Sustainable Innovations in Textile Finishing

Sangeeta Patil [1], Dr Ashok Athalye[2]

[1,2] Institute of Chemical Technology, Mumbai

DOI: https://doi.org/10.51584/IJRIAS.2025.10100000155

Received: 03 November 2025; Accepted: 10 November 2025; Published: 18 November 2025

ABSTRACT

Textile finishing is essential for improving the quality, functionality, and longevity of fabrics. The finishing methods influence the end aesthetic and functional traits of textiles, making them appropriate for various uses, such as apparel, home decor, and industrial textiles. The finishing process includes various methods that enhance properties like softness, colour stability, wrinkle resistance, water repellency, and antimicrobial effectiveness. Conventional finishing techniques often employ large quantities of water, energy, and chemicals, resulting in significant wastewater that contains harmful residues, heavy metals, and microfibers, which can pose a threat to both aquatic life and human health. With sustainability becoming a key focus in the industry, new finishing methods are emerging to lessen environmental impact while still achieving high-performance standards. As global sustainability awareness grows, businesses and consumers are seeking eco-friendly options. Sustainable textile finishing methods offer innovative approaches that minimise environmental impact while maintaining or enhancing textile quality. Textile manufacturers can find a balance between functionality and sustainability by adopting cleaner technologies, resource-saving processes, and bio-based solutions. Over time, textile finishing has evolved into a process of transforming traditional textiles into technical textiles. The future trend in this area is the creation of multifunctional textiles that are efficient, durable, cost-effective and produced in an environmentally responsible manner. This article examines various sustainable finishing methods, highlighting their benefits and the challenges associated with their adoption.

INTRODUCTION

The textile sector, a significant contributor to global pollution, is under growing pressure to adopt sustainable practices. Conventional textile finishing techniques often rely on hazardous chemicals, require significant energy consumption, and involve high water usage, ultimately leading to environmental harm and health hazards. In response, environmentally friendly textile finishing has emerged as a vital area of innovation, concentrating on minimizing the ecological impact of the industry while preserving or improving fabric performance. This introduction examines the principles, techniques, and advantages of eco-friendly textile finishing, referencing recent developments and studies.

Need for Sustainable Textile Finishing

The textile sector is among the largest polluters worldwide, significantly affecting water quality, greenhouse gas emissions, and waste production(Sadhna et al., 2024). Standard finishing methods frequently utilize synthetic chemicals, posing risks to human health and the environment. For example, artificial dyes and finishing agents have been associated with toxic emissions and bioaccumulation in natural ecosystems (Kristanti et al., 2024). Moreover, the growth of fast fashion has exacerbated these challenges, with its swift production cycles leading to increased waste and the depletion of resources.

Conventional textile finishing methods have a severe impact on the environment and public health due to their reliance on toxic substances, excessive water consumption, and harmful emissions. These methods contribute to water pollution and pose health risks to workers and communities. Traditional finishing techniques discharge dangerous chemicals and dyes into waterways, endangering aquatic life and ecosystems(Karypidis et al., 2024). These processes also require enormous amounts of water and energy, worsening resource scarcity and environmental degradation(Sehrawat, 2023). Released untreated wastewater contributes significantly to air pollution, raising greenhouse gas emissions. Textile workers are exposed to cotton dust, endotoxins, and volatile organic compounds (VOCs), which can lead to respiratory diseases and other health issues.

The pollutants emitted into the environment can impact local communities, thereby heightening the risk of health issues associated with poor water and air quality. Although traditional techniques have harmful effects, new green technologies present promising alternatives that could alleviate these issues, underscoring the necessity for a shift toward sustainable methods in the textile sector. The industry is moving toward environmentally friendly options that decrease the use of toxic substances, lower energy consumption, and encourage the utilization of renewable resources. Eco-friendly textile finishing includes a variety of innovative techniques, such as applying natural dyes, biodegradable finishes, and advanced green technologies(Patti, 2025),(Kamboj et al., 2024).

Bio-Based Finishes: Bio-based finishes in textiles are attracting interest as eco-friendly alternatives to traditional synthetic finishes, which often present environmental and health hazards. These finishes use natural materials to provide various functional characteristics to textiles. Bio-based textile finishing incorporates renewable, natural, and biodegradable materials to improve fabric properties while minimizing environmental impact. These sustainable alternatives replace conventional synthetic chemicals with resources that support a circular economy and lessen reliance on petroleum-based materials.

- **Natural Extracts:** Natural extracts from plants such as Azadirachta indica (Neem), Butea monosperma, and Litchi chinensis have been utilized to develop antimicrobial finishes for cotton/polyester blends. The effectiveness of these finishes was demonstrated by a 100% reduction in microbial growth, thereby enhancing textile hygiene(Sadaf et al., 2024). Aloe Vera and Neem extracts are known for their antimicrobial, skin-soothing, and anti-inflammatory properties. Aloe Vera extracts exhibit antibacterial and anti-inflammatory properties, demonstrating effectiveness against various pathogens. Neem extracts contain active compounds such as azadirachtin and nimbin, which offer broad-spectrum antimicrobial effectiveness. These extracts are particularly beneficial for medical textiles, baby clothing, and applications requiring sensitive skin care. Bio-based finishes in textiles are gaining attention as sustainable alternatives to conventional synthetic finishes, which often pose environmental and health risks. These finishes utilize natural materials to impart various functional properties to textiles, Bio-based textile finishing involves the use of renewable, natural, and biodegradable materials to enhance fabric properties while reducing environmental impact. These eco-friendly alternatives replace conventional synthetic chemicals with sustainable resources, supporting a circular economy and reducing dependency on petroleum-based materials. These extracts are particularly beneficial for medical textiles, baby clothing, and sensitive skin applications**.**

- **Chitosan (from Shellfish Waste):** Chitosan is a natural biopolymer derived from the shells of crustaceans, known for its antibacterial, moisture-regulating, and odor-resistant properties. This biopolymer demonstrates strong antimicrobial effectiveness, decreasing the reliance on synthetic antimicrobial agents in textiles(Kreuz, da Silva, et al., 2024). Fabrics treated with chitosan exhibit significant resistance to common bacteria, thereby improving hygiene and extending their lifespan. Additionally, when utilized as a mordant, chitosan enhances color retention and dye absorption, resulting in vibrant and durable hues in dyed textiles (Rani et al., 2024). It also boosts fabrics' antioxidant features and UV protection, making them ideal for outdoor use. Chitosan has extensive applications in sportswear, medical textiles, and protective apparel (Šmid et al., 2023). As a biodegradable substance, chitosan helps mitigate the environmental effects of textile waste[11]. Its non-toxic characteristics render it safe for numerous uses, including direct skin contact (Chandran et al., 2024). A natural biopolymer derived from crustacean shells, offering antibacterial, moisture-regulating, and odour-resistant properties. Chitosan exhibits strong antimicrobial activity, reducing the need for synthetic antimicrobial agents in textiles; (Kreuz, Cadorin, et al., 2024).

- **Pectin (from Fruit Waste):** A sustainable substitute for textile finishing, pectin is made from fruit waste and is especially useful as a thickening ingredient in printing operations. Its extraction from agro-industrial waste, including fruit peels, improves textile quality and lowers environmental waste. In textile printing, pectin is an environmentally friendly thickening that outperforms conventional thickeners like

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

alginate, thanks to its exceptional fastness qualities, which include light fastness ratings of 7. Pectin-enhanced textiles' antibacterial qualities add to their usefulness and suitability for a range of uses(Reda et al., 2024). With an emphasis on lowering CO2 emissions and encouraging more environmentally friendly extraction techniques, the life cycle assessment of pectin production shows considerable environmental benefits(Nadar et al., 2022).

- **Soy Protein Finishes**: The incorporation of soy protein in textile finishing has attracted interest due to its advantageous qualities, enhancing the softness, elasticity, and durability of fabrics while providing an environmentally friendly alternative to synthetic softeners. A range of techniques has been established to improve the performance and visual appeal of textiles, especially those blended with cotton and Modal. Finishing solutions typically incorporate hydrolytic silk protein, tea polyphenols, and essential oils, which assist in maintaining pH levels and repairing damaged fibers during washing. These solutions form a protective layer on the fabric, improving its softness and durability while remaining gentle on the skin. Soy protein can be chemically bonded to cotton and Modal textiles, resulting in a silky texture and enhanced crease recovery. The developed finishing agents are non-toxic and free from harmful substances, promoting environmentally friendly practices.

- **Lignin-Based Coatings**: Lignin-based coatings, derived from the paper and forestry industry, are employed in textile finishing to offer UV protection, antioxidant properties, and antimicrobial effects. This serves as an alternative to traditional synthetic UV stabilizers and flame-retardant materials. A lignin-silica liquid coating (LSL) used in conjunction with DOPO significantly enhances the flame resistance of cotton fabrics, resulting in a 78% decrease in peak heat release and a 65% decrease in total heat release, alongside a 21.7% increase in tensile strength (Li et al., 2024). Lignin from Acacia crassicarpa black liquor exhibits potent antibacterial properties against prevalent skin bacteria. The coating application produces clear inhibition zones measuring between 0.1 and 0.5 cm, signifying notable antibacterial effectiveness. Lignin-modified cationic waterborne polyurethane (WPU) coatings also deliver antibacterial properties, enhancing the utility of the fabric (Tian et al., 2022). Coatings based on lignin can bestow superhydrophobic characteristics upon textiles, achieving water contact angles as high as 157.2°. These coatings remain hydrophobic even after numerous washes and exposure to severe pH environments (Nisar & Raza, 2024). Furthermore, lignin coatings offer UV protection, blocking up to 92.24% of UV-A and 98.62% of UV-B radiation, making them ideal for outdoor use. Lignin-derived nanoparticles, combined with fatty acids, produce multifunctional coatings that offer water repellency, breathability, UV shielding, and antibacterial action, all while being environmentally friendly and durable (Babaeipour et al., 2024).

- **Starch and Cellulose**-The application of starch and cellulose-based substances in textile finishing has attracted considerable interest due to their environmentally friendly characteristics and multifunctional abilities. These bio-based materials, obtained from agricultural byproducts such as corn, potatoes, and cotton, enhance wrinkle resistance, fabric smoothness, and durability while avoiding toxic residues. Starch is a sizing agent to strengthen yarns during the weaving process, providing a protective layer that minimizes breakage and enhances weaving efficiency. Starch-based finishes are applied to textiles to enhance stiffness, texture, and visual appeal. Cationic starches coat cellulose fabrics, facilitating salt-free reactive dyeing and improving dye uptake and color vibrancy (Wurm et al., 2024). Cellulose Nanocrystals (CNCs) - CNCs, extracted from natural cellulose sources, display high stiffness, biodegradability, and superior mechanical properties. They can endow textiles with various functionalities, including antimicrobial characteristics, UV protection, and hydrophilic modifications (Ghazal et al., 2024). Their distinctive rod-like structure enables effective interaction with hydrophilic polymers, thereby improving the overall performance of textile products

Advantages of Bio-Based Finishes

- Environmental Sustainability: Produced using renewable resources, this approach lessens the carbon impact of textile production and dependency on fossil fuels.
- Biodegradability: Bio-based finishes decompose organically without causing environmental contamination, in contrast to synthetic chemical finishes.

- Benefits to Health and Safety: Since textiles are free of dangerous pollutants, customers with allergies or skin sensitivities can feel safer using them.
- Integration of the Circular Economy: A lot of bio-based finishes make use of industrial and agricultural waste, which reduces waste and encourages resource efficiency.
- Improved Fabric Functionality: Offers inherent moisture-regulating, UV-resistant, and antibacterial qualities without the use of artificial additives.

Nanoparticles for Functional Finishes

The ability of nanoparticles to enhance fabric qualities while preserving aesthetic appeal has generated considerable interest in their use in textile finishing applications. Silver, titanium dioxide, and zinc oxide nanoparticles are added to textiles to provide antibacterial, UV protection, water-repellent, and self-cleaning properties. By using fewer dangerous chemicals, this integration enhances textile performance and supports environmental objectives.

- **Antibacterial Properties**: Nanoparticles, particularly metal oxides like zinc oxide and silver, exhibit strong antibacterial activity, effectively reducing bacterial growth on fabric surfaces. The mechanism involves the nano-roughness of surfaces, which disrupts bacterial membranes, leading to cell disintegration.
- **UV Protection and Moisture Management**: Zinc oxide nanoparticles have been shown to provide UV resistance and moisture management in polyester fabrics, enhancing comfort and durability. These properties are crucial for outdoor and athletic textiles, where exposure to sunlight and sweat is common.
- **Self-Cleaning and Stain Resistance:** Titanium dioxide nanoparticles enable self-cleaning through photocatalytic reactions, breaking down organic pollutants when exposed to light. This technology keeps textiles clean and imparts antimicrobial properties, making them suitable for a wide range of applications. Nanoparticles (NPs) have emerged as a promising tool in eco-friendly textile finishing. These tiny particles can be synthesized from bio-based materials or green synthesis methods, reducing the reliance on hazardous chemicals. Nanoparticles can provide functional properties such as antibacterial activity, water repellency, and UV protection while minimizing environmental impact(Mahmoud & Kianfar, 2024).

Use of Enzymes in textile finishing

Enzymes are essential for textile finishing because they provide environmentally safe substitutes for conventional chemical treatments. They improve fabric quality while minimising their environmental impact by employing methods such as bleach clean-up, desizing, bio-polishing, and bio-scouring. By specifically breaking down undesirable components without causing damage to fibers, enzymes including cellulases, amylases, and pectinases enhance softness, durability, and absorbency. Cellulases give denim finishing a worn appearance without harsh chemicals or abrasive materials (Santosh Napte & Prashant Dixit, 2024). Enzymatic treatments also use less water and energy, which makes textile production more economical and environmentally friendly.

Novel Finishing Processes:

The Novel finishing processes, such as plasma pre-treatment, ultrasound irradiation, and sol-gel methods, have been integrated into textile finishing processes to enhance efficiency and reduce environmental impact. These technologies facilitate the grafting of functional groups and nanoparticles onto textile surfaces, ensuring long-term durability and adherence. Additionally, layer-by-layer self-assembly methods have been explored for eco-friendly finishes with tailored properties (Farooq et al., 2025).

- **Ozonation:** A new and environmentally friendly finishing technique has been created to improve textile finishing performance. Without sacrificing textiles' mechanical and comfort qualities, this technique uses controlled ozone exposure to enhance qualities including softness, fire resistance, and water repellence. For instance, post-ozonation has dramatically improved cotton fabrics treated with bio-based finishes in terms of flame retardancy, water repellency, and crease recovery angle.

- **Sol-gel Techniques:** Sol-gel technology in textile finishing represents a revolutionary method that improves the properties of fabrics by applying inorganic or hybrid organic-inorganic layers. This technique is gaining popularity due to its ability to confer multifunctional traits to textiles, including flame resistance, water and oil repellency, UV shielding, and antibacterial properties, all accomplished in a single processing step. The sol-gel process involves transitioning from a liquid "sol" to a solid "gel" state, which can be applied to fabrics using various methods, such as dip-coating or spraying. This approach is not only effective but also eco-friendly, as it employs low amounts of non-toxic chemicals and sidesteps formaldehyde emissions, presenting a sustainable option compared to traditional textile finishing techniques (Camlibel & Arik, 2017; Periyasamy & Militky, 2020). Sol-gel coatings can offer multiple protective features concurrently, including UV shielding, flame resistance, and antibacterial properties. The process is environmentally conscious, utilising low concentrations of chemicals and avoiding hazardous materials such as formaldehyde (Sfameni et al., 2023). Fabrics treated with sol-gel coatings demonstrate improved durability and resistance to wear, preserving their functional attributes over time. Sol-gel can be utilised through techniques such as rolling, padding, dip-coating, and spraying, providing versatility for industrial applications. This technology effectively alters fabric surfaces, making it appropriate for various fabric types and enhancing their performance characteristics.Recent innovations include the creation of coatings that possess self-cleaning, self-sterilizing, and thermochromic features, broadening the potential uses of sol-gel technology in textiles (Ismail, 2016). This method is distinguished by its use of low chemical concentrations and environmentally friendly one-step applications, making it a sustainable choice compared to conventional methods.

- **Plasma Technology**: Plasma treatments improve the surface characteristics of textiles while preserving their overall properties, making them a sustainable and effective option. This technology is increasingly utilized for various functions, including enhanced comfort, antimicrobial features, and increased durability. The upcoming sections outline the main elements of plasma technology in finishing textiles. Plasma treatments alter the surface energy, which enhances the wettability and dyeability of fabrics, thereby improving their comfort features (Azeem et al., 2024). Techniques like atmospheric-pressure dielectric barrier discharge (APDBD) introduce functional groups confer antibacterial, UV-resistant, and flame-retardant properties(Hassabo & El-Sayed, 2021). Plasma technology offers a sustainable alternative to chemical wet processing, minimizing environmental impacts while preserving the fabric's integrity (Ahmed et al., 2022). The method is solvent-free, facilitating textiles' efficient cleaning and functionalization (Barani & Haji, 2024). Plasma treatments can alter textiles to be hydrophilic or hydrophobic and even electroconductive via metallic coatings, which enhances their utility for various applications (Rădulescu et al., 2024). Studies show marked improvements in electromagnetic shielding effectiveness and fireproofing capabilities through plasma-enhanced coatings Plasma technology introduces surface alterations that boost antibacterial, UV, and flame-retardant characteristics. This technique is gaining traction due to its efficiency and reduced environmental footprint compared to conventional wet processing.

- **Laser Technology**: The concepts of laser finishing systems introduced emphasize design capabilities, productivity, and a systemic approach to sustainability, particularly in the processing of denim. Lasers can create a wide array of finishing effects that would typically require several chemical and mechanical processes using different pieces of equipment, making these systems both versatile and environmentally friendly (Kandhavadivu, 2021). Advances in laser technology for denim finishing include techniques such as laser cutting, laser whiskering, torn effects, and laser fading. These eco-friendly alternatives to conventional methods significantly lower water and energy usage while reducing health risks. The study indicates that laser treatment has a significant impact on the physical characteristics of denim, improving properties such as tensile strength and abrasion resistance. By adopting these techniques, denim apparel can achieve distinctive designs, attracting customers while supporting sustainability in the fashion industry. Laser technology removes the necessity for water and chemicals in operations like cutting, engraving, and dyeing, which are normally reliant on substantial water use(Garip et al., 2022). This decrease is critical in minimizing wastewater production and chemical pollution in the textile sector. Innovative laser technology in denim finishing considerably lowers water consumption compared to traditional techniques. This sustainable method allows for exact fading and detailing on denim items without requiring extensive water treatment processes(Nayak et al., 2022). The CO2 laser treatment is

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

extensively utilized in the textile field because of its capacity to swiftly create surface patterns with accuracy, varying sizes, and intensity, all while maintaining the overall properties of textile materials. The laser fading mechanism utilises this process to produce desired fabric surface effects with high precision and efficiency, while avoiding the downsides associated with traditional finishing methods. Laser finishing significantly reduces water usage compared to conventional methods, such as stone washing and sandblasting, which are both water-intensive and environmentally harmful (Khalil et al., 2023). The process is non-polluting, eliminating the need for chemical treatments and thereby decreasing the environmental impact of denim production (Wang et al., 2019).

- **Water Jet finishing**: With high-pressure water jets, water jet technology has become a major advancement in textile finishing, improving fabric treatment procedures. In addition to enhancing fabrics' visual appeal and practical qualities, this technology encourages eco-friendly behavior. The main features of water jet technology in textile finishing are described in the following sections. The microjet treatment method improves fabric smoothness and histological structure by using water jets at pressures ranging from 12.5 MPa to 17 MPa and speeds of 150–250 m/s (Fu et al., 2023). This technique is recognised as an eco-friendly alternative to anti-teasing and fabric-softening solutions. High-speed water jet cleaning devices are designed to remove impurities from textile equipment, ensuring efficient operation and maintenance

Eco-friendly water repellents

Water-repellent finishes play a significant role in enhancing the durability and sustainability of textiles by improving their functionality and prolonging their lifespan. These finishes are crucial for making fabrics resistant to both water and oil, thereby enhancing their effectiveness across various applications. However, the environmental and health concerns associated with conventional water-repellent chemicals have led to the emergence of more sustainable alternatives. The following sections examine various types of water-repellent finishes and their impact on the durability and sustainability of textiles. Due to their outstanding water and oil repellency, long-chain perfluoroalkyl substances (PFAS) have been extensively utilized. Still, they are currently being phased out due to their tendency to bioaccumulate and their toxic effects on the environment. Short-chain PFAS, while less harmful, provide lower surface performance than their long-chain counterparts, prompting the search for alternative options(Shabanian et al., 2023). Bio-based non-fluorinated finishes, such as those derived from palmitic acid combined with succinic or maleic acid, deliver similar performance to traditional fluorocarbons without the associated environmental disadvantages (Sharif et al., 2022). Silane-based nanohybrid materials present an eco-friendly method that achieves superhydrophobic properties on cotton fabrics by using a mix of silica sol nanoparticles and alkyl(trialkoxy)silane, resulting in excellent water repellency and stain resistance(Sfameni et al., 2022) Fluorine-free water-repellent additives introduced during fiber manufacturing can produce long-lasting and environmentally-conscious textiles. These techniques improve water repellency while preserving air permeability, though repeated applications may lead to a decrease in breathability.

Flame retardant

Flame retardant (FR) treatments are crucial in textiles to improve fire resistance, particularly in home furnishings, protective apparel, and automotive fabrics. Conventional FR treatments frequently include hazardous substances like halogenated compounds and formaldehyde-based agents, which present risks to both health and the environment. Consequently, there is a push for the development of sustainable and eco-friendly alternatives.

- Bio-based Flame Retardants: Sourced from renewable materials such as casein, chitosan, and phytic acid, these substances offer effective flame resistance with minimal ecological repercussions.
- Banana Pseudostem Sap (BPS): Research has shown that BPS, when used with phytic acid, considerably enhanced the flame-retardant qualities of cotton fabrics, reaching a Limiting Oxygen Index (LOI) of 27.5, in contrast to an LOI of 18.0 for untreated fabric(Islam et al., 2024).
- By utilizing keratin derived from wool waste, scientists developed a nitrogen/phosphorus-based flame retardant that improved the LOI by 66.7% compared to untreated cotton, demonstrating the dual advantages of reducing waste and increasing fabric safety (Patankar et al., 2021).

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

- Phosphorus-based flame retardants (FRs) are emerging as eco-friendly substitutes for traditional halogenated FRs, presenting a lower environmental impact throughout their lifecycle. These systems utilize renewable resources and innovative chemistry to improve fire safety while reducing ecological harm. The following sections elaborate on the progress and applications of phosphorus-based systems in flame retardancy. Phosphorus-based FRs have lower toxicity and environmental persistence than halogen-based alternatives, addressing rising concerns about bioaccumulation and health hazards(Mensah et al., 2022).

Low Cyclic Silicones

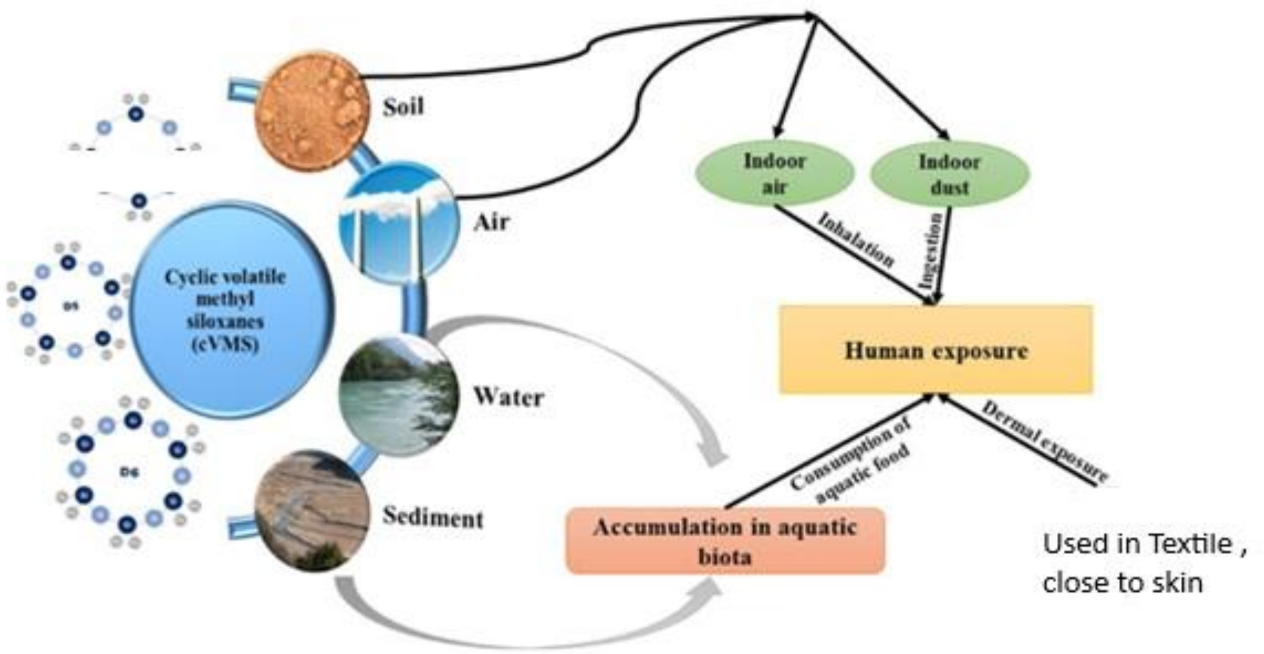
Silicones play a critical role in textile finishing, where they are used to enhance the touch, appearance, performance, and durability of fabrics. Silicone softeners used in the textile industry are primarily composed of polydimethylsiloxane (PDMS) and its chemical derivatives, depending on the desired functionality (e.g., softness, hydrophilicity, anti-wrinkle properties, etc.). During silicone synthesis, cyclic oligomers such as D4, D5, and D6 are formed.

These are formed during siloxanes' ring-opening polymerization (ROP) to create linear polymers like PDMS. These compounds are often present in trace amounts as by-products from the silicone polymerization process. However, their persistence, bioaccumulation and toxicity have raised red flag in environment and regulatory circles(Kumari et al., 2023).

Table 1- Cyclic volatile methylsiloxanes (cVMS) with the following chemical names:

Code	Chemical name	Structure	Molecular formula
D4	Octamethylcyclotetrasiloxane	4 Si–O units in a ring	$C_8H_{24}O_4Si_4$
D5	Decamethylcyclopentasiloxane	5 Si–O units in a ring	$C_{10}H_{30}O_5Si_5$
D6	Dodecamethylcyclohexasiloxane	6 Si–O units in a ring	$C_{12}H_{36}O_6Si_6$

Figure 1 : Schematic View of Cyclic Siloxane release in the environment



Increasing awareness of environmental and health impacts—particularly from residual cyclic siloxanes (D4, D5, D6)—has pushed the industry toward safer alternatives(Nu Nguyen et al., 2021). As a result, low-cyclic silicone products are rapidly becoming the new standard. Low cyclic silicone refers to textile softeners that contain very low levels (typically <0.1%) of cyclic siloxanes. Opt for silicone softeners that minimize the formation or presence of cyclic siloxanes.

Table 2 - Key to Achieve Low Cyclic Silicone in Textile Processing

Steps	Action
Source	**Choose certified low-cyclic silicone products** • Low cyclic content" (<0.1%) • "D4/D5/D6-free" • "ZDHC MRSL conformant" • Work with suppliers who are: REACH-registered with OEKO-TEX® Eco Passport, bluesign®, or GOTS
Formulate	**Use stable, high-molecular-weight emulsions.** • Choose high-molecular-weight silicones (e.g. linear PDMS) • Prefer blocked amino silicones, copolymers, or macroemulsions • Avoid formulations using cyclic siloxanes as solvents or carriers • Use silicones made via ring-opening polymerization to avoid residual low-molecular-weight cyclics like D4 and D5.
Test	**Check D4/D5/D6 levels via GC-MS** • Raw silicone softeners • Ready-to-use formulations • Occasionally, finished fabric if required by clients
Process	**Optimize finishing conditions to avoid emissions** • Optimize curing/drying temperatures (typically 120–160°C) to: • Avoid thermal degradation of silicones • Minimize VOC evaporation • Ensure no residual solvents in the formulation increase volatility • Use exhaust gas filters or air scrubbers if needed
Document	**Maintain proof of compliance** • TDS, MSDS, CoA, and GC-MS reports • Compliance certificates from chemical vendors • Internal test reports

Low-cyclic silicone is no longer just a "green" option, but a technical, legal, and market necessity. It enables textile manufacturers to:

- Achieve sustainability goals
- Meet strict international regulations
- Access global markets
- Maintain fabric quality and consumer satisfaction

In a world increasingly focused on environmental responsibility and product safety, switching to low-cyclic silicone is smart for any forward-thinking textile business. Low cyclic silicone is no longer optional — it's the new baseline for sustainable and responsible textile chemistry. It aligns with both planet-friendly goals and high-performance textile needs.

Challenges and Future Directions

Despite the progress in sustainable textile finishing, several challenges remain. The scalability and cost-effectiveness of bio-based finishes are often limiting factors, as they may require complex extraction and application processes(Devi et al., 2025) (Tegegne et al., 2024). Additionally, the performance and durability of some eco-friendly finishes may not yet match those of conventional methods, necessitating further research and development. Balancing Performance with Sustainability, Complex Compliance and Certification Requirements, Lack of End-to-End Supply Chain Alignment, Knowledge and Skill Gaps, Inconsistent Results, or Fabric Compatibility are some of the key challenges faced in adopting sustainable finishing processes

Future research should focus on optimizing extraction and application methods for natural dyes and bio-based finishes, as well as exploring new materials and technologies to enhance the performance of eco-friendly textiles. Collaboration between academia, industry, and policymakers will be crucial in driving the adoption of sustainable practices and addressing the environmental challenges faced by the textile industry.

CONCLUSION

Sustainable textile finishing represents a vital step toward reducing the textile industry's environmental impact while maintaining high-quality fabric performance. The industry can move toward a more sustainable future by leveraging bio-based finishes, nanoparticles, and advanced green technologies. As consumer awareness and demand for eco-friendly products grow, developing and adopting innovative finishing methods will play a key role in transforming the textile industry into a more environmentally responsible sector.

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