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A REVIEW OF INNOVATIVE SELF-CLEANING, ANTIMICROBIAL AND ODOUR-RESISTANT SURFACE TECHNOLOGIES FOR AUTOMOTIVE INTERIORS.

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ABSTRACT

The growing demand for improved material performance, hygiene and sustainability in modern vehicles calls for the integration of advanced textile technologies into automotive interiors. This review article examines recent technical advances in self-cleaning, antimicrobial and odor-resistant fabric systems specifically designed for vehicular environments. The various functional mechanisms enabling these properties are evaluated, including photocatalytic and superhydrophobic surface engineering for self-cleaning, silver nanoparticles and quaternary ammonium compounds for antimicrobial protection and activated carbon and cyclodextrins for odor absorption. Automotive-specific performance requirements are discussed, with an emphasis on durability, long-term functional stability and improved occupant safety. Despite significant advances, challenges remain such as maintaining efficacy under harsh automotive conditions, ensuring material non-toxicity, achieving cost-effective large-scale manufacturing and complying with regulations. The review concludes by identifying key research gaps and future development opportunities for sustainable, scalable and multifunctional fabrics, including bio-based functional materials, smart and responsive textile systems with advanced coating technologies, which accelerate the development of durable, multifunctional and environmentally friendly automotive interior fabrics.

KEYWORDS: Automotive interiors, self-cleaning surface technologies, antimicrobial coatings, odor-resistant materials, nanotechnology, smart and sustainable fabrics.

1.INTRODUCTION

The growing demand for comfort, hygiene and sustainability in modern vehicles has driven the development of advanced textile materials for automotive interiors. Beyond aesthetics and tactile quality, contemporary consumers increasingly expect interior fabrics to be stain-resistant, inhibit microbial growth and neutralize unpleasant odors, thereby improving overall driving comfort and passenger well-being (Mahltig, 2025). In response, researchers and manufacturers have explored multifunctional textiles that incorporate self-cleaning, antimicrobial and odor-resistant properties by integrating nanotechnology, surface modification and bio-based chemical finishes. These innovations not only contribute to improved hygiene and durability but also align with the global transition toward environmentally friendly and durable materials (Bibi, 2024). Despite these advances, challenges remain in achieving lasting performance under various environmental and mechanical stresses, ensuring non-toxicity and maintaining profitability in mass production. Therefore, this review aims to analyze advances in self-cleaning, antimicrobial, and odor-resistant textiles for automotive interiors, highlight vehicle-specific mechanisms, materials, and applications, and identify research gaps and future sustainable and scalable avenues that support durable, multifunctional, and environmentally friendly automotive textiles.

2. SELF-CLEANING TEXTILE TECHNOLOGIES FOR AUTOMOTIVE INTERIORS

Self-cleaning textiles possess the remarkable ability to remove dirt, stains and even degrade organic contaminants without external intervention, reducing maintenance and improving aesthetics. For automotive interiors, this translates into cleaner seats, headliners and door panels, crucial for maintaining a high-quality and hygienic feel. The main mechanisms explored for self-cleaning properties include photo-catalysis and super-hydrophobicity/omniphobicity (Atwah et al., 2023).

2.1 Self-cleaning mechanisms

Photo catalytic (TiO_2, ZnO nanocoatings)

Photo catalysis employs semiconductor nanoparticles, particularly titanium dioxide (TiO_2) and zinc oxide (ZnO), which, upon exposure to ultraviolet (UV) light, generate reactive oxygen species (ROS) such as hydroxyl radicals (OH) and superoxide anions (O_2^-). These highly oxidative species can effectively degrade organic pollutants, odors and environmental contaminants into simpler, nontoxic compounds such as carbon dioxide (CO_2) and water (H_2O) (Baig, 2025).

In self-cleaning textile applications, photo catalytic properties of TiO_2 and ZnO are leveraged to oxidize organic soils, volatile organic compounds (VOCs) and microbial debris on fabric surfaces under illumination (Mushtaq et al., 2024). TiO_2 is widely used for its chemical stability and low toxicity while recent studies have focused on improving its response to visible light through doping and compound formation, enabling effective photo catalysis beyond the UV spectrum (Ghamarpoor et al., 2024). These advances are especially significant for self-cleaning textile coatings and fabrics where durability, antimicrobial activity and environmental sustainability are critical for practical applications.

Functional mechanisms

Photo catalysis works by exciting semiconductor nanoparticles primarily titanium dioxide (TiO_2) and zinc oxide (ZnO) under ultraviolet (UV) light. This excitation promotes electrons (e^-) movement from the valence band to the conduction band, creating electron-hole pairs (h^+). These reactive species interact with absorbed water and oxygen to generate reactive oxygen species (ROS) such as hydroxyl radicals (OH) and superoxide anions (O_2^-) which are capable of degrading organic contaminants on textile surfaces (Ghamarpoor et al., 2024).

Materials composition

The anatase form of TiO_2 and ZnO nanoparticles is commonly used in textile applications due to their photo catalytic properties. These nanoparticles can be applied to textile fibers using various methods, including sol-gel processes, dip coating, spraying, and plasma treatments (Pant et al ,2019). Improvements in photo catalytic activity have been achieved by doping with noble metals (e.g., Ag, Au) or non-metals (e.g., N, C) which extend their activity to the visible light spectrum, a crucial factor for indoor applications where UV light is limited (El Samra & Sayed, 2024).

Automotive applications

In automotive interiors, photo catalytic textiles are applied to components such as seats, headliners and carpets to address issues such as food spills, sweat stains and volatile organic compounds (VOCs) that contribute to odors. UV light transmitted through car windows can activate these photo catalytic materials which facilitates the degradation of organic pollutants and VOCs. This maintains a cleaner and more pleasant interior environment (Huang et al., 2016).

2.2 Super hydrophilic and Super hydrophobic/Omni phobic self-cleaning

a. Surface texturing and low surface-energy chemicals for self-cleaning textiles

Surface texturing combined with low-surface-energy chemicals enables super hydrophobicity, where rolling droplets remove particulate dirt (the lotus effect) or super hydrophilicity where the sheet of water facilitates cleaning. These strategies have proven effective in the laboratory. However, maintaining durability, particularly resistance to abrasion and repeated flexing in automotive applications remains a significant challenge (Hao et al., 2025).

Super hydrophilic self-cleaning mechanism

Super hydrophilic self-cleaning often accompanies photo catalysis. Following the degradation of organic matter by a photo catalyst, the surface becomes highly hydrophilic, allowing water to distribute evenly and remove inorganic residues such as dust and dirt. This washing effect prevents residue buildup and has been tested in textile applications (Pakdel et al., 2025).

Super hydrophobic and Omni phobic self-cleaning

Super hydrophobic surfaces are characterized by a water contact angle (WCA) greater than 150° and a low sliding angle due to the lotus effect. They are created by combining surface roughness including nanoparticles and etched structures with low-surface-energy materials (fluorocarbons, silicones, waxes). Water droplets accumulate to form spheres and slide off as they collect dirt particles in the process (Zhang et al., 2024).

Omni phobic surfaces extend this repellency to oils and other low-surface-tension liquids which make them highly resistant to a wider variety of automotive spills. Recent advances have focused on improving the durability and mechanical stability of these coatings to withstand the harsh conditions of automotive environments (Liu et al., 2025).

Functional mechanisms

The hierarchical micro and nano-scale roughness of surfaces trap air pockets beneath water droplets which minimize the contact area between the liquid and the solid surface, thereby giving them extreme repellency. This is known as the lotus effect (Latthe et al., 2014).

Materials composition

Fluorinated polymers such as polytetrafluoroethylene (PTFE), perfluoropolyethers, silicones, silica nanoparticles, carbon nanotubes and various waxes are commonly used to achieve super hydrophobicity (Barthwal et al., 2024). However, challenges remain regarding the durability of these coatings against abrasion, washing and UV degradation, as well as environmental concerns related to persistent fluoro-chemicals (PFCs) (Latthe et al., 2014).

Automotive applications

Super hydrophobic coatings are ideal for automotive components such as upholstery, floor mats and trunk liners since they resist liquid spills (e.g., coffee, beverages), mud and dirt. These coatings significantly reduce the need for manual cleaning and protect against permanent staining (Bai et al., 2021).

3. Antimicrobial textile technologies for automotive interiors

Automotive interiors are environments where microorganisms such as bacteria, fungi and viruses can proliferate, especially on frequently touched surfaces and in moist conditions caused by spilled liquids or high humidity. This microbial growth can lead to unpleasant odors, material degradation and potential health risks. Antimicrobial textiles aim to inhibit or eliminate these microorganisms on contact, thereby providing a hygienic environment (Arese et al., 2024).

Recent studies have focused on improving the durability and environmental safety of antimicrobial textiles in automotive applications. For instance, controlled fixation methods have been developed to reduce leaching of antimicrobial agents to mitigate potential environmental impacts (Arese et al., 2024). Additionally, advances in biosynthesis methods have been explored to produce eco-friendly antimicrobial textiles with effective properties (Bibi et al.,2024). These developments are particularly relevant to automotive interiors where antimicrobial textiles can be applied to seats, armrests, steering wheel covers and door panels to reduce microbial growth, common sources of odors and potential allergens. However, there remain concerns about the durability and environmental impact of antimicrobial agents, which calls for further research into sustainable applications (Arese et al., 2024).

3.1 Metallic nanoparticles in antimicrobial textiles

a. Silver nanoparticles (AgNPs)

Silver has long been recognized for its antimicrobial properties. AgNPs release silver ions (Ag^+) which interact with bacterial cell walls, disrupt membrane functions, inhibit enzymatic activity and interfere with DNA replication, ultimately leading to cell death (Rai et al., 2009). Recent studies have focused on improving the durability and environmental safety of AgNPs in textiles. A good example is where controlled fixation methods reduce silver loss and mitigate environmental impact (Hamad et al., 2025).

Functional mechanisms

AgNPs have a high surface-to-volume ratio which enhance their antimicrobial activity. Ag^{+} ions are the primary active species responsible for disrupting microbial cell structures (Hamad et al., 2025).

Materials composition

AgNPs can be added into textile fibers during spinning, being applied as coatings or synthesized in-situ in the fabric. Advances in biosynthesis methods have been explored to produce environmentally friendly AgNPs with effective antimicrobial properties (Bibi et al., 2024).

Automotive applications

AgNPs are effective in seats, armrests, steering wheel covers and door panels to reduce the growth of bacteria and fungi, common sources of odors and allergens. However, there are concerns in regard to the leaching of AgNPs and their environmental toxicity, enabling the embracing of sustainable strategies (Hamad et al., 2025)

b) Copper and copper oxide nanoparticles (CuNPs, CuONPs)

Copper has a broad-spectrum of antimicrobial properties as shown by its ability to destroy cell membranes, generating reactive oxygen species (ROS) and denaturing proteins (Borkow and Gabbay, 2009). Recent studies have summarized the antibacterial properties of CuONPs focusing on mechanisms, modification methods and textile applications (Gudkovn et al., 2024).

Functional mechanisms

Like silver, when copper ions (Cu^{2+}) are released, they cause oxidative stress and cellular damage in microorganisms (Gudkov et al., 2024).

Materials composition

CuNPs and CuONPs can be incorporated into textiles using methods similar to those for AgNPs. Cotton fabrics treated with CuO demonstrate antimicrobial activity, UV protection and super hydrophobicity (Bibi et al., 2024).

Automotive applications

CuNPs and CuONPs offer a cost-effective alternative to silver. They are ideal for interior components such as seats, steering wheels and door panels. They provide antimicrobial protection and improve material performance (Gudkov et al., 2024).

c. Quaternary ammonium compounds (QACs)

CACs are cationic surfactants widely used as disinfectants and sanitizers. When grafted onto textile surfaces, they act as contact antimicrobial agents (Mali et al., 2024). Recent studies highlight the potential of CAC-based coatings for rapid antiviral and antibacterial functionalization of textiles, demonstrating their durability and efficacy (Meier et al., 2023).

Functional mechanisms

Positively charged CAC molecules bind to negatively charged microbial cell membranes, disrupting their integrity and causing leakage of cellular contents which result in cell death. According to Meier et al., (2023), chemically bonded CACs minimize leaching which enable long-lasting antimicrobial activity.

Materials composition

The most common QACs is a 3-(trimethoxysilyl) propyldimethy-loctadecyl ammonium chloride (ODS-QAC), which is applied by grafting or quilting onto textile surfaces (Meier et al., 2023).

Automotive applications

QAC functionalized textiles are ideal for high-touch surfaces such as steering wheels, gear shifts and seat belts as they provide persistent antimicrobial protection without significant leaching, making them suitable for automotive interiors (Meier et al., 2023).

3.2. Natural and bio-based antimicrobials for automotive textiles

a. Chitosan: a biodegradable polymer, is derived from crustacean shells. It has a broad-spectrum of antimicrobial activity. Its poly-cationic nature allows it to interact with negatively charged microbial cell membranes, increasing permeability and inhibiting microbial metabolic processes. Chitosan can be applied as a coating or incorporated into fibers which makes it suitable for environments with high hygiene demands such as automotive interiors (Hu et al., 2021).

b. Essential oils and plant extracts: certain essential oils such as tea tree and thyme possess antimicrobial properties as a result of complex mixtures of compounds that disrupt microbial cell membranes, inhibit enzyme activity or interfere with quorum sensing. Microencapsulation techniques are often employed to ensure controlled release and long-term efficacy in textiles, enabling their integration into automotive fabrics (Zubair et al., 2021).

4. Odor-resistant textile technologies for automotive interiors

Unpleasant odors from sweat, food spills, pets and volatile organic compounds (VOCs) negatively impact the driving experience. Odor-resistant textiles seek to neutralize, absorb or degrade these unpleasant odors, contributing to a fresher cabin environment (Czekaj, 2024).

Table 1: **Summary of odor-resistant textile technologies for automotive interiors.**

Technology	Mechanisms	Materials
Activated Carbon	Activated carbon removes VOCs and odorous molecules through physisorption on its large surface area, governed by van der Waals forces and pore structure optimization (Mishra, 2024).	Derived from biomass or polymeric precursors, activated carbon can be integrated as fibers, nonwoven composites, or coated layers to maximize adsorption performance and durability (Yuan et al., 2023).
Zeolites	Zeolites adsorb VOCs through size-selective molecular sieving and ion-exchange reactions that neutralize acidic and basic compounds (Czekaj, 2024).	Nanostructured zeolites and clinoptilolite composites are incorporated into fiber matrices or applied as coating finishes for sustainable odor adsorption (Czekaj, 2024).
Cyclodextrins (β-CD)	β-cyclodextrin traps hydrophobic odor molecules inside its internal cavity, forming inclusion complexes that prevent odor release (Tang et al., 2022).	Cross-linked or grafted onto fibers via plasma or sol–gel processes to improve wash durability and controlled odor encapsulation (Shukla et al., 2023).
Photocatalytic Degradation (TiO_2, ZnO)	Under UV or visible light, TiO_2 and ZnO generate reactive oxygen species (ROS) that oxidize VOCs into CO_2 and H_2O, decomposing odor molecules (Gunasekaran et al., 2023).	Nanostructured TiO_2/ZnO coatings and hybrid composites are applied to polyester and cotton fabrics via sol–gel and sputtering techniques for stability (Yadav et al., 2022).
Zinc Ricinoleate	Binds odor molecules via chemical complexation and neutralization without affecting perspiration (Sarchem Laboratories, 2025).	Incorporated into microcapsules or polymeric coatings compatible with textile substrates for gradual and controlled odor neutralization (Sarchem Laboratories, 2025).

Odor-resistant textile technologies for automotive interiors have evolved from simple adsorption-based systems to multifunctional nanocomposite designs that combine absorption, chemical neutralization and photo catalytic degradation. Each mechanism targets distinct odor sources such as volatile organic compounds (VOCs), microbial metabolites and organic debris, ensuring greater cabin comfort and improved air quality.

From a mechanistic perspective, absorption remains the most established pathway, with activated carbon and zeolites offering high surface area and selectivity for VOC capture.

These materials operate primarily through physical interactions such as van der Waals forces and molecular sieving. In contrast, cyclodextrins (β-CDs) use host-guest inclusion complexes to trap odor molecules within hydrophobic cavities while zinc ricinoleate neutralizes odor-causing acids and amines through ionic complexation. The most recent systems employ semiconductor oxides (TiO_2 and ZnO) that initiate photo catalytic oxidation upon exposure to light, converting VOCs into harmless byproducts such as CO_2 and H_2O.

In terms of materials development, the integration of odor control agents into fibrous structures, nanocoatings or micro encapsulated systems improve both washing efficiency and durability. For instance, β-CDs are often cross-linked or plasma-grafted onto fibers to ensure long-term functionality while TiO_2/ZnO nanoparticles are deposited using sol-gel or sputtering techniques to achieve uniform, photoactive surfaces. Furthermore, hybrid materials combining zeolites with carbon or metal nanoparticles demonstrate synergistic behavior, simultaneously improving absorption capacity and antimicrobial performance.

In automotive applications, these technologies are now being applied to multiple interior components such as seat fabrics, headliners, carpets and cabin air filters inorder to maintain odor-free and hygienic environments. The integration of textiles for odor control aligns with the automotive industry's transition toward sustainability and user well-being, as many materials such as biomass-derived activated carbon and natural mineral zeolites are environmentally friendly. Luxury and electric vehicle manufacturers are adopting multi-functional coatings that combine deodorization with antimicrobial and self-cleaning properties, improving long-term durability and reducing maintenance needs.

Overally, the synthesis of nano-structured absorbents, inclusion complexes and photo catalytic materials represents a transformative direction in automotive textile innovation. Future developments are expected to focus on smart odor-sensing and regenerative materials, enabling continuous self-purification and adaptive performance under varying environmental conditions.

Integrating multi-functional properties

Combining self-cleaning, antimicrobial and anti-odor functions in a single textile can lead to compatibility issues (e.g., coatings that impair breathing or alter color). Hybrid nanocomposites (e.g., TiO_2–ZnO–graphene with integrated antimicrobial agents) and smart, switchable surfaces show great potential. However, challenges remain regarding industrial scalability, uniform coating across large areas and maintaining the fabric's tactile properties (Richardson et al., 2022).

Table 2: Surface technologies characteristics.

Technology Type	Main Mechanism/ Material	Efficacy	Durability	Safety	Relative Cost	Key References
Photocatalytic (TiO_2, ZnO)	Degradation of organic matter under UV/visible light	High	Moderate	Safe	Medium	Bhapkar, (2024
Superhydrophobic Coatings	Lotus-effect surface structuring	Excellent	Moderate	Safe (fluorine-free)	Medium	Ge, H., et al. (2023)
Graphene-Based Films	Photothermal & conductive activity	High	High	Safe (low loading)	High	Yaragalla,(2021)
Metal Nanoparticles	Ion release & oxidative stress	Very High	Moderate	Moderate (toxic at high loadings)	Medium	Islam et al, (2014).
Bio-Based (Chitosan, Oils)	Electrostatic microbial disruption	Moderate–High	Moderate	Excellent	Low–Medium	Wu et al. (2024)
Activated Carbon / Zeolite Fibers	VOC and odor adsorption	High	High	Safe	Medium	Yuan et al. (2023)
Hybrid Bio-Inorganic	Combined photocatalytic and antimicrobial	Excellent	High	Safe (encapsulated)	Medium–High	Popescu & Ungureanu (2023)

As shown in Table 2 above, emerging textile technologies vary widely in performance, cost and environmental impact. Photo catalytic and graphene-based coatings demonstrate high efficacy and durability but remain relatively expensive while bio-based and activated carbon systems offer safer and more sustainable alternatives with moderate efficiency. Bio-inorganic hybrid composites are particularly promising as they combine the durability of inorganic materials with the bio-compatibility of natural agents. These comparative analyses highlight the importance of developing multi-functional, cost-effective and environmentally friendly coatings that can meet the demanding needs of automotive interiors.

5. Challenges and future research priorities

This section looks at how sustainability and life-cycle considerations influence the selection and optimization of advanced materials for automotive interiors.

Table 3: Material selection and optimization - life cycle and sustainability issues.

Challenge Area	Current Limitation	Findings (2020–2025)	Future Directions
Durability/Longevity	Functional coatings degrade under abrasion, UV light and thermal cycling.	TiO_2 and hybrid nanocoatings improve resistance but still lose efficacy over repeated use (Liu et al., 2025).	Develop strong adhesion binders, plasma/ALD surface engineering, and fiber-level functionalization.
Environmental Impact	Nanoparticle leaching and toxicity of persistent coatings (AgNPs, PFCs).	Biodegradable chitosan and plant-based alternatives show promise (Zhang et al., 2025).	Focus on bio-based, non-leaching coatings and full life-cycle impact analysis
Cost & Scalability	High production costs for nanomaterials and complex finishing lines.	Energy-efficient roll-to-roll and atmospheric plasma systems emerging (Mousa & Hassan, 2025).	Adopt solvent-free, low-cost deposition and scale up synthesis for industrial use.
Aesthetic & Comfort	Functional finishes alter softness, color, or breathability.	Smart and ultrathin coatings minimize tactile changes (Čorak et al., 2024).	Design adaptive, breathable nanolayers maintaining textile aesthetics.
Regulatory & Safety	Lack of unified standards for nanomaterials finishes in automotive interiors.	REACH and ISO standards addressing VOCs and biocides (Kwok et al., 2020).	Collaborate with regulators to standardize test protocols for safety and performance.

6. CONCLUSION

The development of self-cleaning, antimicrobial and odor-resistant textile technologies represents a significant advancement in improving the hygiene, comfort and longevity of automotive interiors. Photo catalysis and super hydrophobicity offer efficient self-cleaning while metallic nanoparticles, QACs and natural compounds provide robust antimicrobial protection. Odor resistance is achieved through absorption by activated carbon and cyclodextrins as well as photo catalytic degradation. The trend towards synergistic and multifunctional approaches promises comprehensive solutions to automobile interior challenges. However, widespread adoption of advanced textiles depends largely on overcoming critical obstacles related to long-term durability, environmental safety, cost-effectiveness and maintaining aesthetic appeal. Therefore, future research should focus on the development of highly durable, nontoxic sustainable materials and application methods. This may include exploring bio-inspired designs, integrating smart functionalities and conducting comprehensive life-cycle assessments. Harmonizing innovative materials science with stringent automotive industry standards and evolving environmental regulations will be key to realizing the full potential of the next-generation textiles, ultimately leading to cleaner, healthier and more comfortable driving experiences all around the world.

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