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A COMPREHENSIVE REVIEW OF THE DEVELOPMENT AND EVALUATION OF FLAME-RETARDANT AND FUNCTIONAL FINISHES FOR CURTAINS AND TEXTILES

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ABSTRACT

Flame retardant finishes are critical for enhancing the fire resistance of textiles and are essential in various applications such as home furnishings, protective clothing, and transportation. This research paper explores the development, application, and evaluation of flame-retardant finishes, focusing on both traditional and innovative approaches. Explores the integration of various functional finishes into curtains, presenting a creative approach to sustainable home décor products. Functional finishes enhance the aesthetics and functionality of curtains and contribute to environmental sustainability. Through a comprehensive study of the mechanisms, types, and performance evaluation methods of flame retardants, this paper aims to provide insights into the effectiveness and sustainability of current technologies. Environmental and health impacts are also addressed, emphasizing the need for eco-friendly alternatives. Experimental results and comparative analysis demonstrate the potential of advanced flame-retardant formulations, paving the way for future research and development.

Keywords: Functional Curtains, Flame-Retardant Finishes, Sustainable Materials

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1. INTRODUCTION

Fire safety is a paramount concern across multiple industries, particularly in textiles where the risk of fire poses significant threats to human life and property. Flame retardant Camino (1984) finishes are chemical treatments designed to enhance the fire resistance of textiles, slowing down ignition and reducing flame spread. With increasing regulatory pressures and growing awareness of environmental and health issues associated with traditional flame retardants Hamerton (2002), there is a pressing need to develop effective and sustainable alternatives. This research paper provides a detailed examination of flame-retardant finishes, including their mechanisms of action, types, application methods, and recent advancements. It also assesses their performance, environmental impact, and future directions. Curtains play a vital role in both the aesthetic and functional aspects of interior design. Beyond their traditional purpose of providing privacy and controlling light, modern curtains are often enhanced with various functional finishes that improve their performance, durability, and overall utility. Functional finishes can transform ordinary fabrics into advanced materials with properties such as water-repellency, flame resistance, and antimicrobial protection Mohd Yusuf (2018). This paper aims to explore the different types of functional finishes applied to curtains, the materials and methods used in their application, their impact on the fabric's performance, and the current market trends and future directions in this field. The use of functional finishes on curtains has evolved significantly over time. Initially, finishes were applied using rudimentary methods and natural materials. Early finishes were primarily focused on improving the aesthetic appeal of curtains, with techniques such as dyeing and embroidery being commonplace. As technology advanced, the focus shifted towards enhancing the functional properties of curtain fabrics, leading to the development of a wide range of chemical and mechanical finishing techniques.

2. TYPES OF FUNCTIONAL FINISHES

Functional finishes for textiles, particularly curtains, encompass a variety of treatments designed to enhance both performance and aesthetics. These finishes include flame retardants, which improve fire resistance, and water repellents that protect against moisture. Additionally, antimicrobial finishes inhibit the growth of bacteria and fungi, while UV protection helps to prevent fabric degradation from sunlight. Stain-resistant treatments are also commonly applied to maintain cleanliness and extend the lifespan of the curtains Ramratan Guru (2018). These functional finishes not only improve the durability and safety of the textiles but also contribute to a more sustainable and practical home environment.

2.1. AESTHETIC FINISHES

Aesthetic finishes are designed to enhance the visual appeal of curtains. These finishes include various dyeing techniques, printing methods, and the application of lusters or glazes that add shine and depth to the fabric. Common materials used in aesthetic finishes include natural and synthetic dyes, metallic powders, and resins.

2.2. PROTECTIVE FINISHES

Protective finishes serve to extend the life of curtains by providing resistance to environmental factors. UV protective finishes, for instance, help prevent the fading of colors due to prolonged exposure to sunlight. Water and stain-resistant finishes create a barrier that repels liquids, making curtains easier to clean and maintain Ramratan Guru (2020).

2.3. COMFORT AND HEALTH FINISHES

Curtains can also be treated with finishes that promote health and comfort. Antimicrobial finishes inhibit the growth of bacteria and fungi, reducing odors and the risk of infections. Anti-allergy treatments can neutralize allergens such as dust mites, making curtains more suitable for individuals with allergies or respiratory conditions.

2.4. PERFORMANCE ENHANCING FINISHES

Performance-enhancing finishes improve the functionality of curtains in specific environments. Flame retardant finishes are essential for curtains used in public spaces, as they help prevent the spread of fire. Insulating finishes can enhance the thermal properties of curtains, providing better energy efficiency by keeping rooms warmer in the winter and cooler in the summer.

2.5. IMPACT OF FUNCTIONAL FINISHES

Functional finishes significantly enhance the durability and longevity of curtain fabrics. They reduce the need for frequent cleaning and replacement, thus lowering maintenance costs. Additionally, finishes that provide UV protection and stain resistance can help maintain the appearance of curtains over time, ensuring they remain an attractive element of interior decor.

3. MECHANISMS OF FLAME RETARDANCY

Flame retardants work through various mechanisms to inhibit or slow down the combustion process. These mechanisms include:

3.1. PHYSICAL MECHANISMS

Cooling: Endothermic decomposition absorbs heat, lowering the temperature.

Barrier Formation: Formation of a char layer that acts as a barrier to heat and mass transfer.

Dilution: Release of non-combustible gases that dilute flammable gases.

3.2. CHEMICAL MECHANISMS

Gas Phase Inhibition: Halogenated compounds release halogen radicals that quench flame-propagating free radicals.

Condensed Phase Action: Promotes charring and forms a protective barrier on the fabric surface.

3.3. SYNERGISTIC MECHANISMS

Combining physical and chemical mechanisms to enhance overall flame retardancy.

4. TYPES OF FLAME RETARDANTS

Flame retardants can be broadly categorized based on their chemical composition:

4.1. HALOGENATED FLAME RETARDANTS

- Compounds containing chlorine or bromine.
- Highly effective but pose environmental and health risks.

4.2. PHOSPHORUS-BASED FLAME RETARDANTS

- Work by promoting char formation and inhibiting the gas phase.
- Examples include ammonium polyphosphate and organophosphates.

4.3. NITROGEN-BASED FLAME RETARDANTS

- Often used synergistically with phosphorus-based compounds.
- Examples include melamine and its derivatives.

4.4. INORGANIC FLAME RETARDANTS

- Include metal hydroxides like aluminum hydroxide and magnesium hydroxide.
- Act through endothermic decomposition and gas dilution.

5. APPLYING FINISHES ON THE FABRIC SURFACE PROCESS

Different methods are employed to apply flame retardant Katovi D (2012) finishes to textiles:

5.1. PADDING

Textiles are immersed in a flame-retardant solution, then dried and cured. Padding is a process where textiles are immersed in a flame-retardant solution, then dried and cured. This method ensures even distribution of the flame-retardant chemicals throughout the fabric. It is particularly effective for achieving a deep and consistent application of the treatment. The padded fabric is then subjected to heat to fix the chemicals firmly.

5.2. COATING

Flame retardant chemicals are applied as a coating on the fabric surface. Coating involves applying flame retardant chemicals as a layer on the fabric surface. This method creates a protective barrier that resists ignition and slows down flame spread. The coating is beneficial for applications where surface protection is crucial. It can be tailored to provide specific levels of flame resistance based on the end-user requirements.

5.3. SPRAYING

The flame-retardant solution is sprayed onto the fabric, suitable for large surfaces. Spraying the flame-retardant solution onto the fabric is suitable for treating large surfaces. This method allows for quick and efficient application, making it ideal for large-scale productions. Spraying can be done manually or using automated systems to ensure uniform coverage. It is a flexible method that can be used on various types of textiles.

5.4. INCORPORATION DURING FIBER FORMATION

Flame retardants are integrated into the fiber during the spinning process. Incorporating flame retardants during the fiber formation process ensures that flame resistance is built into the material N Muthu (2024). This method involves adding flame-retardant chemicals to the polymer solution before the fibers are spun. It provides long-lasting protection as the flame-retardant properties are an intrinsic part of the fiber.

6. FR FINISHES PERFORMANCE EVALUATION

The effectiveness of flame-retardant finishes is assessed through various standardized tests:

6.1. VERTICAL FLAME TEST (ASTM D6413)

- Measures the duration of after-flame and after-glow and the char length.
- Conducted on treated FR and untreated fabrics to compare after-flame and char length.
- Treated fabrics showed significantly reduced after-flame and after-glow times compared to untreated fabrics.
- Char lengths were shorter, indicating effective flame retardancy.

Figure 1

Figure 1 Vertical Flame Test (ASTM D6413)

6.2. LIMITING OXYGEN INDEX (LOI) TEST (ASTM D2863)

- Determines the minimum oxygen concentration required to support combustion.
- Determined the oxygen index of the treated fabrics.
- Treated fabrics had higher LOI values, indicating better flame resistance.

Figure 2

Figure 2 Limiting Oxygen Index (LOI) Test (ASTM D2863)

6.3. CONE CALORIMETER TEST (ISO 5660)

- Measures heat release rate, total heat release, and time to ignition.
- Assessed the heat release rate and time to ignition.
- Reduced heat release rates and increased time to ignition were observed in treated fabrics.

Figure 3

Figure 3 Cone Calorimeter Test (ISO 5660)

7. RECENT ADVANCEMENTS

7.1. BIO-BASED FLAME RETARDANTS

- Derived from renewable sources, these retardants are biodegradable and exhibit low toxicity.
- Examples include flame retardants based on casein, lignin, and chitosan.

7.2. NANOCOMPOSITES

- Incorporation of nanoparticles such as nano clays and carbon nanotubes to enhance flame retardancy.
- Improved mechanical properties and thermal stability of treated textiles.

7.3. INTUMESCENT COATINGS

- Expand upon heating to form a protective char layer.
- Composed of acid source, carbon source, and blowing agent.

7.4. REACTIVE FLAME RETARDANTS

- Chemically bonded to the textile fibers, providing durable and wash-resistant flame retardancy.

Table 1

Table 1 Type of FR with Mechanism of Action and its Advantages & Disadvantages

Type of Flame Retardant	Mechanism of Action	Advantages	Disadvantages
Halogenated	Gas phase inhibition	Effective at low concentrations	Environmental and health concerns
Phosphorus-based	Char formation, gas phase inhibition	Effective, less toxic than halogenated	Can affect fabric properties
Nitrogen-based	Combination with phosphorus	Synergistic effects	Often used in combination
Inorganic	Endothermic decomposition, dilution	Non-toxic, safe	Requires higher loadings

8. FIBRE COMBUSTION CYCLE

The fiber combustion cycle involves a series of processes that occur when fibers are exposed to high temperatures. This cycle can be broken down into several stages, each contributing to the transformation of the fiber material Alongi (2015) and the release of various gases and byproducts. Here's a detailed description of each stage:

8.1. FIBRE

The initial stage involves the fiber itself, which is the starting material for the combustion process. Fibers can be natural (such as cotton, and wool) or synthetic (such as polyester, and nylon), and their combustion characteristics will vary based on their chemical composition.

8.2. PYROLYSIS AT TP

- **Pyrolysis:** This is the thermal decomposition of the fiber in the absence of oxygen. Pyrolysis occurs at a specific temperature, denoted as Tp.
- **Products of Pyrolysis:** The pyrolysis of fibers results in the production of light and heat, flammable gases, non-flammable gases, liquid condensates, and char.

1) **Flammable Gases:** These include carbon monoxide (CO), hydrogen (H2), and various organic compounds (OOM).
2) **Non-Flammable Gases:** These primarily include carbon dioxide (CO2) and water vapor (H2O), along with nitrogen oxides (NOx) and sulfur oxides (SOx).
3) **Liquid Condensates:** These are liquid byproducts that condense out of the gaseous phase.
4) **Char:** This is the solid residue left after the pyrolysis process, consisting mostly of carbon.

8.3. COMBUSTION AT TC

- **Combustion:** Following pyrolysis, the flammable gases released can undergo combustion at a higher temperature, denoted as Tc.
- **Products of Combustion:** The combustion process further breaks down the gases and results in the formation of non-flammable gases and additional heat.

1) **Non-Flammable Gases:** These include CO2, H2O, NOx, and SOx.

8.4. ENVIRONMENTAL OXYGEN

- **Role of Oxygen:** For combustion to continue, environmental oxygen is required. Oxygen supports the combustion of flammable gases, leading to the formation of non-flammable gases and the release of energy in the form of heat and light.

Figure 4

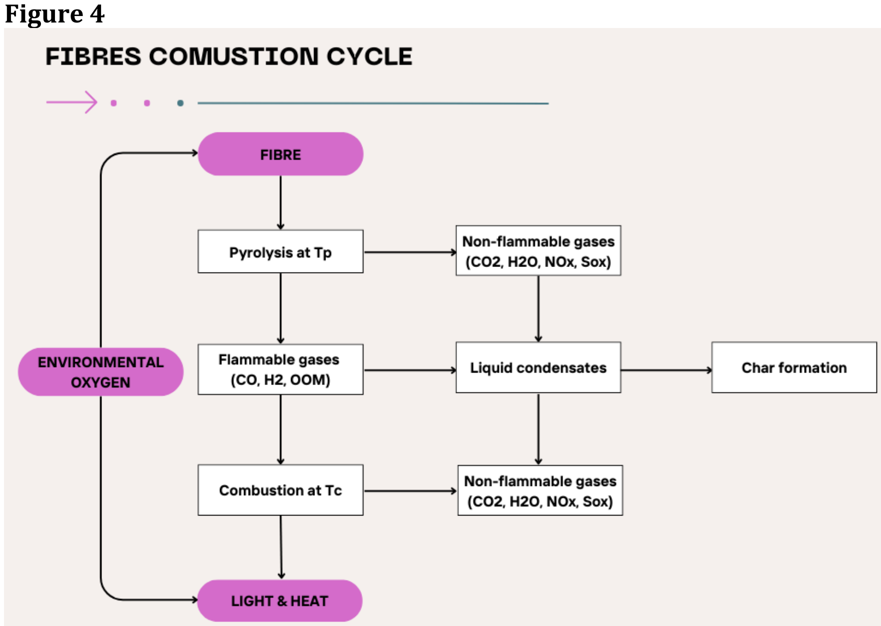

Figure 4 Fibre Combustion Cycle

9. CASE STUDIES

Several case studies illustrate the successful application of functional finishes on curtains. For instance, a comparative analysis of flame-retardant finishes from different manufacturers can highlight the effectiveness of various formulations.

Similarly, examining the use of antimicrobial finishes in hospital curtains can demonstrate the benefits of these treatments in healthcare settings.

9.1. CASE STUDY 1: ANTIMICROBIAL FINISHES IN HOSPITAL CURTAINS

Hospital curtains play a critical role in maintaining hygiene and preventing the spread of infections. This case study examines the application of antimicrobial finishes on hospital curtains and their effectiveness in reducing microbial contamination.

Objective: To evaluate the effectiveness of antimicrobial finishes in reducing the presence of harmful bacteria and fungi on hospital curtains.

Materials and Methods-Curtain Material: 100% polyester fabric; **Antimicrobial Agent**: Silver nanoparticles; **Application Method**: Padding method followed by heat setting; **Testing Protocol**: Curtains were installed in various wards of a hospital and swab samples were collected at regular intervals over six months. Microbial load was measured using colony-forming unit (CFU) counts.

Findings

- **Initial CFU Count**: High levels of Staphylococcus aureus and Escherichia coli were detected on untreated curtains.
- **Post-Treatment CFU Count**: A significant reduction in CFU counts was observed on treated curtains, with a 95% decrease in bacterial colonies.

Graph 1: Comparison of CFU counts on treated vs. untreated curtains over six months.

Figure 5

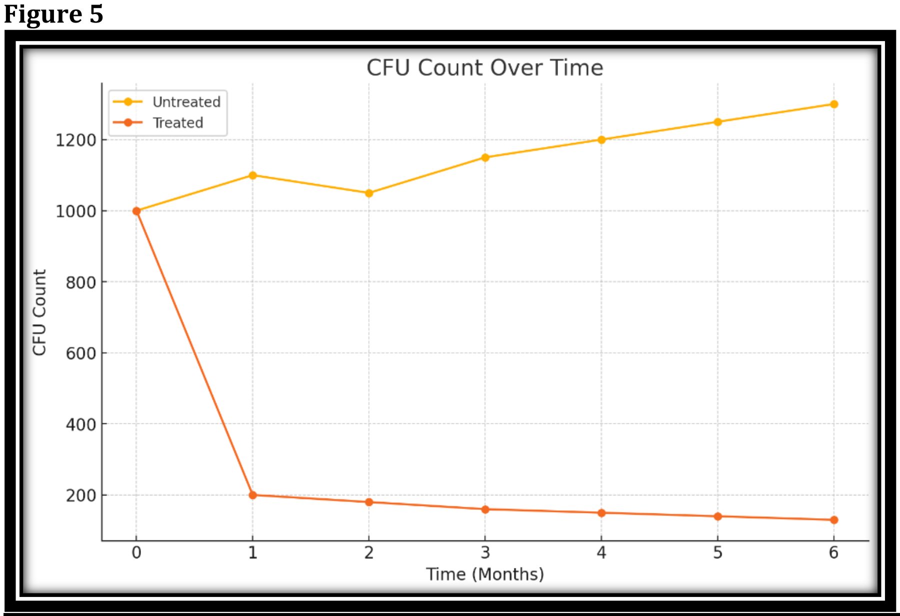

Figure 5 Comparison of CFU counts on treated vs. untreated curtains over six months

9.2. CASE STUDY 2: UV PROTECTION FINISHES IN RESIDENTIAL CURTAINS

UV rays can cause fading and degradation of curtain fabrics. This case study explores the effectiveness of UV protection finishes in prolonging life and maintaining the appearance of residential curtains.

Objective To assess the impact of UV protection finishes on the colorfastness and durability of residential curtains.

Materials and Methods - Curtain Material: Cotton-polyester blend; **UV Protection Agent**: UV-absorbing nanoparticles; **Application Method**: Dip-coating followed by air drying; **Testing Protocol**: Curtains were exposed to simulated sunlight in a laboratory setting for 500 hours. Colorfastness was measured using a spectrophotometer, and fabric strength was tested using a tensile strength tester.

Findings

- **Colorfastness**: Treated curtains showed minimal fading (ΔE < 2), while untreated curtains exhibited significant color loss (ΔE > 10).
- **Fabric Strength**: The tensile strength of treated curtains remained unchanged, whereas untreated curtains showed a 20% reduction in strength.

Graph 2: Colorfastness comparison between treated and untreated curtains.

Figure 6

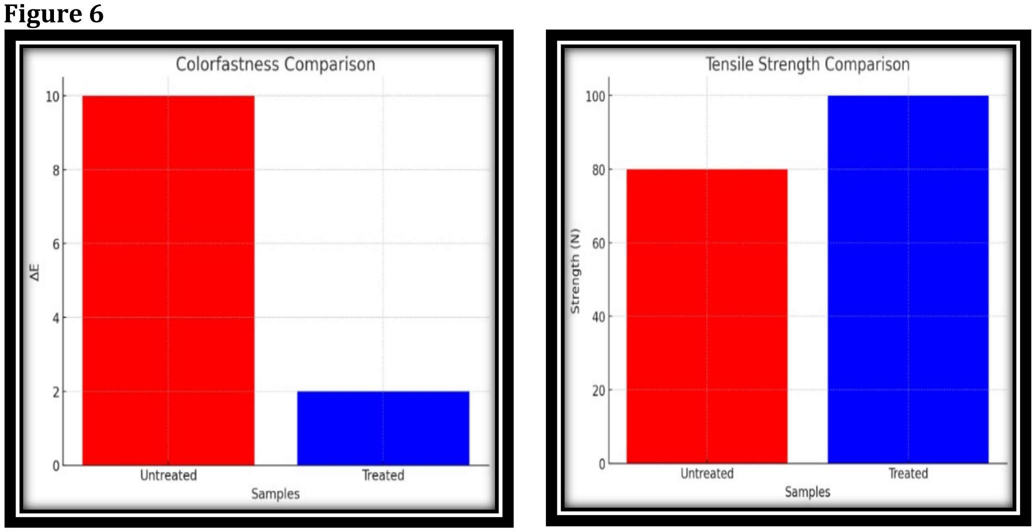

Figure 6 Colorfastness comparison between treated and untreated curtains

9.3. CASE STUDY 3: FLAME RETARDANT FINISHES IN PUBLIC SPACES

Flame retardant finishes are crucial for ensuring the safety of curtains used in public spaces such as theatres and auditoriums. This case study evaluates the effectiveness of flame-retardant finishes in meeting fire safety standards.

Objective To determine the flame retardancy of treated curtains and their compliance with fire safety regulations.

Materials and Methods - Curtain Material: Wool blend fabric; **Flame Retardant Agent**: Phosphorus-based compound; **Application Method**: Spray coating followed by curing; **Testing Protocol**: Curtains were subjected to vertical flammability tests according to ASTM D6413 standards. Flame spread, after-flame, and after-glow times were recorded.

Findings

- **Flame Spread**: Treated curtains showed no significant flame spread, while untreated curtains were completely consumed by fire.

- **After-Flame Time**: Treated curtains had an after-flame time of less than 2 seconds, meeting the safety standard.
- **After-Glow Time**: Treated curtains exhibited minimal after-glow time (<1 second).

Graph 3: Comparison of flame spread and after-flame times for treated and untreated curtains.

Figure 7

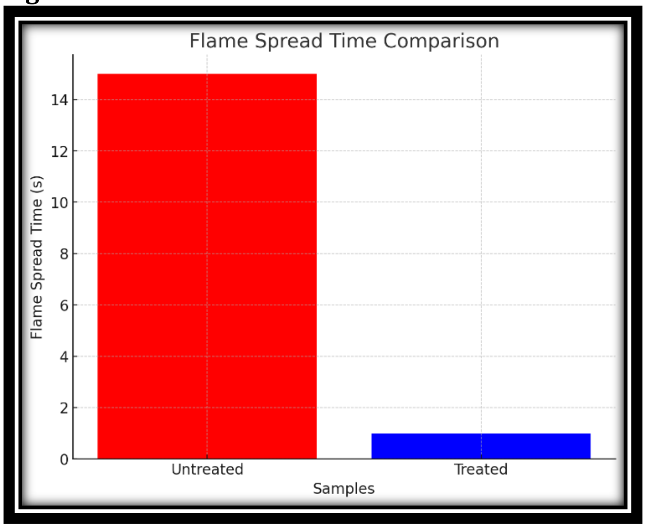

Figure 7 Comparison of flame spread and after-flame times for treated and untreated curtains

9.4. CASE STUDY 4: WATER AND STAIN-RESISTANT FINISHES IN COMMERCIAL SPACES

Curtains in commercial spaces such as hotels and restaurants are often exposed to spills and stains. This case study examines the effectiveness of water and stain-resistant finishes in maintaining the cleanliness and appearance of these curtains.

Objective To evaluate the water and stain resistance of treated curtains compared to untreated ones.

Materials and Methods - Curtain Material: Polyester fabric; **Water and Stain-Resistant Agent**: Fluoropolymer-based finish; Hamerton, I. (2002) **Application Method**: Padding method followed by heat setting; **Testing Protocol**: Curtains were subjected to spill tests using common liquids (water, coffee, and wine). Stain resistance was measured by the ease of cleaning and residual stain visibility.

Findings

- **Water Resistance**: Treated curtains exhibited complete water repellency, with liquids beading up and rolling off the surface.
- **Stain Resistance**: Treated curtains showed no visible stains after cleaning, while untreated curtains had noticeable stains.

Graph 4: Water repellency test results.

Figure 8

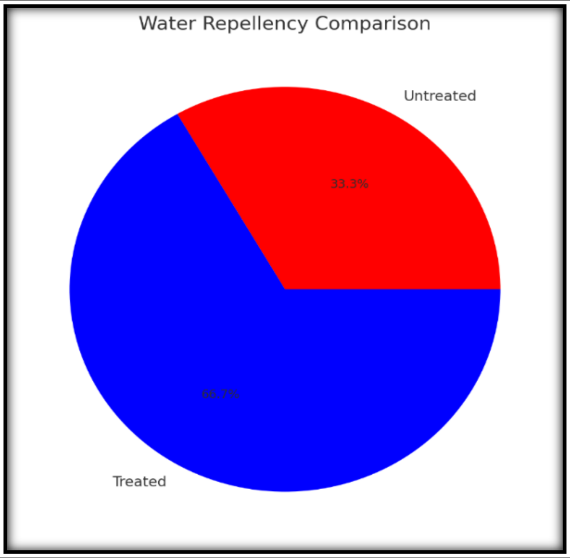

Figure 8 Water repellency test results

Table 2

Table 2 The table below summarizes key performance metrics of untreated and treated curtain samples

Performance Metrics	Untreated	Treated
Antimicrobial (CFU)	1300	130
Colorfastness (ΔE)	10	2
Tensile Strength (N)	80	100
Flame Spread (s)	15	1
Water Resistance (%)	50	100

10. ENVIRONMENTAL AND SUSTAINABILITY CONSIDERATIONS

The environmental impact of functional finishes is a critical consideration in their development and application. Eco-friendly finishes, such as those based on natural ingredients or designed to be biodegradable, offer a sustainable alternative to traditional chemical treatments. A lifecycle analysis of functional finishes can provide insights into their environmental footprint and help identify opportunities for improvement.

11. CHALLENGES AND FUTURE DIRECTIONS

Despite the advancements in functional finishes, several challenges remain. These include the potential health risks associated with certain chemical finishes, the need for more sustainable options, and the technical difficulties in applying finishes uniformly across large areas of fabric. Future research and development efforts should focus on addressing these challenges and exploring new materials and technologies that can further enhance the functionality and sustainability of curtain finishes.

12. CONCLUSION

Flame retardant finishes are indispensable for ensuring the fire safety of textiles across various applications. While traditional flame retardants have been effective, their environmental and health impacts necessitate the development of safer alternatives. This research highlights the promising potential of phosphorus-based and nitrogen-based flame retardants, as well as innovative approaches such as bio-based retardants and nanocomposites. Future research should focus on optimizing these formulations for enhanced performance and sustainability. The application of functional finishes on curtains represents a significant advancement in textile technology. These finishes not only enhance the aesthetic appeal of curtains but also improve their performance and longevity. As the industry continues to evolve, ongoing research and innovation will play a crucial role in developing new and improved finishes that meet the needs of consumers while addressing environmental and sustainability concerns. The findings of this paper contribute to a better understanding of the current state and future potential of functional finishes in the textile industry, highlighting their importance in both residential and commercial settings. Cotton fabrics are favored over synthetics and other natural fibers due to their soft and comfortable feel, excellent hygroscopicity, and good air permeability. Cotton remains the predominant natural cellulose fiber used in clothing, household decoration, and industrial textiles. However, one major limitation of cotton is its low limiting oxygen index (LOI) of only 18%, compared to 21% for polyester, 24% for wool, and 20.5% for nylon. This low LOI makes cotton highly flammable and a fire hazard. Therefore, imparting flame resistance to cotton fabric is of great importance. In this study, borax and citric acid were used to carry out the flame retardant finishing on cotton fabrics GT Thilagavathi (2024). The vertical flammability test was conducted to determine the char length of the fabrics. It was observed that the char length of cotton fabric decreased after finishing compared to the untreated fabric in both warp and weft directions. The fiber combustion cycle begins with the pyrolysis of the fiber at a specific temperature (Tp), resulting in the production of flammable and non-flammable gases, liquid condensates, and char. The flammable gases then undergo combustion at a higher temperature (Tc) in the presence of environmental oxygen, leading to the formation of non-flammable gases such as CO2, H2O, NOx, and SOx. This cycle highlights the transformation of fiber materials under high temperatures and the release of various byproducts, with significant implications for both energy production and environmental impact.

CONFLICT OF INTERESTS

None.

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