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ENVIRONMENTAL SUSTAINABILITY OF SMART TEXTILE FINISHES FOR ODOUR CONTROL, ANTIBACTERIAL AND ANTI-STATIC PERFORMANCE: TECHNOLOGIES, RISKS AND CLEANER PRODUCTION PATHWAYS

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ABSTRACT

The growing demand for functional and smart textiles has accelerated the use of advanced finishing technologies to impart antibacterial, antistatic and odor-control properties to apparel and technical textiles. While these finishes improve comfort, hygiene and performance, there is growing concern about their environmental sustainability, human safety and suitability for cleaner production principles. This review critically examines smart textile finishes used for odor control, antibacterial and antistatic properties, classifying them into chemical, natural and hybrid systems. The mechanisms of action and application methods of established technologies such as metallic salts, quaternary ammonium compounds and polymer-based finishes are analyzed alongside emerging approaches such as nanotechnology, microencapsulation, biofinishing and stimulus-responsive materials. Particular attention is paid to functional durability, economic implications and performance trade-offs with repeated use and washing. The environmental and health risks associated with these finishes are systematically assessed, including chemical toxicity, nanoparticle release, volatile organic compound emissions and regulatory compliance challenges. Drawing on recent advances and policy-oriented sustainability frameworks, the review identifies key limitations of conventional finishing methods and highlights cleaner production pathways, including the use of bio-based agents, low-impact processing techniques and life-cycle-oriented design strategies. By integrating technological performance with environmental and regulatory considerations, this review offers a comprehensive, sustainability-focused perspective to support the development and adoption of safer, more durable and environmentally responsible smart textile finishes.

KEYWORDS: Smart textile finishes, Odor-control treatments, Antibacterial textiles, Anti-static finishing, Nanotechnology in textiles

1. INTRODUCTION

The global demand for functional and smart clothing has increased significantly over the past decade, driven by expanding applications in sportswear, healthcare monitoring and protective work-wear (IDTechEx, 2020). Recent consumer trends also indicate a strong shift toward apparel designed to improve comfort and hygiene, particularly through odour-control, antimicrobial and anti-static functionalities (Gulati et al., 2021). Despite this growing interest, many conventional textile-finishing technologies continue to face performance limitations while struggling to meet sustainability expectations consistent with circular-economy models as highlighted in policy assessments and environmental reports from the European Commission (European Commission, 2020). In response to these challenges, this review examines key smart-finishing technologies used to impart odour-control, antibacterial and anti-static properties to textiles. The review focuses on their mechanisms of action, functional durability and environmental implications, considering both established and emerging approaches in the field (Abo-Basha, 2024).

2. ODOUR CONTROL FINISHES

Body odour in textiles primarily arises from the microbial degradation of sweat components, particularly long-chain fatty acids and amino acids into volatile organic compounds (VOCs) responsible for unpleasant smells (Liu et al., 2021). As such, odour-control finishes incorporate a range of chemical and physical mechanisms to minimize VOC generation and retention on textile surfaces.

2. 1. Physical Mechanisms: Absorptive and Adsorptive materials

Absorptive and adsorptive finishes function through physical interactions with odour molecules, without altering their chemical structure. These materials capture odour molecules before they volatilize. Examples include activated carbon and zeolites, which possess high internal surface area and porous structures, capable of physically trapping VOCs, thereby reducing odour release during wear (Wang et al., 2020). Cyclodextrins, cyclic oligosaccharides with hydrophobic cavities, form inclusion complexes with odour-causing molecules such as isovaleric acid and ammonia. These complexes are stable during use and are later released during washing, enabling regeneration of the textile surface (Alongi et al., 2018).

2.2 Chemical Mechanisms: Antimicrobial Finishes

Odour formation in textiles is closely linked to microbial metabolism; therefore, **antimicrobial finishes represent a chemical approach to odour control** by targeting the source of odour generation.

These finishes inhibit the growth of odour-causing bacteria such as *Staphylococcus epidermidis* and *Corynebacterium* species, which are responsible for metabolizing sweat components into malodorous VOCs. By suppressing bacterial proliferation, antimicrobial agents significantly reduce odour formation rather than merely masking or trapping odours (Gulati et al., 2021).

2.3. Chemical Mechanisms: Catalytic and Photocatalytic Conversion

Some advanced odour-control finishes rely on **chemical degradation mechanisms**, particularly catalytic and photocatalytic reactions that transform odour molecules into non-odorous compounds.

a) Titanium dioxide (TiO_2) nanoparticles are a prominent example. When exposed to UV or visible light, TiO_2 generates reactive oxygen species (ROS) that oxidize organic odour compounds into environmentally benign products such as carbon dioxide and water (Liao et al., 2021). This photocatalytic mechanism is especially valued for its self-regenerating capability and long-term effectiveness, making it suitable for applications involving repeated odour exposure.

2.4. Application Contexts

Odour-control technologies are widely implemented in sportswear, performance socks, work wear and healthcare uniforms, where sustained freshness and hygiene are critical. Their growing adoption is linked to consumer demand for durable, comfort-enhancing functional textiles (Dastjerdi & Montazer, 2020).

Antibacterial Finishes

Microbial growth on textiles can result in unpleasant odours, staining, deterioration of fabric properties and potential health risks due to infections (Møllebjerg et al., 2021). To mitigate these effects, antibacterial finishes are applied to textiles, employing a variety of mechanisms and active agents. Table 1 below summarizes the common antibacterial agents, their modes of action and their typical applications in textile finishing.

Table 1: Antibacterial agents and their applications.

Finish Type	Agent / Technology	Action Mechanism	Advantages	Limitations	References
Antibacterial – Chemical Agents	Silver nanoparticles (AgNPs)	Release Ag^{+} ions → disrupt cell walls, DNA and metabolic processes	Broad spectrum, durable, effective at low concentration	Potential nanoparticles release, environmental concerns	El-Naggar et al., 2022
	Quaternary ammonium compounds (QACs)	Cationic groups bind to cell membranes → cell-lysis	Cost-effective, strong antimicrobial action	Reduced effectiveness on soiled fabrics, some toxicity concerns	Gao & Cranston, 2020
	Triclosan	Inhibits fatty-acid synthesis in bacteria	Historically effective	Regulatory restrictions due to resistance and toxicity	Dhawan & Kaur, 2021
	Chitosan	Poly-cationic biopolymer disrupts microbial membranes	Biodegradable, non-toxic, renewable	Moderate durability unless crosslinked	Zikeli, 2020
Antibacterial – Natural Agents	Plant extracts (neem, tea tree, aloe, etc.)	Bioactive phytochemicals disrupt bacterial function	Renewable, consumer-preferred, eco-friendly	Low wash durability; instability under UV	Joshi et al., 2019

The antibacterial finishes used in functional textiles can be broadly categorized into synthetic chemical agents and natural bio-based agents, each offering distinct mechanisms and performance characteristics. Among chemical agents, silver nanoparticles (AgNPs) remain one of the most widely researched and applied due to their broad-spectrum antimicrobial activity achieved through the controlled release of Ag^{+} ions, which disrupt bacterial membranes, metabolic pathways and DNA (El-Naggar et al., 2022). Although highly effective, their application raises concerns related to nanoparticle release and environmental persistence. Similarly, quaternary ammonium compounds (QACs) act through strong cationic interactions with bacterial cell membranes, providing cost-effective and rapid antimicrobial performance; however, their activity may diminish on heavily soiled textiles and they pose certain human and ecological toxicity concerns (Gao & Cranston, 2020). Traditional agents like triclosan once offered high efficacy, but increasing evidence linking them to antibiotic resistance and ecological harm has led to regulatory restrictions, limiting their use in modern textile finishing (Dhawan & Kaur, 2021).

Biopolymer-based agents such as chitosan provide a more sustainable alternative, relying on their poly-cationic structure to disrupt microbial cell membranes. Their biodegradability and biocompatibility make them particularly attractive for eco-conscious applications, although their durability is moderate unless incorporated via cross linking or hybrid finishing systems (Zikeli, 2020). In contrast, natural plant-derived extracts, including neem, tea tree oil and aloe offer antimicrobial activity through diverse phytochemicals. These finishes align well with consumer preference for natural, non-toxic products but typically suffer from low wash durability and potential instability under UV light (Joshi et al., 2019).

While synthetic agents offer strong and durable antimicrobial activity, they often raise toxicity or environmental concerns. Natural agents, although safer and more sustainable, require further advancement to improve durability and stability. These contrasts underscore the need for hybrid systems, improved binding technologies and greener chemistries as the field move towards sustainable functional textiles.

Table 2: Anti-static technologies, mechanisms, performance and limitations.

Anti-Static Technology	Mechanism	Advantages	Limitations	References
Hydrophilic Finishes	Hydrophilic polymers or softeners absorb atmospheric moisture, increasing surface	Low cost, easy application; improves moisture management and comfort.	Non-durable; loses effectiveness in low humidity; easily washed off.	Huang et al. (2021)

	conductivity and enabling charge dissipation.			
Carbon Black (CB)	CB nanoparticles form conductive pathways within coatings or fibers, enabling rapid charge dissipation.	Highly conductive, cost-effective, good mechanical reinforcement.	Difficult dispersion; darkens fabric color; may affect aesthetics.	Singh et al. (2021)
Conductive Polymers (PANI, PPy, PEDOT:PSS)	Intrinsically conductive polymers enable electron transport along polymer chains.	Lightweight, flexible, tunable conductivity, minimal color change.	Stability and adhesion challenges; moderate wash durability.	Al-Qudah et al. (2023); Sharma et al. (2023)
Metallic Fibers (Stainless Steel, Copper, Silver)	Metallic fibers provide inherent conductivity, enabling permanent dissipation of static charge.	Excellent, long-lasting conductivity; unaffected by humidity or washing.	High cost; may reduce softness; potential corrosion for some metals.	Mughal et al. (2022)
Carbon Fibers / Conductive Fiber Blends	Conductive fibers blended with synthetics create permanent anti-static pathways.	High durability; intrinsic conductivity; stable after washing.	May stiffen fabric; cost depends on fiber ratio.	Wang & Hauser (2020)
Carbon Nanotubes (CNTs), Graphene, Ag Nanowires	Form nanoscale conductive networks with high electron mobility on or within fibers.	High conductivity at low loading; lightweight; multifunctionality potential.	High cost; dispersion challenges; wash durability varies.	Khan et al. (2022)
Ionic Liquids / Quaternary Ammonium Salts	Provide mobile ions that increase surface conductivity on fibers.	Effective at low concentrations; easy to apply via padding or coating.	Poor wash durability; may migrate or leach out.	Shamsi et al. (2021)
Plasma Treatment (Low-Temperature Plasma)	Introduces polar and oxygen-containing groups onto fiber surfaces, increasing moisture regain and improving	Eco-friendly; enhances durability of subsequent finishes; no chemical wastewater.	Requires specialized equipment; effects may diminish over time without topcoats.	Černáková et al. (2018); Kandhavadivu et al. (2023)

	adhesion of conductive agents.			
In-Situ Polymerization	Conductive monomers (e.g., pyrrole, aniline) are polymerized directly on textile surfaces to form uniform conductive layers.	Strong adhesion, uniform coating, good conductivity.	More complex processing; stiffness may increase; durability varies.	Al-Qudah et al. (2023)
Surface Coating (General Method)	Coating of conductive agents onto fiber surfaces (CB, CPs, ionic salts).	Versatile; suitable for most fabrics; scalable with pad-dry-cure.	Wash-off is common unless binders or plasma pretreatment are used.	Patnaik et al. (2020)
Fiber Blending (General Method)	Conductive fibers (metallic, carbon, bicomponent) incorporated directly into yarn structure.	Permanent conductivity; unaffected by washing; ideal for workwear and ESD garments.	Higher cost; may affect comfort or drape.	Al-Qudah et al. (2023)
Conductive Polymers (PANI, PPy, PEDOT:PSS)	Intrinsically conductive polymers enable electron transport along polymer chains.	Lightweight, flexible, tunable conductivity, minimal color change.	Stability and adhesion challenges; moderate wash durability.	Al-Qudah et al. (2023)
Metallic Fibers (Stainless Steel, Copper, Silver)	Metallic fibers provide inherent conductivity, enabling permanent dissipation of static charge.	Excellent, long-lasting conductivity; unaffected by humidity or washing.	High cost; may reduce softness; potential corrosion for some metals.	Mughal et al. (2022)

Anti-static finishes for textiles rely on different mechanisms to mitigate electrostatic charge accumulation, an issue particularly common in synthetic fibers such as polyester and nylon. Table 2 above highlights four primary technological approaches, each varying in durability, efficiency, cost and environmental impact.

Hydrophilic anti-static finishes operate by increasing the moisture content on the fiber surface, enabling the dissipation of electrical charges. These finishes are simple to apply and cost-effective, making them suitable for mass-market applications. However, their effectiveness is inherently dependent on ambient humidity and they exhibit poor durability during laundering, limiting their use in long-term or high-performance products (Huang et al., 2021).

In contrast, conductive additive technologies such as carbon black, metallic nanoparticles and conductive polymers like PEDOT:PSS, work by forming conductive pathways that actively neutralize static charges. These materials offer high efficiency and tunable electrical properties, making them suitable for advanced applications including smart textiles and technical apparel. Nevertheless, the incorporation of conductive additives may alter fabric softness or flexibility while the cost can vary widely depending on the material used (Song et al., 2022).

More permanent anti-static performance is achieved through fiber-blending approaches, where stainless steel or carbon fibers are integrated directly into the textile structure. These fibers impart intrinsic conductivity that does not wash off, providing excellent long-term durability. However, such blends can compromise the softness and drape of the fabric and often increase production costs, restricting their use to specialized sectors such as protective clothing and industrial uniforms (Wang & Hauser, 2020).

The final category, plasma treatments, introduces polar functional groups onto fiber surfaces using low-temperature plasma, enhancing surface conductivity without adding chemicals. This method aligns well with sustainable textile processing due to its low environmental impact and absence of chemical residues. Despite these benefits, plasma finishing requires specialized equipment and may be less accessible for small-scale manufacturers (Černáková et al., 2018).

Overally, the summarized evidence reflects a progression from low-cost, short-term solutions towards more durable and sustainable anti-static technologies. The trade-offs between efficiency, durability, environmental impact and fabric aesthetics remain central considerations in selecting appropriate anti-static finishes for different textile applications.

Table 3: Mechanisms and application methods.

Application Method	**Mechanism**	**Advantages**	**Cost**	**Limitations**	**References**
Pad–Dry–Cure (PDC)	Finishing chemicals	Highly compatible with	Low cost due to	Moderate durability;	Jain et al. (2020);

	and binders are applied using padding, followed by drying and curing to crosslink or polymerize functional agents onto the fiber surface.	large-scale industrial production; effective for many finishes (antibacterial, hydrophilic anti-static, flame retardant); good adhesion of chemical finishes.	established machinery and simple processing.	finishes may lose efficacy after repeated washing due to bond hydrolysis or abrasion; may cause fabric stiffness or reduced breathability; higher energy and chemical demand.	Patnaik et al. (2020)
Sol–Gel Coating	Metal alkoxides undergo hydrolysis and condensation to form inorganic–organic hybrid networks (e.g., silica matrices) that uniformly anchor nanoparticles or active compounds to the fabric.	Very high efficacy; excellent wash durability; can provide multifunctionality (antibacterial + UV protection + antistatic); uniform nanoparticle dispersion; controlled release possible.	Higher cost due to specialized precursors and the need for precise pH and process control.	High durability due to strong chemical bonding; minimal wash-off; slower processing; more complex formulation; higher raw material cost.	Tylkowski et al. (2021)
Microencapsulation	Active compounds (e.g., fragrances, plant extracts, PCMs) are enclosed in polymer microcapsules that release their contents	High efficacy for controlled-release applications; protects sensitive actives from degradation; ideal for odor control, antibacterial actions, thermoregulatio	Moderate to high due to capsule synthesis and specialized application techniques.	Variable durability; microcapsules may rupture or detach during laundering or abrasion; high concentrations may alter fabric handle	Rai et al. (2022)

	gradually via rupture, pressure, friction, or temperature.	n, and insect repellency.		or texture.	

Table 3 above highlights three major application techniques: Pad-Dry-Cure (PDC), Sol–gel coating and Microencapsulation showing the diverse mechanisms and performance characteristics that determine their suitability for specific functional textile applications. The PDC method remains the most widely adopted industrial process due to its simplicity, low operational cost and compatibility with continuous production systems. It is effective for applying a broad range of finishes including antibacterial and hydrophilic anti-static agents (Jain et al., 2020) . However, its durability largely depends on the chemical nature of the finish and the curing conditions with many PDC-applied treatments showing reduced performance after repeated laundering due to surface abrasion or chemical bond degradation (Patnaik et al., 2020)

In contrast, Sol–gel technology offers a more advanced and durable finishing approach. By forming inorganic–organic hybrid networks that firmly anchor functional nanoparticles or active compounds, Sol–gel coatings provide superior wash fastness, strong surface adhesion and the capacity for multi functionality (such as combining antimicrobial, UV-protective and anti-static effects). Despite its higher cost and more complex process requirements, Sol–gel technology is especially valuable where long-term performance is critical (Tylkowski et al., 2021).

Rai et al. (2022) assert that microencapsulation represents a complementary strategy that excels in controlled-release applications. By enclosing active compounds in polymeric microcapsules, this technique enables sustained or stimuli-responsive delivery of functionalities such as fragrance, antibacterial agents and thermo regulation. While microencapsulation enhances product longevity and protects sensitive bioactive components, its durability may diminish over repeated washing and high capsule concentrations may affect the fabric.

Overally, these three finishing methods reflect a trade-off between cost, durability, functionality and processing complexity. Their selection in industrial practice depends on the targeted performance requirements and sustainability considerations of modern smart textile applications.

3. CRITICAL ASSESSMENT OF SMART TEXTILE FINISHING TECHNOLOGIES

The functional efficacy of smart textile finishes odor control, antibacterial and anti-static depends on the interplay between their chemical/physical mechanisms, application methods and durability under practical conditions. Standardized evaluation and testing provide crucial insights into how these finishes perform, but several trends and limitations emerge when comparing different approaches.

a. Odor-control finishes

Odor-control textiles typically employ absorption, antimicrobial or catalytic degradation mechanisms to neutralize malodorous compounds. Dynamic headspace GC–MS and sensory panel evaluations indicate that adsorptive finishes such as cyclodextrins and activated carbon are highly effective at short-term odor removal while antimicrobial coatings prevent odor formation by inhibiting bacterial growth (Jain et al., 2020). However, durability remains a significant limitation. Instrumental studies show that repeated laundering reduces the effectiveness of adsorptive finishes due to the desorption of odor molecules and loss of active sites (Patnaik et al., 2020). Moreover, sensory evaluation often highlights discrepancies between perceived and instrumental odor reduction, indicating that human perception and environmental factors (humidity, temperature etc) are not fully accounted for in standard tests. This suggests a gap in long-term and real-world evaluation, particularly for wearable textiles used in active or healthcare settings (Møllebjerg et al. 2021)

b. Antibacterial finishes quantitative (AATCC 100, JIS L 1902) and qualitative (AATCC 147) tests consistently show that chemical antibacterial agents such as silver nanoparticles and quaternary ammonium compounds achieve high bacterial reduction (>99%) under controlled laboratory conditions (Rai et al., 2022). Natural antibacterial agents which include plant extracts and chitosan exhibit moderate efficacy but poor wash durability limits their practical application (Zikeli, 2020). Despite the rigor of standard tests, current evaluation methods often fail to simulate mechanical stress, perspiration or repeated laundering which can drastically reduce real-world efficacy. In addition, most antibacterial assays focus on model bacteria (S. aureus, E. coli), neglecting clinically relevant or mixed microbial populations thus creating a gap in understanding broad-spectrum performance in realistic environments (Gao & Cranston, 2020).

c. Anti-static finishes, these rely on hydrophilic polymers, conductive additives, fiber blending or plasma treatment to dissipate electrical charges. Surface resistivity and chargedecay measurements (AATCC 76, AATCC 134, IEC 61340-2-3) indicate that metallic fibers and conductive nanomaterials provide superior conductivity and wash durability compared to surface-applied hydrophilic finishes (Singh et al., 2021). According to Kandhavadivu et al., (2023), plasma-treated fabrics show improved adhesion of conductive coatings and environmental compatibility. Nonetheless, many studies report that surface coatings, ionic liquids and polymer-based coatings lose efficiency after multiple washes, highlighting a critical gap in durability assessment. Furthermore, most evaluation focuses on electrical performance under standard lab conditions, without considering real-world factors such as humidity variation, friction, or long-term wear, which can alter anti-static behavior (Mughal et al. (2022).

4. INSIGHTS AND GAPS

A comparison of finishing technologies reveal several key trends:

a. Efficacy versus durability trade-off - chemically intensive finishes (e.g., silver nanoparticles, conductive metals etc) achieve high initial performance but may raise cost, environmental and safety concerns. Natural or physically adsorptive approaches are safer and more sustainable but suffer from limited wash durability (Rai et al., 2022)

b. Testing limitations - most standard methods assess single performance metrics under controlled laboratory conditions, rarely combining mechanical stress, repeated laundering, environmental conditions or multi-functional performance in a single evaluation (Patnaik et al., 2020).

c. Human-centric gaps - for odor control and comfort-related finishes, sensory evaluation is often underrepresented, despite being critical for end-user satisfaction. Current methods may not capture the dynamic interaction between textiles, sweat, microbiota and ambient conditions (Jain et al., 2020).

d. Need for integrated evaluation frameworks - comprehensive testing should combine instrumental, microbiological, electrical and sensory methods, coupled with durability simulation to better reflect real-world performance. Emerging methods such as long-term wear trials, simulated perspiration chambers and combined mechanical/laundry stress testing are recommended to close these gaps (Kandhavadivu et al., 2023).

While existing evaluation methods provide robust comparative data for smart textile finishes under laboratory conditions, there is a consistent gap in assessing durability, multi-functionality, and real-life performance, particularly for combined odor-control, antibacterial and anti-static textiles. Addressing these gaps requires integrated testing protocols that consider environmental conditions, mechanical stress, human perception and repeated laundering, allowing for more accurate predictions of long-term functionality and consumer satisfaction.

Table 4: **Environmental and safety considerations.**

Finish Type	Environmental/Safety	Eco-Friendly Alternatives	Regulatory/Standards Guidance	References
Heavy-Metal-Based Antibacterial (Ag, Cu, Zn)	Release into wastewater → ecotoxicity, bioaccumulation; potential skin exposure	Plant-based antimicrobials, chitosan, cyclodextrins	REACH restrictions on hazardous substances; OEKO-TEX® Standard 100 ensures safe levels	Khan et al., (2022) Rai et al., (2022)
Formaldehyde-Releasing Finishes	Carcinogenic, irritant; occupational and consumer health risks	Low-formaldehyde or formaldehyde-free cross linkers; enzymatic finishing	OEKO-TEX® Standard 100; blue sign® standard	Pathak & Hegde (2025).
PFAS-Based Water/Oil Repellency	Persistent organic pollutants (POPs); bioaccumulative; difficult to degrade	Fluorine-free water/oil repellent finishes; bio-based hydrophobic coatings	ZDHC MRSL; REACH	Choudhury et al., (2020)
VOC Emissions	Air pollution; occupational exposure during curing and finishing	Low-VOC finishing formulations; water-based dispersions	Local occupational safety regulations; OEKO-TEX®	Sharma (2024)
Nanoparticles (Ag, TiO_2, ZnO)	Potential aquatic toxicity; unknown long-term skin exposure	Biopolymer encapsulation; plant-based nanoparticles; green synthesis methods	REACH; OEKO-TEX® Standard 100	Sharma (2024)
Conventional Conductive Agents (metallic fibers, CB)	High energy consumption during production; potential corrosion of metallic fibers	Conductive polymers (PANI, PEDOT) derived from renewable precursors; carbon-based	ZDHC; OEKO-TEX® Standard 100	Al-Qudah et al., 2023

		nanomaterials		
Wastewater from Textile Finishing	Residual chemicals, dyes, nanoparticles, heavy metals → water pollution	Closed-loop water recycling, bioremediation, advanced treatment (membranes, oxidation)	REACH; ZDHC MRSL; local wastewater discharge regulations	Pathak & Hegde (2025).
General Toxic Chemicals in Finishes	Skin irritation, allergenicity, occupational hazards	Enzymatic finishes; bio-based chemicals; non-toxic surfactants	OEKO-TEX® Standard 100; blue sign® standard	Rai et al., 2022

The environmental and safety assessment of smart textile finishes reveals significant challenges associated with traditional chemical agents, including heavy metals, PFAS, formaldehyde, VOC emissions and nanoparticles. These chemicals, while effective in imparting antibacterial, odor-control and anti-static functionalities, pose ecotoxicological risks, potential human health hazards and regulatory compliance challenges (Al-Qudah et al., 2023). To mitigate these impacts, industry is increasingly adopting bio-based, biodegradable and enzymatic alternatives as well as sustainable conductive materials, fluorine-free repellents and advanced wastewater treatment technologies. Standards and certifications such as REACH, OEKO-TEX® Standard 100, bluesign® and ZDHC MRSL guide manufacturers in producing safer and environmentally responsible textiles. Despite these advances, a critical gap remains in the systematic evaluation of long-term environmental fate, nanomaterial release and life-cycle impacts, highlighting the need for integrated assessments that balance performance, durability and sustainability (Sharma 2024).

5. CHALLENGES AND FUTURE TRENDS

While significant progress has been made in smart finishes, several challenges remain. Addressing these challenges and leveraging emerging technologies will shape the future of functional textiles.

a. Balancing functionality with sustainability

One of the foremost challenges is to develop high-performance finishes that are simultaneously sustainable. Often, the most effective functional finishes (e.g., certain fluorocarbons for water repellency and heavy metal-based antimicrobials) pose environmental or health risks (Rai et al., 2022). The quest for eco-friendly alternatives often involves trade-offs in terms of performance, cost and durability. Future research must focus on green chemistry principles, designing finishes that are inherently less toxic, biodegradable, produced from renewable resources and use less energy and water in their application (Pathak & Hegde 2025).

b) Development of hybrid multi-functional finishes

The demand for textiles with multiple functionalities is growing particularly in sportswear, healthcare and protective clothing. Instead of applying individual finishes which can compromise fabric properties and increase production costs, the trend is towards single-step multi-functional finishes. For instance, a finish that combines silver nanoparticles (antibacterial, anti-odor) with a hydrophilic polymer (anti-static) or a microencapsulated essential oil with inherent antimicrobial and anti-odor properties (Choudhury et al., 2020). In light of the above, developing synergistic systems where different components work together to provide comprehensive protection is key. This requires careful selection of compatible agents and optimized application methods to ensure durability and retain desired fabric aesthetics.

6. ADVANCES IN NANOTECHNOLOGY, MICROENCAPSULATION AND BIO-FINISHING

Recent researches (Choudhary et al., 2021) , highlight nanotechnology, microencapsulation and bio-finishing as key frontiers for enhancing smart textile functionality while addressing durability, safety and sustainability challenges.

According to Gao and Cranston (2020), nanotechnology is rapidly advancing the performance of smart textiles. Novel nanomaterials including functionalized graphene, metal-organic frameworks (MOFs) and MXenes offer tailored properties for antimicrobial, odor-control, UV-protective and anti-static applications. Improved dispersion techniques and robust anchoring methods, such as embedding nanoparticles in Sol-gel matrices or polymer networks, enhance durability and reduce environmental release (Sharma, 2025). However, the potential toxicity, bioaccumulation and lifecycle impacts of nanoparticles remain critical considerations for large-scale adoption.

On the other hand, microencapsulation technology enables controlled or stimuli-responsive release of active agents, enhancing the longevity and functionality of smart finishes (Sharma, 2025.Innovations focus on environmentally friendly shell materials (e.g., bio-based polymers), responsive triggers (pH, temperature, light) and the encapsulation of diverse actives including fragrances, antimicrobials or phase change materials (PCMs) for thermal regulation. However, according to Choudhary et al., (2021), recent developments in self-healing microcapsules provide the potential for prolonged durability and maintenance-free textiles.

Bio-finishing approaches leverage enzymes, microbial synthesis and plant-derived compounds to achieve functionalization while reducing environmental impact. Enzyme-assisted finishes enable fiber-specific modifications under mild conditions whereas engineered microbes can produce functional molecules such as antimicrobial peptides (Zikeli, 2020). A wider range of plant extracts is also being explored for sustainable odor control, antibacterial and UV-protective properties (Rai et al., 2022). The challenges include standardizing performance ensuring industrial scalability and maintaining cost-effectiveness.

7. NEXT-GENERATION SMART AND RESPONSIVE TEXTILES

The vision for next-generation smart textiles moves beyond passive finishes towards actively responsive garments.

Key developments include:

a. Thermochromic materials, these are fabrics that change color in response to temperature fluctuations, enabling visual feedback for thermal comfort (Gao & Cranston, 2020).

b. Phase change materials (PCMs), these are microencapsulated PCMs which absorb or release heat to regulate body temperature, providing dynamic thermal management (Choudhary et al., 2021).

c. Sensors and actuators, the integration of conductive threads, electroactive polymers and smart polymers allows fabrics to sense environmental parameters such as humidity, pollutants or UV exposure and respond accordingly (Al-Qudah et al., 2023).

d. Electroactive polymers, these enable wearable electronics, shape-changing textiles and responsive actuation for smart garments (Shamsi et al., 2021).

e. Self-cleaning and self-healing textiles, the surfaces are engineered to shed dirt, resist stains or repair minor mechanical damage thereby increasing lifespan and reducing maintenance ((Alongi & Malucelli, 2019).

These advances require interdisciplinary collaboration between textile chemistry, materials science, nanotechnology, biotechnology and electronics. The integration of these domains is critical for the development of truly intelligent garments that combine functionality, comfort, durability and environmental responsibility (Kandhavadivu et al., 2023).

8. CONCLUSION

The advancement of smart and functional textile finishes has transformed modern apparel, work-wear and healthcare textiles by addressing consumer demands for odor control, antibacterial properties and anti-static performance**.** This review highlights that chemical, natural and hybrid finishing technologies**,** applied via methods such as pad-dry-cure, sol-gel coating, microencapsulation, fiber blending and plasma treatment, offer varied efficacy, durability, and cost profiles. While conventional chemical agents provide high functional performance, their environmental footprint and potential health risks underscore the importance of sustainable alternatives. Bio-based, enzymatic and nanotechnology-driven solutions demonstrate promise for eco-friendly, durable, and multifunctional textiles, although challenges remain in wash durability, industrial scalability and cost-effectiveness (Khan et al., 2022).

The evaluation and testing methods including antibacterial assays, odor absorption tests, surface resistivity measurements and wash durability protocols play a pivotal role in assessing the performance and longevity of smart finishes. However, standardized testing protocols remain inconsistent and long-term studies on environmental and human safety are limited, revealing a critical gap in the literature (Jain et al., 2020).

Future developments are likely to focus on nanotechnology, microencapsulation and bio-finishing**,** integrated with responsive and adaptive functionalities such as thermochromic, phase-change thermal regulation and self-healing or self-cleaning properties. Interdisciplinary research combining material science, textile chemistry, biotechnology and electronics is essential for producing next-generation smart textiles that balance high performance, comfort, durability and sustainability**.**

In summary, while smart textile finishes have made remarkable progress in enhancing textile functionality, their holistic evaluation including performance, durability, safety and environmental impact is critical for guiding research, industry adoption and regulatory compliance. The integration of eco-friendly materials, innovative application methods and responsive functionalities represents the path forward for sustainable, intelligent textile solutions.

9. RECOMMENDATIONS

Future research should prioritize the following areas:

9.1. Development of multi-functional and sustainable finishes focusing on creating single systems that deliver multiple properties (odor control, antibacterial, anti-static) using non-toxic, biodegradable or bio-renewable materials, applied through eco-efficient processes.

9.2. Enhanced durability and wash fastness by investigating novel binding mechanisms, encapsulation techniques and surface modification strategies (e.g., advanced plasma treatments, covalent grafting) to ensure the longevity of functional properties over repeated laundering and wear.

9.3. Ecotoxicological assessment, by conducting thorough lifecycle assessments and toxicological studies for new finishing agents, especially nanomaterials to ensure safety throughout their entire lifecycle, from production to disposal.

9.4 Scalable and cost-effective solutions, this is done through the translation of laboratory-scale innovations into industrially viable and economically competitive processes through continuous improvement of existing methods or development of novel high-throughput techniques.

9.5 Integration with smart textile systems, explore seamless integration of functional finishes with sensing, actuation and communication technologies to pave way for next-generation smart and responsive clothing that can monitor health, adapt to environments and provide enhanced user experiences.

By addressing these recommendations, the textile industry can continue to advance towards a future where clothing is not only fashionable and comfortable but also intelligent, protective and environmentally responsible.

10. REFERENCES

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