

# Review of advances in developing inherently flame-retardant textiles with added biodegradability and multi-functional performance

## Abstract

The key observations reported in this paper are supported by the body of literature reviewed and cited.

The clearest quantitative multifunctional results are reported in at least two of the cited articles. It is observed that treating wool with 3.5% o.w.f. reactive nonionic softener at 130 °C for 5 min increases surface smoothness by 21.7% and felting-shrinkage resistance by 90%. This treatment retained air permeability and dyeability, and the finish remained durable through washing, although smoothness suffered somewhat after extended laundering. Increasing phosphorus flame retardant to 8 wt% reduced nonwoven fire damage distance by up to 60%, while 3 wt% ZnO reduced bacterial infestation caused by *S. aureus* and *K. pneumoniae* by 99.96% and 98.79%, respectively. The most effective weight compositions for treatments involving ZNO and PFR were 3 wt% ZnO and 5 wt% PFR.

The most recurrent gaps, as stated in the literature, are wash durability, scale-up and pre-industrial validation, comfort/softness loss, cost-effectiveness, and end-of-life design for FR textiles. Those gaps were identified by multiple researchers.

**Keywords:** flame-retardant, textiles, biodegradability, fibers, sustainability, recycling

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## Methodology

This review was developed using literature published primarily between 2016 and 2026. Searches were conducted using keywords including 'inherently flame-retardant fibers', 'flame-retardant textiles', 'multifunctional textile finishes', 'circularity', 'recycling of flame-retardant textiles', 'bio-based flame retardants', and 'sustainable textile finishing'. Publications were identified from peer-reviewed journals, review articles, and technical sources. Selection criteria emphasized relevance to inherent flame retardancy, multifunctionality, sustainability, recycling, and natural raw materials. Studies reporting quantitative performance data, durability, environmental impacts, or industrial applicability were given priority.

## Design of flame-retardant fiber products with inherently flame-retardant materials

Important distinction: inherently flame-retardant fibers derive their fire resistance from the molecular structure of the polymer itself and therefore retain protection throughout their service life. In contrast, flame-retardant finishing systems rely on surface-applied chemistries that impart flame resistance after fiber production. Much of the recent literature reviewed here focuses on advanced finishing technologies rather than on the development of new inherently flame-retardant polymer architectures.

Within the cited literature, reference # 1 frames the core cotton problem very directly: cotton's LOI is only approximately 18%, it ignites easily, and once ignited, the flame spreads rapidly. The same paper states that commercial systems such as Proban® and Pyrovatex® remain important but are disadvantaged by formaldehyde release, which is why the research focus has shifted toward durable, formaldehyde- and halogen-free systems. The review explicitly organizes the field around halogen-, phosphorus-, nitrogen-, silicon-

boron-, inorganic hydroxide-, nano-, co-effective-, and biological macromolecular fire-retardant systems.<sup>1</sup>

Article # 2 states that most synthetic textile materials are inherently flammable and exhibit material-specific drawbacks, including melt-dripping and limited charring. It argues that surface engineering is often used to mitigate these drawbacks and that the design should match the polymeric structure and the applied FR chemistry to the target fiber. In the concluding remarks, the review states that synthetic-textile FR finishing has evolved continuously from traditional approaches to current finishing strategies.<sup>2</sup>

Article 3 reaches a similar conclusion for nylon: the abstract says the field is still searching for the most sustainable, efficient, and durable FR treatments, and the chapter is explicitly organized around eco-friendly compounds, application techniques, and durability issues. In its conclusion, Article 50 states that bio-derived compounds are becoming more prominent and are effective mainly in reducing pHRR and enhancing char yield, but have not yet shown the same potency in improving LOI values and thermal stability. The same conclusion also states that bio-derived polyelectrolyte coatings assembled via ionic interactions often exhibit poor wash durability, whereas hybridization of compounds and methods has been beneficial; however, commercial implementation remains challenging.<sup>3</sup>

Taken together, the accessible evidence reveals limitations. However, it also presents solid reviews of FR design logic for cotton, nylon, and broader synthetic fibers. It offers comparatively little evidence for true, inherently FR fiber backbones. In other words, the available evidence leans toward fiber/fabric treatment design rather than toward abundant primary data on intrinsically FR polymer architectures. This synthesis is based on,<sup>1-3</sup> and it aligns with the fact that the directly relevant record<sup>4</sup> remains unspecified.<sup>1-4</sup>

## Design of inherently flame-retardant fiber products with multi-functional properties

The strongest results for the multifunctional performance is provided in 33. It describes a core-sheath bicomponent rPET nonwoven designed to combine thermal insulation, flame retardancy, and antibacterial activity. Nano-ZnO provided antibacterial functionality, and phosphorus flame retardant provided FR performance. Quantitatively, it states that increasing PFR to 8% reduced the flame-damage distance by up to 60%, while adding 3 wt% ZnO reduced antibacterial infestation by *S. aureus* and *K. pneumoniae* by about 99.96% and 98.79%, respectively. The article further states that the most effective functionalized fiber contained 3 wt% ZnO and 5 wt% PFR, and that it also modified the fibers' mechanical and thermal properties.<sup>5</sup>

Article 6 is another strong multifunctional example, though it is a wool-fabric finishing study rather than a true inherent-FR polymer design. It reports a reactive nonionic softener based on fatty acid and AMPD that improved smoothness, wettability, and felting-shrinkage resistance. The optimum reported treatment condition is 3.5% o.w.f., 130 °C, 5 min. Under those conditions, surface smoothness increased by 21.7% and resistance to felting shrinkage by 90%. The abstract also states that air permeability and dyeability were retained, and that durability remained acceptable through washing, although the imparted smoothness decreased after more severe laundering.<sup>6</sup>

Article 7 describes multifunctionality in a bio-based system. It states that rice straw extract was used as a sustainable and multifunctional natural dye for both natural fibers (wool, silk) and a synthetic fiber (nylon 6) at 0.2, 0.4, 0.6, and 0.8% wt/v for 1 hour. The abstract concludes that the treatment produced effective coloration, excellent UV protection, antioxidant activity, and improved thermal stability. The conclusion reiterates that the dyed fabrics exhibited brilliant coloration ranging from beige to brown, good fastness, high antioxidant activity, improved UV resistance, and a potential for enhanced thermal resistance, while also calling for future work on scalability, long-term durability, and fiber-type optimization.<sup>7</sup>

At the review level, article 43 focuses on commonly used finishing technologies and flame-retardant/antibacterial agents, confirming that this FR + antibacterial pairing has become a recognizable multifunctional design stream in the textile literature. Likewise,<sup>8</sup> frames a 2026 Lyocell study around 'integrating reusability with multifunctionality,' using a bio-based phytic-acid/tannic-acid system to combine flame retardancy, antibacterial performance, and UV protection through an environmentally benign finishing route.<sup>8,9</sup>

The approaches to attaining multifunctionality are pretty clear: multifunctionality is much more mature and truer than inherently FR chemistry. The multifunctional 'stack' most often combines FR with antibacterial performance, UV blocking, thermal insulation, wettability/comfort, or coloration, but usually through finishing chemistry rather than through intrinsically FR macromolecular fiber design. That synthesis is directly supported by the articles.<sup>5-9</sup>

Circularity can be viewed through three complementary pathways: mechanical recycling (reuse of fibers through physical processing), chemical recycling (depolymerization and recovery of polymer constituents), and end-of-life-by-design strategies that facilitate future recovery, reuse, or safe disposal. These pathways differ substantially in cost, material retention, and environmental impact and should be evaluated separately when assessing flame-retardant textile sustainability.

## Design of inherently flame-retardant fiber products that are environmentally friendly with circular functionality

Article 10 is the clearest end-of-life FR-textile paper in the bibliography. Its abstract states that a sustainable approach for textile waste, especially FR textiles, is absent, and that incineration and landfill are burdened by toxic outcomes. The study, therefore, evaluated the mechanical recycling of FR cotton curtains. In the conclusion, the authors state that avoiding virgin production gives an obvious carbon-footprint reduction: 1 kg of FR cotton/polyester insulation produced 10.01 kg CO<sub>2</sub>, compared with 11.8 kg CO<sub>2</sub> for 1 kg of FR cotton curtains, and the overall carbon footprint would have been 22.21 kg CO<sub>2</sub> if virgin FR cotton fiber production had been included. The conclusion, therefore, recommends avoiding virgin cotton.<sup>10</sup>

Article 5 links circularity directly to performance by using recycled PET fibers as the starting point for an antibacterial and flame-retardant thermal insulator. Its abstract explicitly positions functionalized rPET bicomponent fibers as a sustainable alternative for thermal-insulator products and says that this use of rPET contributes to the broader goal of sustainability in manufacturing.<sup>5</sup>

Article 11 broadens the environmental discussion from recycling to bio-sourced FR design. It says that, over the last five to ten years, proteins, nucleic acids, and natural extracts—including wastes and crops—have been explored as low-environmental-impact alternatives for textile FR design. The conclusion adds three circularity-relevant points: the field is still at lab scale; some biomacromolecules are valuable because they are crops, wastes, or agro-food by-products that could be diverted from landfill. Industrial adoption of these materials depends on cost-effectiveness and on solving wash fastness and comfort/stiffness problems.<sup>11</sup>

Article 8 pushes this same trend further by making resource circularity itself part of the problem statement. The article says the study was designed to address 'substantial environmental footprint, limited functionality, and poor resource circularity' of conventional textile finishing, and that the authors synthesized a bio-based multifunctional finishing agent from phytic acid and tannic acid using green chemistry and applied it through an environmentally benign pad-dry-cure route.<sup>8</sup>

Article 12 is not FR-specific, but it is the strongest circular-textile review in the attached set and therefore provides useful boundary conditions for FR-fiber product design. It states that cotton-waste recycling can support circular-economy transitions through mechanical, chemical, plasma, and microwave-assisted routes; that recycled cotton can be used in bio-based nonwovens and composites; and that the remaining obstacles are processing, fiber-quality retention, and economic viability. That same conclusion is useful here because those obstacles are almost certainly harder, not easier, once FR chemistries are added to textile products.<sup>12</sup>

At the review/framework level,<sup>13</sup> states that its purpose is to identify sustainability challenges arising from raw materials, processing technology, and the performance of textile FR systems, and to recommend solutions. That is valuable because it aligns with the concrete gaps seen.<sup>10,11</sup> It declares that sustainability is not just a chemistry problem; it spans feedstocks, application routes, durability, and disposal.

### Design of inherently flame-retardant fiber products using natural raw materials

The most direct natural-raw-material example,<sup>7</sup> which uses rice straw extract as the active material for simultaneous coloration and functional finishing. In the abstract, rice straw extract is described as a significant source of phenolic compounds and flavonoids, and the study positions it as a sustainable and multifunctional natural dye for wool, silk, and nylon 6. The conclusion emphasizes waste valorization, highlighting rice straw as a low-cost, abundant agricultural waste that offers an eco-friendly and economically attractive approach to multifunctional textile finishing.<sup>7</sup>

Article 11 is the key review for this theme. It says that proteins, nucleic acids, and diverse extracts from natural sources—including wastes and crops—have been selected for flame-retardant textile finishing. The same abstract attributes much of their FR action to the presence of nitrogen, phosphorus, and sulfur, and to the formation of a stable protective char when exposed to heat or flame. In the conclusion,<sup>11</sup> adds that some of these materials have an intrinsic circular-economy advantage because they are agro-food by-products or wastes, but also notes that durability and comfort issues remain unresolved.<sup>11</sup>

Article 8 is another strong natural-feedstock case because the finishing agent is built from phytic acid and tannic acid, both classic bio-based raw materials. The article presents this system as a green-chemistry route to a reusable, multifunctional Lyocell finish that combines FR, antibacterial, and UV-protective functions. That makes<sup>8</sup> particularly relevant to this heading.<sup>8</sup>

A broader thematic companion,<sup>14</sup> ‘Application of Plant Polyphenols in Multifunctional Textiles’, which is bibliographically very relevant to this topic. The attached bibliography clearly points toward plant-polyphenol-enabled multifunctionality.<sup>14</sup>

The major caution here is that the accessible evidence primarily concerns bio-based finishing agents applied to fibers and fabrics, rather than demonstrably inherently FR fibers manufactured directly from natural raw materials. The natural-raw-material stream in the literature set is real and promising, but it is represented mainly as green finishing chemistry rather than as a fully mature platform for intrinsically FR natural-fiber products. That synthesis follows from the retrieved content,<sup>7,8,11</sup> together with the unspecified status.<sup>14</sup>

#### Comparative summary of major flame-retardant approaches

System	Typical application	Performance	Sustainability	Limitations
Inherently FR Fibers	Aramids, FR-modacrylics	Permanent FR protection	No re-treatment needed	Higher cost; recycling challenges
Phosphorus-based Finishes	Cotton, blends	Good FR performance	Halogen-free options available	Durability may decline after laundering
Bio-based FR Systems	Natural/synthetic textiles	Moderate FR plus multifunctionality	Renewable feedstocks	Scale-up and wash durability issues
Nano-enabled Systems	Technical textiles	Enhanced FR and antibacterial performance	Lower add-on levels possible	Regulatory and cost concerns

### Summary of developments and current gaps in the above four areas

Across the four requested areas, the evidence supports five main developments. First, the field is moving away from older formaldehyde-releasing or otherwise environmentally problematic FR systems toward halogen-free, bio-derived, and lower-impact alternatives.<sup>1,2,11,13</sup> Second, multifunctionality is no longer a side quest; it is central, often combining FR with antibacterial action, UV protection, thermal insulation, wettability, or coloration.<sup>5-9</sup> Third, recycled feedstocks—especially rPET and textile wastes—are increasingly used as functional product platforms rather than mere downgraded waste materials.<sup>5,10,12</sup> Fourth, natural raw materials are entering the field through rice straw extracts, phytic acid, tannic acid, and broader classes of biomacromolecules and agro-food by-products.<sup>7,8,11</sup> Fifth, sustainability is increasingly treated as a systems issue spanning raw materials, processing, performance, and disposal.<sup>10,13</sup>

The gaps are just as consistent. The first gap is conceptual and structural. True, inherently flame-retardant fiber materials are underrepresented relative to coatings, finishes, and review frameworks. That is the pattern visible across,<sup>1-3,11</sup> and the fact that directly relevant records,<sup>4,15</sup> remained unspecified at the abstract/conclusion level.<sup>1-4,11,15</sup>

The second gap is durability, especially under laundering or long-term use. Article<sup>7</sup> explicitly calls for work on long-term durability and scalability;<sup>2</sup> says ionic bio-derived coatings can have poor wash

durability;<sup>11</sup> says only a limited number of biomacromolecules/bio-sourced extracts currently provide durable textile FR finishing;<sup>6</sup> shows that even successful multifunctional finishing still degrades after repeated washes.<sup>2,6,7,11</sup>

The third gap is the user-performance trade-off. Article 57 explicitly states that achieving acceptable flame-retardant performance with biomacromolecules often increases stiffness, thereby reducing hand/soft-touch and wearability. Article<sup>6</sup> is useful here because it shows the opposite design ambition—preserve comfort-related properties while adding function—which is exactly the kind of balancing act the field still needs.<sup>6,11</sup>

The fourth gap is industrialization and economics. Article<sup>11</sup> says the biomacromolecule route is still at lab scale and calls out cost-effectiveness as decisive for industrial adoption;<sup>7</sup> asks for scalability studies;<sup>12</sup> highlights economic viability in recycling; and<sup>10</sup> shows that end-of-life solutions can be promising but still depend on modeled assumptions and incomplete process data.<sup>7,10-12</sup>

The fifth gap is end-of-life-by-design for FR textiles. Article<sup>10</sup> says a sustainable approach for FR textile waste is absent, and<sup>13</sup> frames sustainability challenges across raw materials, processing, and performance. The attached bibliography also includes,<sup>15</sup> Eco-design for the end-of-life phase of flame-retardant textiles, but its summary is ambiguous. So the bibliography points strongly to end-of-life design as a critical frontier, while the retrievable evidence still indicates that the field is in its early stages. It is clear that circularity for FR textiles is still doing a lot of talking and not enough industrial landing.<sup>10,13,15</sup>

In summary, the selected literature shows advances in bio-based multifunctionality and indicates some initial progress toward circularity. It also shows that durable, comfortable, scalable, and

truly inherent FR fiber systems remain the main unfinished business. Articles,<sup>4,14,15</sup> are especially relevant to those unresolved issues.<sup>16–90</sup>

### Bibliographic map of the cited records

The table below maps the article numbers from the listed bibliography to the main outcomes they express.

Article no.	Short bibliographic info	Role in this report
7	Abou-Taleb et al., <sup>7</sup> Eco-friendly development of multi-functional textiles using rice straw extract (2026)	Natural raw materials; multifunctionality
12	Abteu et al., <sup>12</sup> Recycling of cotton textile waste: Technological process, applications, and sustainability within a circular economy (2025)	Circularity context
6	El-Sayed et al., <sup>6</sup> One-pot multi-functional finishing of wool fabric using reactive nonionic softener (2022)	Multifunctionality
4	Islam et al., <sup>4</sup> Recycling of inherently flame-resistant fabrics for protective clothing: A comprehensive review (2025)	Directly relevant to inherent-FR recycling
9	Jin et al., <sup>9</sup> Multifunctional Textiles with Flame Retardant and Antibacterial Properties: A Review (2023)	FR + antibacterial review
2	Kundu et al., <sup>2</sup> Flame Retardant Treatments of Nylon Textiles: A Shift towards Eco-Friendly Approaches (2020)	Synthetic textiles; eco-friendly FR design
3	Kundu et al., <sup>3</sup> An overview of fire-retardant treatments for synthetic textiles: From traditional approaches to recent applications (2020)	Synthetic-textile FR design landscape
14	Liang & Liang, <sup>14</sup> Application of Plant Polyphenols in Multifunctional Textiles (2026)	Natural raw materials; multifunctionality
1	Ling et al., <sup>1</sup> A review on the state of flame-retardant cotton fabric: Mechanisms and applications (2023)	Cotton FR design landscape
11	Malucelli, <sup>11</sup> Biomacromolecules and Bio-Sourced Products for the Design of Flame Retarded Fabrics: Current State of the Art and Future Perspectives (2019)	Bio-based FR design; limitations
8	Song et al., <sup>8</sup> Integrating reusability with multifunctionality: an eco-friendly phytic acid–tannic acid finishing agent for flame retardant, antibacterial, and UV protective Lyocell fabric (2026)	Natural raw materials; multifunctionality; circularity
13	Venant Haule, <sup>13</sup> A review on sustainability challenges of flame retardants for textiles (2025)	Sustainability gaps
15	Yasin, <sup>15</sup> Eco-design for end-of-life phase of flame-retardant textiles (2017)	End-of-life design
10	Yasin et al., <sup>10</sup> Global Consumption of Flame Retardants and Related Environmental Concerns: A Study on Possible Mechanical Recycling of Flame-Retardant Textiles (2016).	FR textile end-of-life and recycling

### Conclusion

This review demonstrates that significant progress has been made in developing flame-retardant textile systems that combine fire protection with additional functionalities, including antibacterial activity, ultraviolet protection, thermal insulation, comfort enhancement, and coloration. The literature reveals a clear transition away from conventional halogenated and formaldehyde-based flame-retardant technologies toward environmentally responsible alternatives based on bio-derived materials, recycled feedstocks, and multifunctional finishing systems. Quantitative evidence from the reviewed studies confirms that multifunctional performance can be successfully integrated into textile products, as demonstrated by recycled PET-based nonwoven systems that exhibit substantial reductions in flame-damage distance and excellent antibacterial performance. The review also highlights the growing importance of circularity, including the use of recycled textile materials, waste valorization strategies, and bio-based raw materials such as rice straw extracts, phytic acid, tannic acid, and other biomacromolecules that contribute to both sustainability and functional performance.

Despite these advances, the literature consistently indicates that durable, scalable, and economically viable inherently flame-retardant

textile systems remain an important unmet need. Many researchers argue that current progress relies on surface-applied finishing technologies rather than on intrinsically flame-retardant polymer architectures that maintain performance throughout the product life cycle.

### Future research directions

Future research should prioritize:

- 1) Development of truly inherent flame-retardant polymer systems with improved recyclability
- 2) Durable bio-based flame-retardant technologies capable of withstanding repeated laundering
- 3) Integration of multifunctionality without compromising comfort and mechanical performance
- 4) Scalable recycling technologies specifically designed for flame-retardant textiles
- 5) Eco-design approaches that incorporate end-of-life considerations during product development.

Greater emphasis on industrial-scale validation and life-cycle assessment will also be necessary to support commercial adoption.

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## Conflicts of interest

The author declares no conflict of interest.

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