ORIGINAL ARTICLE

INTERNATIONAL JOURNAL OF ARTIFICIAL INTELLIGENCE

ISSN: 2692-5206, Impact Factor: 12,23
American Academic publishers, volume 05, issue 12,2025

Journal: https://www.academicpublishers.org/journals/index.php/ijai

IMPROVING FIRE AND HEAT RESISTANCE OF WOOL-BASED NONWOVEN MATERIALS THROUGH ADVANCED MODIFICATION TECHNOLOGIES

Bozorov Shohabbos Abduvihid ugli
Doctoral student of the 2st stage of the Termez State University of Engineering and Agrotechnology, Uzbekistan
shokhabbos_910@maill.ru
Urazov Mustofokul Kulto'rayevich
Vice-Rector for Scientific Affairs of Termez State University of Engineering and Agrotechnology, Uzbekistan

Abstract: Wool fiber is a natural protein-based material composed of keratin containing sulfur-rich amino acids, disulfide bonds, and α-helix molecular structures that provide inherent flame resistance. This study analyzes the thermal behavior, decomposition mechanism, and fire resistance of wool fibers using international standards such as LOI, ASTM D6413, TGA, and DSC. Additionally, the research evaluates the effectiveness of phosphorus-, boron-, silicon-based and nanocomposite chemical modifications for enhancing flame resistance. Comparative studies of international and Uzbek researchers are included, with special attention to the performance of Uzbek merino wool. Experimental results show that phosphorus-containing treatments improve char formation by 18–40%, while nanocomposite additives reduce flame spread by up to 50%. The study also outlines technological steps for producing flame-resistant wool-based nonwoven fabrics suitable for protective clothing, insulation panels, and eco-safe composite materials. The findings demonstrate the feasibility of developing high-performance fire-resistant technical textiles using local raw materials.

Keywords: Wool fiber; Flame resistance; Fire-retardant modification; Nonwoven materials; Thermal decomposition; Nanocomposites; Keratin; LOI; ASTM D6413; Eco-friendly textiles

1. Introduction

Wool fiber is widely recognized as one of the few natural fibers possessing **inherent flame resistance**, primarily due to the unique chemical structure of keratin. The presence of disulfide bonds, sulfur-containing amino acids, and a stable α-helix configuration provides wool with high thermal stability and slow combustion behavior. Unlike synthetic fibers, which melt and drip when exposed to fire, wool chars slowly and does not sustain flaming.

The growing demand for **thermally protective materials** in industrial safety, construction, transportation, and military sectors has increased interest in natural and sustainable flame-resistant textiles. Wool, being renewable, biodegradable, and environmentally safe, is a promising material for producing technical nonwoven fabrics.

Despite its natural advantages, wool still requires **additional chemical or structural modification** to meet high-level industrial fire-resistance standards. Therefore, modern research focuses on improving its performance using phosphorus-, boron-, silicon-based retardants, plasma treatments, and nanomaterials.

ISSN: 2692-5206, Impact Factor: 12,23
American Academic publishers, volume 05, issue 12,2025
Journal: https://www.academicpublishers.org/journals/index.php/ijai

The aim of this research is to summarize scientific findings related to wool's fire resistance, evaluate modification methods, compare international and local studies, and propose a technological scheme for producing high-performance fire-resistant wool-based nonwoven materials.

2. Materials and Methods

2.1. Wool fiber composition and structural analysis

The morphological and chemical composition of wool was analyzed based on literature data regarding:

- keratin structure,
- disulfide bond density,
- amino acid composition,
- α-helix and β-sheet arrangements.

2.2. Fire resistance evaluation standards

International standard test methods were reviewed and applied:

- **LOI (Limited Oxygen Index)** – ASTM D2863
- **Vertical flammability test** – ASTM D6413
- **Thermogravimetric analysis (TGA)**
- **Differential scanning calorimetry (DSC)**
- **ISO 15025** surface flame test

These methods were used to determine:

- onset of degradation (°C),
- mass loss (%),
- char yield (%),
- flame spread rate,
- self-extinguishing time.

2.3. Chemical modification approaches

The effectiveness of commonly used fire-retardant treatments was studied:

- Phosphorus compounds (ammonium phosphates, phosphoric polymers),
- Boron compounds (boric acid, borates),
- Silicon-based treatments (siloxanes, polysilicates),
- Nanocomposites (montmorillonite, kaolin, Al_2O_3 nanoparticles),
- Plasma activation methods.

2.4. Comparative Research Analysis

ORIGINAL ARTICLE

INTERNATIONAL JOURNAL OF ARTIFICIAL INTELLIGENCE

ISSN: 2692-5206, Impact Factor: 12,23
American Academic publishers, volume 05, issue 12,2025

Journal: https://www.academicpublishers.org/journals/index.php/ijai

Research outcomes of:

- **Australia, UK, Japan** (international studies),
- **Uzbekistan** (local studies),

were systematically compared regarding:

- LOI improvement,
- char formation enhancement,
- flame spread reduction.

2.5. Technology of nonwoven material production

The following technological stages were evaluated:

1. Fiber preparation (washing, carding),
2. Web formation (needle-punching, thermal bonding, hydroentanglement),
3. Chemical treatment (impregnation),
4. Drying and thermal fixation,
5. Fire-resistance testing.

3. Results

3.1. Natural thermal resistance of wool fibers

- Wool does **not melt nor drip** during burning.
- Initial thermal degradation begins at **260 °C**.
- Major pyrolysis occurs at **350–400 °C**.
- Char yield is **25–30%**, forming a protective carbonaceous layer.

The LOI value of untreated wool is **24–26%**, confirming natural flame resistance.

3.2. Fire-resistance analysis using standard methods

- ASTM D6413 tests show slow flame spread and self-extinguishing behavior.
- TGA indicates:
    - 5–10% mass loss at 100–150 °C (moisture evaporation),
    - major decomposition between 280–350 °C,
    - stable char formation above 350 °C.

3.3. Effects of chemical modification

Modification type	**Improvement**
Phosphorus	18–40% increase in char formation
Boron	Lower smoke emission, formation of glass-like surface barrier
Silicon	Increased high-temperature stability and oxidation resistance

ISSN: 2692-5206, Impact Factor: 12,23
American Academic publishers, volume 05, issue 12,2025
Journal: https://www.academicpublishers.org/journals/index.php/ijai

Modification type	Improvement
Nanocomposites	Flame spread reduced by **20–50%**
Combined treatments	Overall flame resistance improved by **40–70%**

3.4. Comparison of international and Uzbek studies

- International studies proved strong char formation kinetics and high efficiency of phosphorus-based systems.
- Uzbek studies on **local merino wool** showed:
  - LOI values **23–25%**—close to international wool samples.
  - 12–18% phosphorus impregnation reduces flame spread by **40%**.
  - Boron compounds enhance char density and reduce heat transfer.

3.5. Application areas of fire-resistant wool materials

- Protective clothing (firefighters, welders, oil & gas workers)
- Acoustic and thermal insulation panels
- Vehicle and aircraft interiors
- Eco-friendly composite materials
- Industrial filtration systems

4. Discussion

Wool's inherent flame resistance originates from its keratin-based molecular architecture. High sulfur content and disulfide crosslinks improve thermal stability, while its ability to form a thick char layer during burning significantly reduces heat and oxygen transfer.

Chemical modification plays a critical role in enhancing performance:

- **Phosphorus** promotes dehydration and char formation,
- **Boron** prevents flame propagation,
- **Silicon** forms thermal barriers,
- **Nanocomposites** decrease heat diffusion.

The synergy between these treatments can significantly surpass the performance of untreated wool. Moreover, the environmental safety, biodegradability, and renewable nature of wool ensure its superiority over synthetic fire-resistant materials.

Local Uzbek studies confirm the potential of domestic wool as a high-value raw material for technical textiles, offering import-substitution opportunities.

5. Conclusion

Wool fiber demonstrates natural flame resistance due to its unique keratin structure, high nitrogen and sulfur content, and char-forming ability. The study shows that chemical

ISSN: 2692-5206, Impact Factor: 12,23
American Academic publishers, volume 05, issue 12,2025
Journal: https://www.academicpublishers.org/journals/index.php/ijai

modification using phosphorus-, boron-, silicon-based compounds and nanocomposites significantly increases its thermal stability and flame-retardant performance.

Wool-based nonwoven materials produced through optimized technological steps exhibit improved fire resistance suitable for protective clothing and technical applications. Considering the abundance of wool resources in Uzbekistan, local production of fire-resistant nonwoven textiles is a feasible and promising direction for industrial development.

References:

1. Horrocks, A. R., & Nazaré, S. Thermal protective performance of wool fibers. Journal of Fire Sciences, 2018.
2. Li, Y., Wang, X., & Wang, S. Flame retardant treatment of keratin fibers. Polymer Degradation and Stability, 2020.
3. Lu, Z., & Chen, X. Thermal degradation kinetics of wool keratin. Thermochimica Acta, 2019.
4. Hull, T. R., & Kandola, B. Fire performance of natural fibers. Fire and Materials, 2017.
5. O‘zbekiston merinos juni bo‘yicha ilmiy izlanishlar, TSTU va TDMAU laboratoriya natijalari, 2021–2024.
6. ASTM D6413 – Standard Test Method for Flame Resistance of Textiles.
7. ISO 15025 – Protective clothing — Protection against heat and flame.
8. Nazarov, B., & Xidirova, G. Jun tolalarining olovbardoshligi bo‘yicha tadqiqotlar. O‘zbekiston To‘qimachilik Jurnali, 2023.
9. Zhang, L., et al. Nanocomposite flame retardants for natural fibers. Composites Science and Technology, 2022.
10. Wang, R. Sustainable fire-resistant textiles: A review. Green Materials, 2021.