

REVIEW ARTICLE

Antimicrobial Textile Finishes: A Critical Synthesis of Efficacy, Durability and Safety

Evidence from laboratory studies and implications for applied textile design and manufacturing

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ABSTRACT

Antimicrobial textile finishes are increasingly proposed for healthcare, sportswear and hygiene applications, yet the evidence base is fragmented across chemistries, test methods and durability claims. This critical synthesis examines 10 supplied sources covering synthetic agents such as polybiguanide [1] and N-halamine [7], inorganic and metal-organic systems including sol-gel coatings [4] and HKUST-1 [3], and bio-based options such as chitosan nanoparticles [2], essential oils [5] [6], propolis and honey [8], and green-synthesised silver nanoparticles [9]. Reported antibacterial efficacy is often high, but durability varies widely: PHMB retained 100% bactericidal effect after 52 washes [1], N-halamine-treated PET maintained 80% efficacy after 50 washes [7], and silver-fibroin viscose reached 99.99% after 30 washes [9], whereas chitosan finishes showed activity after only 10 washes [2] [8]. Safety is largely inferred rather than demonstrated; no source reports systematic human skin or environmental toxicity data. The review identifies methodological heterogeneity, limited reporting of hand feel and strength trade-offs, and a gap between laboratory washing simulations and real-use conditions. Practical implications include the need for standardised durability testing, explicit reporting of mechanical and comfort penalties, and cautious communication of safety claims.

Keywords: antimicrobial textiles; durability; safety; finishing; nanoparticles; healthcare textiles

SECTION 01

Why antimicrobial finishes are difficult to evaluate

Antimicrobial textile finishes are attractive because they promise to inhibit microbial growth on fabrics used in healthcare, sportswear, food packaging and water purification [10]. The underlying rationale is straightforward: textiles provide a large surface area, moisture and nutrients that can support microbial proliferation, and a finish that either kills microorganisms or inhibits their growth may reduce odour, degradation and infection risk [10]. However, the evidence base is not a single coherent body of work. The supplied sources span synthetic biocides, inorganic nanoparticles, metal-organic frameworks and natural compounds, and they use different test organisms, inoculation methods, washing protocols and reporting units [1] [2] [3] [4] [5] [6] [7] [8] [9] [10]. This heterogeneity makes direct comparison of efficacy claims difficult and means that a headline figure such as '99.99% reduction' cannot be interpreted without knowing the test method, the contact time and the number of washes [9].

A second difficulty is that antimicrobial performance is only one of several properties that determine whether a finish is viable. The same sources that report high antibacterial activity also report penalties to hand feel, tearing strength, breaking strength, stiffness or air permeability [1] [2] [7]. For example, PHMB coating on cotton produced excellent durability but slightly negative effects on hand feel and tearing strength [1], while N-halamine treatment of PET reduced breaking strength by up to 12% [7]. These trade-offs are often reported as secondary observations rather than as primary outcomes, which limits the ability to design a finish around a specified performance envelope.

A third difficulty concerns safety. The supplied sources describe antimicrobial mechanisms and efficacy, but none reports a systematic assessment of human skin toxicity, inhalation risk, or environmental fate. Claims that natural compounds have no reported negative side effects on human skin [8] are statements about the absence of reported effects rather than evidence of safety. Similarly, the green synthesis of silver nanoparticles is presented as environmentally friendly [9], but the source does not quantify silver release, persistence or ecotoxicity. Safety therefore remains an inference from chemistry and intended use rather than a demonstrated property of the finished textile.

SECTION 02

Synthetic and regenerable chemistries: high efficacy with durability trade-offs

Synthetic antimicrobial agents dominate the more durable end of the evidence. PHMB, a polybiguanide derivative applied to cotton by pad-dry-cure, was optimised to withstand simulated healthcare laundering; the treated fabric showed 100% bactericidal effect after 52 washing cycles, with a slight reduction after 104 washes [1]. This is among the strongest durability claims in the supplied set, and it is notable that the study examined detergent effects and washing cycles in detail rather than reporting a single wash test [1]. The same study, however, found negative influences on hand feel and tearing strength, indicating that durability was achieved at a cost to other fabric properties [1].

N-halamine chemistry offers a different durability model based on regenerability. A precursor monomer was synthesised and applied to PET fabrics, which became antibacterial after chlorination, achieving 100% inactivation of *E. coli* O157:H7 and *S. aureus* [7]. After 50 wash cycles, the chlorinated fabrics maintained 80% antibacterial efficacy, and storage stability and UV irradiation tests showed regenerable properties [7]. The ability to recharge the antimicrobial function is a meaningful advantage over non-regenerable finishes, but the source also reports a breaking strength reduction within 12%, which the authors describe as satisfying for antimicrobial finishing [7]. That judgement is context-dependent: a 12% strength loss may be acceptable for some applications but not for others, and the source does not provide a benchmark against untreated controls across multiple fabric weights.

Taken together, these synthetic systems show that durable antimicrobial activity is achievable, but they also show that durability claims are protocol-dependent. The PHMB study used simulated healthcare laundering [1], while the N-halamine study used a specified number of wash cycles [7]. Neither source reports the full washing conditions in a way that would allow a manufacturer to predict performance under a different detergent, temperature or mechanical action regime. The evidence supports the principle that synthetic finishes can be durable, but it does not yet support a generalisable durability model.

SECTION 03

Inorganic and metal-organic systems: multifunctionality and fixation challenges

Inorganic finishing via sol-gel routes is presented as an environmentally friendly approach that can impart wear resistance, UV protection and antimicrobial effects in one-step applications with low concentrations of non-hazardous chemicals [4]. The review of inorganic finishing describes the synthesis of inorganic nanoparticles and nanosols from metal alkoxides or metal salts, leading to chemical or physical modification of fibre surfaces and multifunctional properties [4]. This multifunctionality is attractive for applied textile design because it addresses several performance requirements simultaneously, but the source is a review and does not provide a standardised comparison of antimicrobial efficacy across the systems it covers [4].

Metal-organic frameworks represent a more recent approach. HKUST-1, composed of copper and trimesic acid, was synthesised directly in wool fabric at 24 and 48 hour intervals to improve antibacterial properties and address the low fixation and poor durability associated with applying the MOF under the fibre surface [3]. The resulting fabrics showed antibacterial activity against *E. coli*, and were characterised by SEM, EDS, XRD, FTIR-ATR and colorimetric analysis, with antimicrobial

testing following AATCC Test Method 61-2007-2A [3]. The in-situ synthesis strategy is a reasonable response to the fixation problem, but the source reports activity against a single organism and does not report washing durability results in the abstract, so the durability claim remains to be demonstrated [3].

The contrast between these two sources illustrates a recurring theme: inorganic and metal-organic systems offer multifunctionality and potentially strong fixation, but the evidence for durable antimicrobial performance is less complete than for the synthetic organic systems discussed above. The sol-gel review emphasises process advantages [4], while the HKUST-1 study emphasises synthesis conditions and characterisation [3]. Neither provides the kind of multi-cycle, multi-organism durability data that would allow a manufacturer to specify a finish with confidence.

SECTION 04

Bio-based finishes: efficacy, variability and the durability gap

Bio-based antimicrobial finishes are widely promoted as eco-friendly alternatives, and the supplied sources cover chitosan nanoparticles, essential oils, neem oil, propolis, beeswax and honey. Chitosan nanoparticles combined with citric acid as a multifinishing formulation imparted antibacterial and easy-care characteristics to cotton, with activity against gram-positive and gram-negative bacteria even after 10 washing cycles [2]. The study also reported reasonable strength loss, comparable wrinkle recovery angles, higher fabric stiffness and suitable durability, and identified a finishing mechanism [2]. A separate review of biologically active natural compounds on cotton reports that chitosan used with a durable press finishing agent retained antibacterial activity to a level of 80% after 10 repeated launderings, and that treated cotton showed a 97% reduction in *S. aureus* colonies compared with a wood pulp/polyester spun-laced nonwoven [8]. The same review notes that concentration, molecular weight, degree of deacylation and bacterial strain affect chitosan's antibacterial behaviour [8], which is an important admission of variability.

Essential oils and other natural oils are also proposed for textile finishing. A lemongrass oil nanoemulsion was applied to nylon net fabric by layer-by-layer deposition of polyelectrolyte multilayers, and the treated samples were tested for mosquito repellency, microbial growth, fragrance retention and wash durability, with GCMS and SEM used to confirm the presence of active ingredient after washing [5]. The study reports good mosquito repellency and fragrance retention, but the abstract is truncated and does not provide a clear numerical durability figure [5]. A separate work on neem oil describes nano and micro emulsions prepared with various emulsifiers to improve add-on and wash fastness, citing neem oil's insecticidal, antibacterial and antimicrobial properties as inspiration [6]. This source is largely a process description and does not report quantitative antimicrobial efficacy or durability results [6].

The bio-based evidence therefore shows a consistent pattern: promising antimicrobial activity, but durability that is generally lower than the synthetic systems and often reported after only 10 washes [2] [8]. The variability of natural compounds is also a recurring theme, with chitosan performance depending on molecular parameters and bacterial strain [8], and essential oil performance depending on emulsion stability, particle size and the number of polymeric layers applied [5]. For applied textile design, this means that bio-based finishes may be suitable for applications where frequent laundering is not expected, or where the finish can be reapplied, but they are not yet equivalent to the more durable synthetic systems for high-wash healthcare applications.

SECTION 05

Green-synthesised silver: a bridge between efficacy and durability

Green-synthesised silver nanoparticles occupy an interesting position because they combine a bio-based synthesis route with inorganic antimicrobial activity. Silver nanoparticles were fabricated using *Cordyline fruticosa* L. leaf extract as a reducing and capping agent, producing spherical particles with an average size of 28.5 nm that were highly crystalline and well capped by phytochemicals [9]. The particles showed effective antibacterial activity against six pathogenic bacteria, including *E. coli*, *P. aeruginosa*, *S. enterica*, *S. aureus*, *B. cereus* and *E. faecalis* [9]. When applied to viscose fabric by pad-dry-cure, the treated fabrics showed synergistic antimicrobial activity against *E. coli* and *S. aureus*, and when silk fibroin regenerated from

Bombyx mori cocoon waste was used as an eco-friendly binder, the antimicrobial efficacy still reached 99.99% against the tested bacteria even after 30 washing cycles [9].

This source is notable because it reports both broad-spectrum activity and a specific durability figure, and because it uses a waste-derived binder to improve immobilisation [9]. The authors propose the material for sportswear and medical textile applications on the basis of antimicrobial efficiency, laundering durability and green synthesis [9]. However, the source does not report silver release, skin contact safety or environmental persistence, and the durability test is limited to 30 washes, which is fewer than the 50-52 cycles reported for the synthetic systems [1] [7]. The evidence therefore supports the potential of green-synthesised silver for durable antimicrobial finishing, but it does not resolve the safety questions that are central to the assignment.

SECTION 06

Processing routes and their implications for manufacturing

The processing techniques available for antimicrobial textiles include pad-dry-cure, spraying, exhaust methods, screen-printing, surface modification and spinning technologies, and the choice of route affects both efficacy and durability [10]. Pad-dry-cure is the most commonly reported method in the supplied sources, used for PHMB on cotton [1], chitosan nanoparticles with citric acid on cotton [2], silver nanoparticles on viscose [9] and N-halamine on PET [7]. The prevalence of pad-dry-cure reflects its compatibility with conventional textile finishing equipment, but it also means that the durability of the finish depends heavily on the affinity between the agent and the fibre, which is why fixation strategies such as in-situ synthesis [3] and silk fibroin binders [9] are being explored.

The source on processing techniques frames the central challenge as achieving efficiency against a broad spectrum of microorganisms, non-toxicity, durability and compatibility [10]. This framing is useful because it makes explicit that antimicrobial efficacy is not the only criterion. The supplied studies confirm that compatibility issues are real: PHMB affected hand feel and tearing strength [1], chitosan nanoparticles increased fabric stiffness [2], and N-halamine reduced breaking strength [7]. For manufacturing specialists, these trade-offs must be quantified before a finish can be specified, and the absence of standardised reporting makes it difficult to compare finishes across studies.

A further manufacturing consideration is the distinction between biocidal and biostatic approaches, which the PHMB study identifies as two ways to inhibit microbial growth on textile surfaces [1]. Biocidal finishes kill microorganisms, while biostatic finishes inhibit their growth. The choice between them has implications for the duration of protection, the potential for resistance development and the safety profile, but the supplied sources do not systematically compare the two approaches. This is a gap that applied textile design would need to address through targeted testing rather than through inference from existing studies.

SECTION 07

Safety, uncertainty and the limits of the evidence

Safety is the least well-supported dimension of the supplied evidence. The review of natural compounds states that up to date none of the natural compounds have been reported to have negative side effects on the human skin when used as antibacterial clothing [8]. This is a claim about the absence of reports, not a demonstration of safety, and it does not cover inhalation, ingestion or environmental exposure. The silver nanoparticle study describes the synthesis as green and the binder as eco-friendly [9], but it does not report silver ion release, dermal penetration or ecotoxicity. The sol-gel review describes low concentrations of non-hazardous chemicals as an advantage [4], but non-hazardous is asserted rather than demonstrated with toxicological data.

The uncertainty extends to efficacy claims as well. The lemongrass study reports good mosquito repellency and fragrance retention, but the abstract is truncated and does not provide a complete durability figure [5]. The neem oil work is primarily a process description without quantitative antimicrobial results [6]. The HKUST-1 study reports activity against *E. coli* but does not report washing durability in the abstract [3]. These gaps mean that the evidence base is uneven, with some systems well

characterised for durability and others characterised mainly for synthesis and initial activity.

A final uncertainty concerns the relationship between laboratory testing and real-world performance. The PHMB study used simulated healthcare laundering [1], and the N-halamine study used a specified number of wash cycles [7], but neither reports the full range of conditions that a textile would encounter in use, including abrasion, perspiration, UV exposure and repeated disinfection. The N-halamine study did include storage stability and UV irradiation tests [7], which is a useful step, but the general problem remains that laboratory durability is not the same as service life. For applied textile design, this means that durability claims should be treated as indicative rather than predictive, and that field testing or accelerated ageing relevant to the intended application is necessary before a finish is adopted.

CONCLUSION

Conclusions

The supplied evidence shows that antimicrobial textile finishes can achieve high efficacy and, in some cases, substantial durability. PHMB on cotton retained 100% bactericidal effect after 52 washes [1], N-halamine on PET maintained 80% efficacy after 50 washes with regenerable properties [7], and green-synthesised silver with a silk fibroin binder reached 99.99% efficacy after 30 washes [9]. Bio-based finishes such as chitosan nanoparticles and chitosan with durable press agents showed activity after 10 washes [2] [8], while essential oil and neem oil systems are less well characterised for durability [5] [6]. Inorganic and metal-organic approaches offer multifunctionality and improved fixation potential [3] [4], but their durability evidence is less complete. Across all systems, efficacy is accompanied by trade-offs in hand feel, strength or stiffness [1] [2] [7], and safety is largely inferred rather than demonstrated [4] [8] [9]. For applied textile design and manufacturing, the practical implication is that finish selection should be driven by the intended use and laundering regime, that durability testing should be standardised and reported in full, and that mechanical and comfort penalties should be quantified alongside antimicrobial performance. Safety claims should be made cautiously until dermal, inhalation and environmental data are available. The evidence supports continued development of antimicrobial finishes, but it does not yet support uniform claims of durable, safe performance across chemistries and applications.

SCOPE

Limitations

This synthesis is based on 10 supplied sources, several of which are reviews or process descriptions rather than primary durability studies [4] [6] [10]. The sources use different test organisms, inoculation methods, washing protocols and reporting units, which limits direct comparison. Some abstracts are truncated or omit key results, including the lemongrass study's durability figure [5] and the HKUST-1 study's washing durability data [3]. No source reports systematic human skin toxicity, inhalation risk, silver release or environmental fate, so safety conclusions are inferential. The review does not claim systematic-review methods, does not include unpublished or non-supplied literature, and does not assess study quality with a formal risk-of-bias tool. Durability figures are laboratory-based and may not predict real-world service life. The assignment is an AI-assisted editorial review and has not been externally peer reviewed.

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