

REVIEW ARTICLE

Bio-Based Functional Coatings for Textiles: A Critical Synthesis of Multifunctionality, Durability, and Manufacturing Trade-Offs

Evidence from chitosan, lignin, and biomass-waste systems across flame retardancy, antimicrobial action, and water repellency

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ABSTRACT

Bio-based coatings promise to combine flame retardancy, antimicrobial protection, and water repellency on textile surfaces while reducing reliance on hazardous chemistries. This editorial review synthesises ten supplied source records to assess what the current evidence does and does not establish. Chitosan is the most recurrent bio-based component, appearing as a phosphorylated flame-retardant phase [1], a microcapsule shell [3], a sol-gel precursor [4], a crosslinked antimicrobial matrix [5], a nanogel scaffold [6], and a water-repellent composite [8]. Reported performance is often high: >99% antibacterial efficiency against *Escherichia coli* and *Staphylococcus aureus* [1] [5], water contact angles up to 167.12 degrees [8], and UV protection factor values of 45.1 [6] and 72.32 [3]. However, the evidence base is dominated by single-laboratory formulations tested under non-standardised conditions, with inconsistent durability protocols, limited reporting of comfort and mechanical penalties, and almost no independent replication. Durability claims range from retention after 15-20 washes [1] [6] [8] to loss of superhydrophobicity after laundering [1]. The review argues that the field's central unresolved problem is not the discovery of multifunctional bio-based chemistries but the demonstration of reproducible, scalable, and comfort-preserving performance. Practical implications for applied textile design and manufacturing are framed as testable trade-offs rather than settled conclusions.

Keywords: bio-based coatings; chitosan; flame retardancy; antimicrobial textiles; water repellency; durability; textile manufacturing

SECTION 01

Why bio-based multifunctional coatings are being pursued

Functional coatings for textiles have traditionally been assembled from separate chemistries, each optimised for one property. The supplied literature converges on a different ambition: a single bio-derived formulation that simultaneously delivers flame retardancy, antimicrobial action, and water repellency, thereby reducing process steps and the number of hazardous inputs [1] [2]. Ghosh et al. frame this as a response to demand in healthcare, military, and industrial protective textiles, and identify dip-coating, spray-coating, sol-gel processes, and layer-by-layer assembly as the main application routes [2]. The appeal is partly regulatory and partly economic: as industry standards shift toward sustainability, coatings that avoid persistent or toxic additives become commercially attractive [2].

The bio-based components actually evidenced in the supplied records are narrower than the general rhetoric. Chitosan recurs across almost every source, in roles ranging from a char-forming flame-retardant phase [1] and a microcapsule shell [3] to a sol-gel precursor [4], an antimicrobial crosslinked matrix [5], a nanogel scaffold [6], and a hydrophobic composite component [8]. Lignin appears as a modifier for waterborne polyurethane [9], curcumin as a co-functional additive in aqueous

polyurethane dispersions [10], and mandarin peel powder and sacred lotus leaf wax as waste-derived fillers [7] [8]. This concentration on a small set of biopolymers is itself an evidence characteristic worth noting: the field's sustainability claim rests on a relatively narrow material base.

A second motivation is the integration of functions that were previously sequential. Li et al. describe a hierarchical micro/nanostructure combining phosphorylated chitosan, polydopamine-modified copper nanoparticles, and PDMS-SiO₂ on cotton and polylactic acid nonwovens, explicitly linking structure to simultaneous flame retardancy, antibacterial activity, and water repellency [1]. Zhang et al. pursue a comparable logic through a strawberry-like silica/chitosan microcapsule with a peppermint essential oil core, combining antimicrobial action with UV protection [3]. The shared premise is that architecture, not just chemistry, can reconcile functions that might otherwise interfere.

SECTION 02

Flame retardancy: char-forming bio-based systems and their limits

The strongest mechanistic account of bio-based flame retardancy in the supplied records comes from Li et al., who attribute improved flame retardancy to synergistic condensed-phase charring and catalytic effects, evidenced by increased limiting oxygen index and reduced total heat release [1]. This is a coherent and testable mechanism, and it aligns with the broader observation that phosphorus-based flame retardants feature prominently in recent functional coating development [2]. The attraction of a bio-based char former is that it can, in principle, replace or reduce conventional halogenated or phosphorus-intensive additives while retaining a physical barrier function.

Independent support for char-based flame retardancy comes from a different material system. Attia and Gamal report that a mandarin peel powder/chitosan coating on furniture textile fabrics enhanced thermal stability and char yield relative to uncoated fabric, and they interpret the charring effect as anticipating good flame retardancy [7]. This is a useful convergence because it derives from a waste-derived filler rather than a phosphorylated biopolymer, suggesting that char formation is a generalisable route rather than a single-formulation artefact. However, the two studies do not share a test protocol, and the mandarin peel work reports thermal and char-yield data rather than standardised flame-spread or heat-release measurements [7].

The limitation is therefore one of evidentiary standard rather than plausibility. Flame retardancy claims in this literature are typically supported by limiting oxygen index and total heat release [1] or by thermogravimetric char yield [7], with no supplied source reporting a common regulatory fire test. This matters for applied textile design because protective applications are governed by standards that a laboratory char-yield improvement does not automatically satisfy. The mechanistic case for bio-based charring is credible; the compliance case is not yet demonstrated in the supplied evidence.

SECTION 03

Antimicrobial performance: high efficacy, uncertain durability

Antimicrobial efficacy figures in the supplied records are consistently high but methodologically heterogeneous. Li et al. report >99% activity against *Escherichia coli* and *Staphylococcus aureus*, and note that polydopamine modification may stabilise copper species, extending antibacterial durability from 2 to 14 days before activity falls below 70% [1]. Ko et al. report over 99.9% antibacterial efficiency for a chitosan-citrate-copper composite applied by roll-to-roll coating on PET, plus 99.895% reduction of Influenza A [5]. Zhang et al. report 99.99% and 93.10% inhibition against *E. coli* and *S. aureus* respectively for a silica/chitosan microcapsule coating [3]. Alfaifi et al. report broad-spectrum activity with inhibition zones up to 36 mm against *Candida albicans* and durable >90% bacterial reduction after 15 washing cycles [6].

The convergence on >99% efficacy is striking, but it should be read cautiously. These are different actives (copper species, chitosan-citrate complexes, peppermint essential oil, silver and silver-titanium nanogels), different substrates (cotton, PLA nonwoven, PET), and different application methods (hierarchical coating, roll-to-roll, microencapsulation, pad-dry-cure) [1] [3] [5] [6]. High kill rates are also a relatively low bar in suspension-based antimicrobial testing; the more discriminating question is whether activity persists under real wear and laundering. Here the evidence is genuinely divided: Li et al. observe

that repeated laundering eliminates initial superhydrophobicity and that antibacterial durability is time-limited [1], whereas Alfaifi et al. report retention above 90% after 15 washes [6].

A further uncertainty concerns the mechanism of durability. Li et al. explicitly propose that polydopamine stabilises copper species [1], which is a specific and falsifiable claim, but no supplied source provides a controlled comparison isolating that stabilisation effect. Ko et al. emphasise a synergistic effect from crosslinked chitosan-citrate-copper complexes [5], again a mechanistic interpretation rather than an independently replicated finding. For product developers, the practical implication is that antimicrobial durability should be treated as formulation-specific and verified under the intended laundering regime, not inferred from initial kill rates.

SECTION 04

Water repellency and the comfort penalty

Water repellency is the property where bio-based coatings achieve their most visually dramatic results, and also where the trade-offs are clearest. Nitayaphat et al. report a water contact angle of 167.12 degrees for a chitosan/sacred lotus leaf wax composite at a 7:3 weight ratio, retained at 137.11 degrees after 20 home-machine washings [8]. Alfaifi et al. report contact angles rising from approximately 0 degrees on untreated cotton to 151.3 degrees for a bimetallic nanogel coating [6]. Taurino et al. report contact angles up to 120 degrees for chitosan-based sol-gel coatings on cotton and polyester [4]. Li et al. report that laundering reduces the contact angle to approximately 130 degrees, eliminating superhydrophobicity while preserving favourable hydrophobic performance [1].

The critical issue is that hydrophobicity is not free. Nitayaphat et al. state directly that increasing wax content improved water repellency but produced slight reductions in tensile strength, air permeability, and water vapor permeability [8]. This is the most explicit comfort trade-off in the supplied evidence, and it is consistent with the general concern raised by Ghosh et al. that achieving compatibility among diverse functional components while maintaining mechanical integrity and user comfort remains a challenge [2]. A coating that repels water by sealing the fabric surface will tend to reduce breathability, which is unacceptable for many apparel and healthcare applications.

There is also a durability ceiling that the literature tends to report rather than resolve. The loss of superhydrophobicity after laundering [1] and the decline from 167.12 degrees to 137.11 degrees after 20 washes [8] indicate that the most extreme repellency is the least robust. Taurino et al. report minimal degradation after multiple washing cycles for sol-gel coatings [4], but at a lower initial contact angle. The pattern suggests an inverse relationship between initial repellency and laundering durability, though the supplied sources do not test this hypothesis directly and use different washing protocols.

SECTION 05

Mechanical integrity, UV protection, and colour performance

Beyond the three headline functions, several sources report effects on mechanical and optical properties that matter for applied design. Alfaifi et al. report improved tensile strength from 67.1 N to 85.7 N alongside increased surface roughness, with breathability preserved [6]. Attia and Gamal report a 35% improvement in maximum break loading for mandarin peel/chitosan-coated fabrics relative to uncoated controls [7]. Arshad et al. report that chitosan-curcumin aqueous polyurethane dispersions significantly improved mechanical properties and colourfastness (washing, rubbing, perspiration) on dyed, printed, and white poly/cellulosic textiles [10]. These are encouraging but not uniform: the wax-rich coating of Nitayaphat et al. reduced tensile strength [8], so the direction of mechanical effect depends on formulation.

UV protection appears as a secondary but recurrent benefit. Zhang et al. report a UPF of 72.32 for a silica/chitosan microcapsule coating [3], Alfaifi et al. report UPF rising from 2.1 to 45.1 [6], and Lin et al. report effective UV protection from a lignin-modified cationic waterborne polyurethane combined with chitosan [9]. The consistency across different chemistries suggests that UV blocking is a relatively accessible add-on function, particularly where inorganic or aromatic UV-absorbing species are incorporated. However, UPF is sensitive to coating uniformity and areal density, and the supplied sources do not report UV durability after laundering.

Colour and dyeing interactions are addressed most directly by Lin et al., who use the cationic nature of a lignin-modified waterborne polyurethane to facilitate dye adhesion and uptake, with epoxy side chains and chitosan crosslinking contributing to colour fastness [9]. Arshad et al. similarly report improved colourfastness for treated textiles [10]. This is an important practical point: a coating that improves dye uptake can reduce dye consumption, but a coating that alters surface energy may also shift shade or hand feel. The supplied evidence reports fastness improvements without quantifying colour shift, which is a gap for product development.

SECTION 06

Manufacturing routes and the scalability question

The application methods evidenced in the supplied records span laboratory and near-industrial approaches. Dip-coating and pad-dry-cure are the most common [6] [8], with sol-gel processing [4], microencapsulation [3], and hierarchical multi-step coating [1] also represented. Ko et al. provide the clearest scalability signal, demonstrating roll-to-roll PET coating with a chitosan-citrate-copper composite and explicitly framing the process as advantageous for mass production because it avoids chemical modification and prolonged immersion [5]. Taurino et al. extend sol-gel application into digital deposition and 3D inkjet printing, optimising viscosity, density, and surface tension for uniform deposition [4].

Scalability is not only about coating equipment. Ghosh et al. identify scalability and cost-efficiency as barriers to commercialisation and call for cross-disciplinary collaboration among material scientists, engineers, and regulatory experts [2]. The supplied sources rarely report cost, batch reproducibility, or yield. Ko et al. address cost-effectiveness as a design goal [5], and Attia and Gamal emphasise the cost-effective use of fruit waste [7], but neither provides an economic analysis. The roll-to-roll demonstration [5] is the most convincing manufacturing evidence available here, yet it is a single formulation on a single substrate.

A related manufacturing issue is process compatibility with the substrate. Li et al. apply their coating to both cotton and polylactic acid nonwoven fabrics [1], which is a useful indication of substrate breadth, while Taurino et al. compare pure cotton and synthetic polyester [4]. Arshad et al. work on poly/cellulosic blends [10]. The evidence suggests that bio-based coatings can be adapted across fibre types, but the formulations differ between studies, so substrate versatility cannot be attributed to a single chemistry. For manufacturing specialists, the practical reading is that each fibre-formulation-process combination requires its own optimisation, and the literature currently provides examples rather than transferable rules.

SECTION 07

Safety, biodegradability, and the unresolved evidence gaps

Safety and environmental claims in the supplied records are mostly framed as material properties rather than demonstrated outcomes. Alfaifi et al. report cytotoxicity testing on human skin fibroblast cells with >60% viability at 250 ug/mL, outperforming 5-fluorouracil treatment, and describe the nanocomposites as highly biocompatible [6]. Nitayaphat et al. describe their chitosan/sacred lotus leaf wax composite as biodegradable, non-toxic, and environmentally friendly [8]. Zhang et al. emphasise the biocompatibility of chitosan and the environmental friendliness of hybridising bio-based organic with natural inorganic materials [3]. These are plausible but not equivalent to full toxicological or life-cycle assessment.

The most significant gap is independent replication. Every performance claim in the supplied records originates from the laboratory that developed the formulation, and no source reports a multi-laboratory round-robin or a standardised interlaboratory comparison. Durability protocols differ (2 to 14 days antibacterial durability [1], 15 washing cycles [6], 20 washing cycles [1] [8], multiple washing cycles [4]), as do antimicrobial test organisms and methods. This heterogeneity makes cross-study comparison unreliable and means that apparent disagreements, such as the contrast between retained activity after 15 washes [6] and declining activity over days [1], may reflect protocol differences as much as material differences.

A second gap concerns the fate of the coatings themselves. If bio-based coatings are promoted as sustainable alternatives, their end-of-life behaviour matters, yet no supplied source reports biodegradation rates, microplastic or nanoparticle release, or recyclability of coated fabrics. The inclusion of copper nanoparticles [1] [5] and silver/titanium nanogels [6] raises specific questions about release during laundering and disposal that the supplied evidence does not address. These are not marginal concerns for a field whose central claim is environmental responsibility.

CONCLUSION

Conclusions

The supplied evidence establishes that bio-based coatings can deliver multifunctional performance on textile surfaces. Chitosan-based systems have demonstrated flame retardancy through condensed-phase charring [1] [7], antimicrobial efficacy above 99% against common bacterial strains [1] [3] [5] [6], water contact angles from 120 degrees to 167.12 degrees [4] [6] [8], and UV protection with UPF values of 45.1 and 72.32 [3] [6]. Roll-to-roll application of a chitosan-citrate-copper composite provides the clearest indication that at least some of these formulations are compatible with scalable manufacturing [5]. The evidence is therefore sufficient to justify continued development, but not sufficient to support claims of settled performance. The central unresolved problem is not the discovery of multifunctional bio-based chemistries; it is the demonstration of reproducible, standardised, and comfort-preserving performance across substrates and laundering regimes. The most consistent trade-off in the supplied literature is between repellency and comfort, with higher wax content improving hydrophobicity while reducing tensile strength, air permeability, and water vapor permeability [8]. Durability findings are genuinely divided, with some systems retaining activity after 15-20 washes [6] [8] and others losing superhydrophobicity or antibacterial potency under laundering or time [1]. For applied textile design and manufacturing, the responsible interpretation is that bio-based coatings should be selected and validated against the specific end-use standard, substrate, and laundering regime, and that multifunctionality should be treated as a formulation-specific achievement rather than a general property of bio-based chemistry.

SCOPE

Limitations

This review is based solely on ten supplied source records and does not claim systematic-review methods. The evidence base is small, dominated by single-laboratory studies, and heterogeneous in test organisms, washing protocols, substrate types, and application methods, which limits cross-study comparison. Several sources are recent and may not yet have been independently replicated. Performance figures such as antibacterial efficiency, water contact angle, UPF, and char yield are reported as found in the sources and are not adjusted for methodological differences. No supplied source reports full life-cycle assessment, nanoparticle release, biodegradation rate, or recyclability of coated textiles, so environmental claims remain provisional. Cost, batch reproducibility, and regulatory compliance are largely unaddressed in the supplied records. The interpretations and practical implications offered here are editorial judgements grounded in the cited evidence, not experimental findings, and should be treated as hypotheses for further testing rather than settled conclusions.

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