

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Table 2

Performance Analysis of Advanced Functional Finishes on Silk

Finish Type	Main Function	Key Agent	Effectiveness (e.g., UPF, Microbial Reduction)	Durability (After 10 Washes)	Impact on Silk Hand Feel
Citric Acid Cross-linking	Crease Recovery	Citric Acid	Crease Recovery Angle: +50-70%	Good (20-30% loss)	Slight Stiffening
Phytic Acid FR	Flame Retardancy	Phytic Acid	LOI: 28-30% (Self-extinguishing)	Moderate (Requires binding agent)	Minimal Change
ZnO Nano-finish	UV Protection	ZnO Nanoparticles	UPF: 40-50+ (Excellent)	Good (if cross-linked)	Slight Stiffening
Ag Nano-finish	Antimicrobial	Silver Nanoparticles	Microbial Reduction: >99%	Fair to Good	Minimal Change
Chitosan Finish	Antimicrobial/Dye Aid	Chitosan	Microbial Reduction: >90%	Fair	Softer Hand

Analysis and Discussion: The table reveals that while nano-finishes like ZnO and Ag offer exceptional initial performance, their durability can be a challenge, necessitating robust application techniques like cross-linking. Bio-based finishes like phytic acid and chitosan are highly effective initially but may require re-application or better fixation methods for long-term use. Citric acid cross-linking provides a good balance of performance and durability for wrinkle resistance.

Impact on Silk Properties: While most advanced finishes aim to be minimally invasive, some trade-offs exist. Nano-finishes and polymer cross-linking can sometimes stiffen the fabric. Optimizing concentration and application

ISSN 3030-3907

methods is crucial to preserve silk's luxurious hand feel and breathability. Harsh cross-linking conditions can also lead to a reduction in tensile strength.

CONCLUSION

The transformation of mulberry silk from a traditional luxury fiber into a modern, high-performance textile is well underway. The innovations in sustainable dyeing and functional finishing detailed in this analysis are key drivers of this transformation. The industry is moving towards:

Closed-Loop Systems: Technologies like supercritical CO2 dyeing represent the ideal of zero-discharge production.

Bio-Based and Circular Economy: The use of natural dyes, bio-mordants, chitosan, and phytic acid aligns with the principles of green chemistry and a circular bio-economy.

Multifunctionality: The future lies in single finishes that impart multiple properties simultaneously, e.g., a ZnO nano-finish that provides both UV protection and antimicrobial activity.

Intelligent Silk: The integration of smart materials (e.g., phase change materials for thermoregulation, aroma microcapsules) will open new markets in healthcare (drug-delivery sutures), sports, and military apparel.

For successful commercialization, ongoing research must focus on scaling up these technologies, reducing costs (especially for enzymes and nano-materials), and rigorously testing the long-term durability and toxicological safety of the finished products. By adopting these advanced dyeing and finishing paradigms, the silk industry can secure a competitive edge, cater to niche high-value markets, and reaffirm its commitment to sustainability and innovation.

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