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Advances in Bio-Based Materials for Textile Conservation: A Sustainable Future

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Abstract

The increasing limitations of conventional synthetic polymers, including their low biodegradability, potential toxicity and incompatibility with natural fibers, have created an urgent need for safer and more sustainable alternatives in textile conservation. In this context, bio-based materials derived from renewable resources have gained significant attention as innovative solutions. This review brings together current knowledge on a wide range of bio-based polymers, examining their fundamental properties, functional performance and suitability for conservation applications. Materials such as bacterial cellulose, silk fibroin, chitosan, gelatin, nanocellulose, alginate, lignin-based compounds and soy protein are discussed in detail, with emphasis on characteristics like mechanical strength, biocompatibility, transparency, antimicrobial activity and reversibility, which are essential for preserving delicate textile artifacts. The paper further highlights the diverse applications of these materials, including reinforcement of weakened fabrics, development of protective coatings, formulation of eco-friendly adhesives, gentle cleaning systems, dye stabilization and moisture regulation. These materials not only provide improved compatibility with historic textiles but also contribute to environmentally responsible conservation practices by reducing reliance on hazardous chemicals. Despite their advantages, certain challenges such as high production costs, sensitivity to moisture, durability concerns and lack of standardized methodologies remain. However, ongoing advancements in hybrid materials, surface modification techniques and sustainable processing approaches are expected to address these limitations. Overall, bio-based materials are emerging as key contributors to the future of textile conservation, offering a balanced approach that integrates scientific innovation with environmental sustainability.

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Introduction

The protection, stabilization and long-term preservation of textile artifacts such as traditional fabrics, historic clothing and archeological remains are the focus of the specialized discipline of textile conservation. Over time, mechanical stress, biological attack and exposure to the environment may all lead to these materials to deteriorate. In addition to preserving their physical integrity, these objects must be preserved in order to protect cultural heritage and historical knowledge for future generations. Therefore, conservation measures need to be carefully crafted to guarantee their efficacy and compatibility with the original materials.

Historically, synthetic polymers like polyester films, acrylic resins and other petroleum-based materials have played a major part in conservation treatments. Although these materials have offered protection and short-term structural support, their long-term behavior and effects on the environment are raising more concerns. Conservation experts are concerned about problems like poor biodegradability, possible toxicity and restricted compatibility with natural textile fibers. By generating chemical reactions, discolouration or stiffness in delicate fabrics, these compounds could accelerate deterioration in certain situations (Santos *et al.,* 2021). As a result, there is an increasing need to switch to safer and more environmentally friendly options.

In recent years, bio-based materials have emerged as a promising solution to these challenges, marking a significant advancement in conservation science. These materials are derived from renewable biological sources and are generally characterized by their biodegradability, non-toxicity and compatibility with natural fibers. Bio-based materials are better suited for conserving resources than synthetic polymers because they frequently have structural and chemical similarities to conventional textile fibers like cotton, wool and silk (Smith and Jones, 2020). This inherent compatibility reduces the possibility of negative reactions and aids in preserving the artifact's authenticity. Numerous bio-based materials have been investigated for use in textile conservation.

These include chitosan made from chitin, silk fibroin taken from silkworm cocoons, bacterial cellulose created by certain microorganisms, gelatin made by hydrolyzing collagen and nanocellulose collected from plant sources (Miller *et al.,* 2022). These materials are valuable for various conservation needs due to their distinct physical and chemical properties. Their ability to either replicate or complement the structure of original textile fibers enhances their effectiveness in restoration and preservation processes.

For instance, bacterial cellulose can strengthen fragile textiles without changing their texture or look because of its highly ordered nanofibrillar structure, which closely resembles natural plant fibers. In the same way, silk fibroin has exceptional strength, flexibility and biocompatibility, which makes it especially appropriate for the preservation of delicate silk artifacts. However, chitosan has extra antibacterial qualities that can help shield fabrics from biological deterioration. These materials' multipurpose qualities give conservators adaptable instruments that can tackle environmental and structural issues. Furthermore, the use of bio-based materials in conservation techniques has accelerated because to the growing emphasis on sustainability. By lowering exposure to dangerous chemicals, these materials not only lessen reliance on non-renewable resources but also promote safer working conditions. Their use aligns with global efforts toward sustainable development and green material innovation, making them highly relevant in modern conservation strategies.

Despite its benefits, the use of bio-based materials is continuously developing and research into their full potential is currently ongoing. To guarantee long-term efficacy, scientists and conservators are striving to enhance their functionality, robustness and application methods. The increasing amount of research demonstrates how important these materials can be in making textile conservation a more advanced and sustainable field of study. All things considered, bio-based materials signify a progressive move away from traditional conservation strategies and toward more suitable and environmentally acceptable options. Incorporating them into textile conservation techniques not only improves preservation results but also advances the more general objective of environmental sustainability. These materials are anticipated to play a crucial role in upcoming conservation techniques as the field's study continues to grow.

Materials Used for Textile Conservation

Bio-based materials used in textile conservation vary widely in origin, structure and function. Some of the most studied materials and their characteristics used for textile conservation are discussed further.

Bacterial Cellulose

Acetobacter xylinum is one of the species that make bacterial cellulose (BC). BC produces an extremely pure and crystalline nanofibrillar network since it lacks lignin and hemicellulose, in contrast to plant cellulose (Kumar *et al.,* 2021). Because of this, it has remarkable flexibility, water retention and tensile strength. The nanostructure is useful for strengthening delicate textiles, particularly cotton and linen, because it resembles natural fibers. It can be produced into hydrogels or thin films that work well on delicate fabric surfaces. Additionally, bacterial cellulose is translucent and breathable, two qualities that are crucial for preserving the artifact's original appearance and avoiding moisture buildup.

Silk Fibroin

A fibrous protein with superior mechanical qualities and biocompatibility, silk fibroin is derived from the silk glands of Bombyx mori silkworms (Lee *et al.,* 2020). The conservation of silk textiles has made extensive use of it as a consolidant. It is a perfect option for repairing or reinforcing historic silk fabrics because of its strength, toughness and flexibility, which are comparable to those of genuine silk fibers. Treatment options are flexible because silk fibroin can be treated as aqueous solutions or molded into films. Its low chemical reactivity also lessens the possibility that the treated fabrics may deteriorate or become discolored.

Chitosan

Chitin, which is present in insects, fungus and crustacean shells is deacetylated to produce chitosan (Zhang *et al.,* 2019). It is a linear polysaccharide with inherent antifungal and antibacterial qualities that aid in shielding fabrics from microbial biological degradation. Chitosan creates breathable, biocompatible films and coatings that can act as a protective layer without sacrificing the flexibility of textiles.

Additionally, because of its positive charge, it can attach to negatively charged textile strands, enhancing stability and adherence. Additionally, chitosan's capacity to chelate metal ions presents a possibility for shielding textiles from harm caused by metals.

Gelatin

In conservation, gelatin, a byproduct of collagen hydrolysis is frequently utilized as a consolidant and adhesive (Wang *et al.,* 2021). It can be used to reinforce delicate fibers without creating brittleness since it generates flexible films that can be plasticized to customize mechanical properties. Gelatin is chemically compatible with animal-based textiles like wool and silk since it is proteinaceous. However, for increased longevity, it must be carefully formulated or combined with other agents due to its vulnerability to moisture and microbial attack.

Nanocellulose

According to Gomez *et al.,* (2022), nanocellulose includes cellulose nanocrystals (CNC) and cellulose nanofibrils (CNF) that come from plants like wood, cotton or agricultural leftovers. These nanoscale cellulose particles have exceptional mechanical strength and excellent aspect ratios. Nanocellulose can be added to gels, films or coatings as a reinforcing agent. It improves fabrics' mechanical capabilities and offers clear protective coatings that maintain artifacts' tactile characteristics and look. Nanocellulose surface modifications have been made to increase adhesion to different fibers and water resistance.

Other Emerging Bio-Based Materials

In addition to the widely studied bio-based polymers, several other emerging materials are gaining attention for their potential applications in textile conservation. These materials offer unique functional properties that can complement existing conservation techniques and provide more tailored solutions for preserving diverse textile artifacts.

Alginate

Brown seaweed contains alginate, a naturally occurring carbohydrate. It is well known for its exceptional capacity to create gels when divalent ions, like calcium, are present. Because of this characteristic, alginate is especially helpful in conservation procedures that call for localized treatment and regulated application. By using alginate-based gels as cleaning agent carriers, stains and impurities can be removed precisely without causing the textile surface to become wet. Furthermore, biocompatible, flexible and breathable alginate films can be used as protective coatings or encasing layers. Because of these qualities, alginate can protect fragile textiles while they are being stored, displayed or transported (Patel *et al.,* 2021).

Lignin

Plant cell walls include lignin, a complex aromatic polymer that has recently garnered attention for its inherent antioxidant and ultraviolet (UV) absorption qualities. Since exposure to light and oxidative conditions can cause fading and fiber deterioration, these qualities are very important for textile conservation. Textiles can be made more resilient to environmental stresses by adding lignin-based formulations to coatings or composite materials. Furthermore, lignin is an affordable and sustainable choice due to its abundance as a by-product of the paper and bio-refinery sectors. However, issues like its natural hue and structural diversity necessitate additional processing and modification to increase its acceptability for conservation applications (Nguyen and Tran, 2020).

Soy Protein

Another intriguing bio-based material being investigated for textile conservation is soy protein, which is obtained from the processing of soybeans. It is helpful for bonding, consolidation and surface stabilization of delicate fabrics because it may create films and adhesive systems with desired mechanical qualities. Because soy protein is protein-based, it works well with animal-derived fibers like wool and silk, lowering the possibility of negative chemical reactions. It is also renewable, biodegradable and reasonably priced when compared to certain other bio-based polymers. Through cross-linking and blending methods, ongoing research aims to increase its durability, water resistance, and long-term stability (Rodriguez *et al.,* 2021).

All things considered, the investigation of these new bio-based materials broadens the spectrum of resources accessible for textile conservation. Because of their varied characteristics, conservators can choose materials according to the particular needs of the artifact, including its fiber composition, condition and exposure to the environment.

These materials are anticipated to become more crucial in the development of effective, sustainable and artifact-compatible conservation procedures as research progresses.

Properties

Bio-based materials exhibit a diverse range of functional and structural characteristics that make them highly suitable for applications in textile conservation. Their effectiveness lies not only in their environmental advantages but also in their ability to interact safely and efficiently with fragile textile substrates. The key properties that define their suitability are discussed below:

Biocompatibility: The near chemical and structural similarity of bio-based materials to natural textile fibers like cotton, silk and wool is one of their biggest advantages. This resemblance reduces the possibility of unfavorable chemical reactions, discoloration or fiber damage by ensuring improved interaction between the conservation substance and the original substrate. While cellulose-based materials work well with plant-derived fibers, materials like silk fibroin and chitosan work especially well with textiles made of proteins. For ancient textiles to remain authentic and intact, compatibility is crucial.

Reversibility: A key concept in conservation is reversibility, which enables subsequent conservators to alter or remove earlier treatments without endangering the original artifact. Gelatin, starch derivatives and soy protein formulations are just a few of the bio-based materials that can be readily reversed with mild solvents like water or low-impact solutions. This guarantees that conservation initiatives are flexible enough to adjust to changes in conservation tactics or technological breakthroughs.

Mechanical Strength and Flexibility: Reinforcement is required because aging and environmental exposure can cause textile artifacts to lose strength. Nanocellulose and silk fibroin are examples of bio-based polymers that offer exceptional mechanical strength without sacrificing flexibility. This combination is essential because it permits strengthening without adding stiffness or further stress to fibers that are already delicate. Because they are lightweight, the textile's original drape and texture are further guaranteed.

Transparency and Optical Stability: One of the main goals of conservation is to preserve the aesthetic appeal of textile objects. When applied to textiles, bio-based materials such as bacterial cellulose and nanocellulose can create ultrathin, transparent sheets that are not noticeable. These materials preserve the artifact's aesthetic and historical significance by not substantially changing its color, texture or surface features. In order to avoid yellowing or cloudiness in treated regions, optical stability over time is also crucial.

Antimicrobial and Antifungal Activity: Microorganism-induced biological deterioration is a significant issue in textile preservation. Antimicrobial and antifungal characteristics are inherent in some bio-based materials, especially chitosan. By preventing the growth of germs and fungi, these characteristics lessen the need for artificial chemical biocides. In addition to extending the textile's lifespan, this guarantees safer conservation procedures for the item and the conservator.

Resistance to Environmental Stressors: Textiles are extremely susceptible to environmental elements like oxidative conditions, temperature changes and ultraviolet (UV) light. To increase their resistance to these stresses, several bio-based materials have undergone engineering or modification. For instance, modified nanocellulose systems can offer improved thermal and oxidative stability, whereas formulations incorporating lignin can absorb UV light. These advancements aid in the long-term conservation of textile artifacts in a variety of environmental settings.

Moisture Management and Hygroscopic Behavior: In order to preserve textiles, moisture control is essential since too much humidity can encourage the formation of mildew, while too little moisture can make fibers brittle. Numerous bio-based materials have hygroscopic qualities that enable them to collect and release moisture as needed, such as gelatin, alginate and bacterial cellulose. This lessens the strain on fibers and stops biological deterioration by preserving a stable microenvironment around the cloth.

Sustainability and Environmental Compatibility: Bio-based materials greatly lessen the environmental impact of conservation efforts because they are derived from renewable biological sources. They are non-toxic, biodegradable and frequently derived from industrial or agricultural waste, such as cellulose from plant wastes or chitosan from shell waste. Their application promotes sustainable material cycles and is consistent with international initiatives to reduce resource depletion and environmental damage.

Processability and Functional Adaptability: The capacity of bio-based materials to be altered and customized in accordance with particular conservation needs is another crucial characteristic. Properties including viscosity, adhesion, flexibility and water resistance can be changed by physical, chemical or enzymatic means. Because of this flexibility, conservators can create specialized treatment plans for a variety of textiles, from more durable historical materials to extremely delicate archaeological relics.

Applications

Bio-based materials are gaining increasing attention in the field of textile conservation due to their wide range of functional benefits. Their unique compatibility with natural fibers, environmental safety and adaptability to various conservations needs make them suitable for multiple applications. These applications are being explored in both preventive and restorative textile conservation practices.

Structural Reinforcement of Fragile Textiles

The mechanical strengthening of old or degraded textiles is one of the most popular applications of bio-based materials. Textiles may eventually lose their structural integrity as a result of mechanical stress, biological attacks or exposure to the environment. These weak spots can be stabilized by applying thin, transparent films of bio-based polymers such as silk fibroin and bacterial cellulose. For instance, by adding more tensile strength without changing the textile's original appearance, silk fibroin films have been successfully employed to reinforce delicate silk artifacts (Lee *et al.,* 2020). Similarly, delicate plant-based fibers are supported by bacterial cellulose sheets, which can imitate the suppleness and surface smoothness of cotton and linen (Kumar *et al.,* 2021).

Protective Coatings and Barriers

Surface coatings made of bio-based materials including alginate, chitosan and nano-cellulose are used to create barriers against microbial growth, dust, UV light and humidity. For example, chitosan's antibacterial and antifungal qualities are particularly helpful in stopping the biological deterioration of textiles kept in humid conditions (Zhang *et al.,* 2019). Because of its mechanical strength and transparency, nanocellulose coatings offer a protective, breathable layer without compromising the fabric's tactile or visual properties (Gomez *et al.,* 2022). Additionally, alginate coatings have been utilized to encapsulate textile fibers and lessen surface abrasion, particularly when handling or transporting museum objects.

Biocompatible Adhesives and Consolidants

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Cleaning and Stain Removal

For cleaning ancient textiles, enzymatic and bio-based cleaning solutions have evolved as mild substitutes for harsh chemical solvents. Protease or lipase enzymes are occasionally added to chitosan-based gels to remove greasy or protein-based stains without causing harm to the textile fibers (Zhang *et al.,* 2019). These biodegradable cleaning methods are particularly crucial for maintaining the integrity of historic textiles that might not be able to tolerate chemical exposure. Furthermore, alginate hydrogels can serve as absorbent medium that confine the cleaning activity and reduce the amount of moisture and residues that spread to nearby locations.

Dye and Color Stabilization

Additionally, bio-based compounds are used to stabilize natural dyes in textiles that have aged. Plant-based dyes used in many traditional textiles are susceptible to light, pH and environmental contaminants. It has been demonstrated that protective coatings made of nanocellulose or compounds containing lignin can lessen dye oxidation and fading while maintaining the fabric's breathability (Nguyen and Tran, 2020). Additionally, it has been shown that chitosan can bind specific dye molecules to stop them from migrating or bleeding during cleaning or handling.

Humidity and Environmental Control

Humidity management systems for textile storage and display are developed using certain bio-based materials, particularly those with hygroscopic qualities like gelatin or nanocellulose.

By controlling moisture levels, these materials lessen the possibility of mold growth or fiber weakening brought on by extreme dryness or moisture. For instance, bacterial cellulose and alginate have been used to barrier films or moisture-absorbing pads for exhibition cabinets (Patel *et al.,* 2021).

Support Linings and Backings

Support linings or backing materials are used to strengthen delicate objects during textile mounting and storage. Sustainable substitutes for synthetic linings are provided by bio-based textiles such as hemp-based materials, bamboo fibers and organic cotton.

To increase durability and compatibility with the artifact, these natural textiles can be treated with bio-based adhesives and antimicrobials (Smith and Jones, 2020).

Encapsulation and Packaging

Textile conservation packaging also makes use of bio-based products. For instance, biodegradable films composed of cellulose, gelatin, or polylactic acid (PLA) might be utilized for transit or archival preservation. Compared to packaging made of plastic, these materials are more environmentally friendly and offer mechanical protection.

Challenges in Adopting Bio-Based Materials

Despite the significant advantages offered by bio-based materials in textile conservation, their large-scale adoption is still constrained by several technical, economic and practical challenges. Addressing these limitations is essential to ensure their effective integration into routine conservation practices.

High Production and Processing Costs: The comparatively high cost of production of bio-based products is one of the main obstacles to their widespread application. Materials like silk fibroin and bacterial cellulose need specialized equipment, controlled processing conditions and purifying procedures, all of which raise costs. These materials are frequently less economically viable than mass-produced synthetic polymers, especially for organizations with tight conservation budgets. A major area of effort continues to be lowering production costs through better manufacturing processes and the use of waste-based resources.

Limited Long-Term Durability: Bio-based materials are prized for their biodegradability, although this characteristic may raise questions about their long-term stability. Materials used in conservation are supposed to continue to function for long stretches of time without needing to be replaced frequently. When exposed to environmental elements including light, oxygen and temperature changes, some bio-based polymers may gradually deteriorate. This calls into question their dependability for long-term uses, particularly in archival or museum environments where preservation takes decades.

Moisture Sensitivity and Environmental Instability: Because they are hydrophilic, many bio-based materials show a great attraction for moisture. Excessive humidity can cause swelling, loss of mechanical strength or increased susceptibility to microbial growth, but it can also help regulate moisture. This feature can jeopardize the textile artifact as well as the applied material in uncontrolled circumstances. To reduce these dangers, thorough environmental monitoring and material change are required.

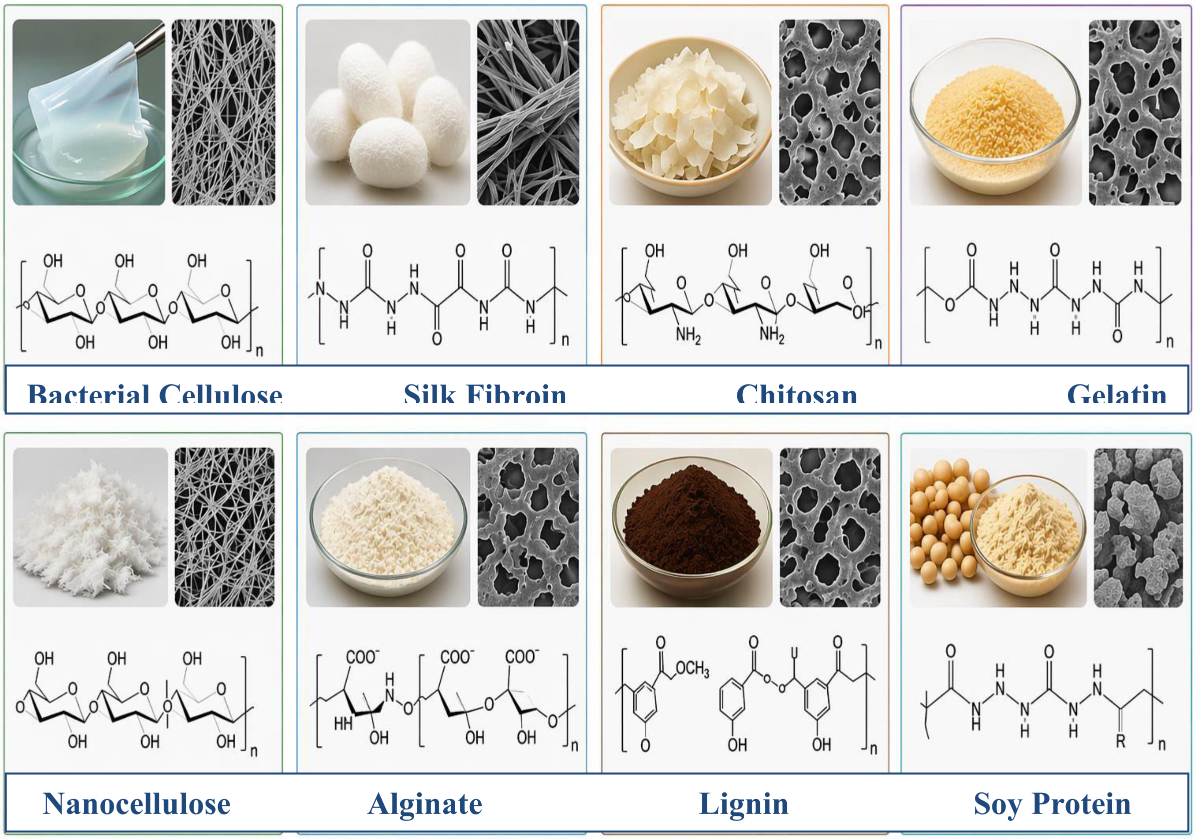

Fig.1 Materials used for textile conservation

Lack of Standardized Protocols and Guidelines: The subject of using bio-based materials for textile conservation is still developing, and there aren't many well recognized guidelines or standards. Conservators frequently use case-specific or experimental techniques, which could result in inconsistent treatment outcomes. To guarantee reproducibility, dependability, and wider adoption of these materials throughout the conservation community, standardized processes, testing techniques and evaluation criteria must be developed.

Variability in Material Properties: Because bio-based products come from natural sources, their chemical makeup and physical characteristics may differ. Their performance qualities, such as strength, viscosity and stability, can be influenced by variables like the origin of the source, extraction techniques and processing conditions. Achieving consistent results can be difficult due to this inconsistency, especially when scaling up applications or comparing results across many research.

Insufficient Long-Term Performance Data: The scarcity of long-term data on the behavior of bio-based materials in conservation settings is another significant obstacle. Even though numerous studies show encouraging short-term outcomes, more thorough study is still required to evaluate their aging behavior, interactions with various textile substrates and long-term resistance to environmental stress. Conservators could be reluctant to completely switch to bio-based materials in the absence of such information.

Technical and Handling Constraints: To get the best results, some bio-based compounds need to be prepared and applied precisely. Their efficacy can be affected by variables like drying conditions, viscosity control and pH sensitivity. Furthermore, some materials could require particular storage conditions or have shorter shelf life, which makes them less practical for regular use. For conservators to ensure correct handling and application, training and skill development are crucial.

Scalability and Industrial Implementation: Although many bio-based materials exhibit great promise in the lab, it is still difficult to apply them on a large or commercial scale. It is necessary to solve issues pertaining to reliable quality production, supply chain constraints and industrial viability. Scientists, producers, and conservation experts must work together to bridge the gap between study and practical application. Overall, although bio-based materials offer a viable and sustainable path for textile conservation, their widespread adoption depends on resolving these issues. Addressing these constraints and realizing the full promise of bio-based solutions in conservation practice would require ongoing study, technical advancement and interdisciplinary cooperation.

In conclusion, Bio-based materials are increasingly redefining the approach to textile conservation by offering environmentally responsible and material-compatible alternatives to conventional synthetic polymers. Their origin from renewable resources, coupled with properties such as biodegradability, non-toxicity and structural similarity to natural fibers, makes them highly suitable for the preservation of delicate textile artifacts. Unlike traditional materials, bio-based polymers can interact more harmoniously with historic textiles, thereby reducing the risk of chemical incompatibility, physical stress or long-term degradation. As a result, they not only support the structural stability of artifacts but also help maintain their aesthetic and historical authenticity. The versatility of these materials is evident in their wide range of applications, including reinforcement of fragile textiles, development of breathable protective coatings, formulation of reversible adhesives and implementation of gentle, bio-based cleaning systems. Additionally, their ability to provide antimicrobial protection, regulate moisture and enhance resistance to environmental stressors further strengthens their role in both preventive and restorative conservation practices. Such multifunctional performance highlights their potential to address complex conservation challenges in a more integrated and sustainable manner.

Despite these advantages, certain limitations continue to hinder their widespread adoption. Issues related to production cost, sensitivity to environmental conditions, variability in material properties and the lack of standardized application protocols need to be addressed. Furthermore, comprehensive long-term studies are essential to evaluate their durability and behavior over extended periods, particularly in museum and archival environments. Addressing these challenges will require continued research, material optimization and the development of clear guidelines for practical implementation. Looking ahead, advancements in material science, such as the development of hybrid bio-polymers, surface modification techniques and improved processing methods, are expected to enhance the performance and reliability of bio-based materials. Collaborative efforts among researchers, conservators and industry stakeholders will play a crucial role in translating laboratory-scale innovations into real-world conservation practices. Ultimately, the integration of bio-based materials represents a significant step toward achieving a balance between cultural heritage preservation and environmental sustainability. Their continued development and adoption hold great promise for shaping a more sustainable and scientifically advanced future for textile conservation.

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