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ECO-FRIENDLY FIRE RETARDANT TEXTILE FINISHING: UTILIZING POMEGRANATE PEEL FOR SUSTAINABLE FLAME RESISTANCE

Tanuja Kohli [1] and Meenu Srivastava [2]

[1] Ph.D. student and [2] Professor

Department of Textiles and Apparel Designing, College of Community and Applied Sciences,

Maharana Pratap University of Agriculture and Technology, Udaipur 313001,

Rajasthan, India.

[1] **Correspondence Author: Tanuja Kohli**

ABSTRACT

The increasing environmental and health concerns associated with synthetic flame retardant agents have driven the search for sustainable, non-toxic alternatives. This study investigates the potential of pomegranate peel extract as a natural and eco-friendly fire-retardant finish for textiles. Pomegranate peel, an agricultural waste product, is rich in polyphenols and tannins, which exhibit inherent flame-retardant properties. The extract was applied to textile fabrics, and its fire resistance was evaluated using standard flammability tests. Additionally, the treated fabrics were assessed for durability, mechanical properties, and biodegradability. The results indicate that pomegranate peel extract significantly enhances the flame resistance of textiles while maintaining their

structural integrity. Furthermore, the natural finish is biodegradable and free from harmful chemicals, making it an environmentally sustainable alternative to conventional flame retardants. This research highlights the potential of utilizing agricultural by-products in textile applications, contributing to the development of green, non-toxic fire-retardant solutions for the industry.

Keywords: Eco-friendly flame retardants, Pomegranate peel extract, Sustainable textiles, Natural fire resistance, Biodegradable textile finishing, Polyphenols and tannins, Agricultural waste utilization, Green chemistry in textiles.

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1. Introduction

The demand for fire-retardant textiles has significantly increased across various industries, including apparel, home furnishings, and protective clothing. Traditionally, synthetic flame retardant agents, such as halogenated compounds and organophosphates, have been widely used to enhance the fire resistance of textiles. However, these chemicals pose serious environmental and health concerns due to their toxicity, persistence, and potential bioaccumulation[1]. As a result, there is a growing need for eco-friendly and sustainable alternatives that can provide effective flame resistance without adverse effects. In this context, natural sources have emerged as promising substitutes for conventional flame retardants. Among these, agricultural by-products like pomegranate peel offer an innovative and sustainable solution. Rich in polyphenols and tannins, pomegranate peel exhibits inherent flame-retardant properties while also being biodegradable and non-toxic[2]. Utilizing such waste-derived materials aligns with the principles of green chemistry and circular economy, reducing both environmental pollution and reliance on hazardous chemicals.

This research explores the potential of pomegranate peel extract as an environmentally friendly flame-retardant finish for textiles. By investigating its effectiveness in enhancing fire resistance and analysing its impact on fabric properties, this study aims to contribute to the development of safer and more sustainable fire-retardant textile treatments.

2. Materials and methods

This study focused on the synthesis of bio-based FR agent using plant-derived polyphenols, tannins and lignin. Organic cotton fabric with a GSM of 114.5 g/m^2, thickness 0.27 mm, and a fabric count of 99 ends per inch x 87 pics per inch was selected for the study.

Butane-1,2,3,4-tetracarboxylic acid (BTCA), a green cross-linker, has been used which was 98% pure, with a melting point of 195–197^{0}C and <15% H_2O. It is a polycarboxylic acid crosslinking agent that isn't formaldehyde base[3]. The natural source *Punica grantum* was procured from local area in raw/natural form after a thorough study regarding the phytochemical constitution of the source. Phenolic content in Indian pomegranate peel extract approximately 284mgs of gallic acid equivalent (GAE) per gram of dried peel[4].

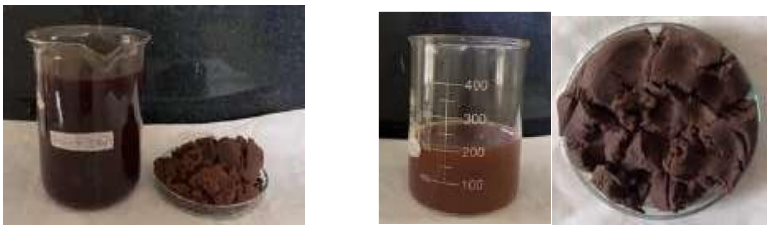
2.1 Fabric preparation

The selected fabric was scoured to remove dust, dirt, stains, oil and other impurities. Premordanting was done using Potassium aluminum sulfate (Alum). After that, cross-linking agent (BTCA) and catalyst SHP (Sodium hypo phosphite) was applied to the fabric by keeping MLR ratio 1:20. It was discovered that using BTCA at a concentration of 80 g/L and SHP at 36.6g/L enhanced the treated cotton's characteristics and inhibited the migration of cellulose chains. Furthermore, BTCA contributes to the improvement of the wash durability of finished fabric[4]. The fabric was immersed in the mixture for 1 hour, then dried for 5 minutes at 80^{0}C and cured for 2 minutes at 120^{0}C. The temperature was set at 120^{0}C because it is found that the rate of cross-linking reaction, which is based on the thermal vibration of the cellulose chain that BTCA grafted is sensitive to temperatures higher than 170^{0}C.

2.2 Extraction of FR agent

After procurement, the bio-resource (*Punica grantum*) was washed thoroughly with distilled water, and dried at room temperature, relative humidity: 74%. After that, dried source was converted into fine powders by the use of grinder machine. Extraction of bio molecules was done by dissolving different sources in methanol (CH_3OH) followed by aqueous medium. Firstly, extraction was done by keeping M:L=1:10 containing 70:30 ratio of solvent and aqueous medium. Prepared solution then treated at 60 degrees Celsius for 20 hours and filtered. For the extraction of solvent medium solution was kept at room temperature for 24-48 hours. After that, Extracted source

again dissolved in complete aqueous medium and treated under 60 degrees Celsius for 10 hours. Then final extraction of compounds was done.



Solvent extraction Aqueous extraction

Fig 1. Extraction of compounds

Extracted solutions then treated under ultrasonic cleaner which works through high-frequency sound waves to agitate the liquid solution of water or solvent, and cause cavitation of solution molecules. This cavitation creates a void (or cavity) which gets trapped as a bubble in a liquid solution of water or solvent and implode with such force that contaminants adhering to surfaces dislodged.

Prepared finish was applied onto surface modified organic cellulosic fabric samples at four different concentrations (20%, 30%, 40% and 50%) using padding method. The padding machine facilitates the most even coating of the material. The study's fabric samples were coated using a model padding mangle in the lab. With 70% wet pickup, one nip and one dip were permitted. The cloth was immersed in a padding solution with an MLR of 1:15 that contained extracts of particular bioresources and combinations for 45 minutes. After that, the fabrics were moved between two rollers so that the extract solution could be applied uniformly to the surface. In addition to eliminating extra pad liquor and air, the pressure produced by the rollers facilitates the entry of the particles into the spaces between the fibres. The fabrics were then removed and allowed to dry for 30 minutes at 80°C in the oven, followed by a 2-minute curing period at 120°C.

Fig 2. Modified fabric samples 3. Results and discussion

After the application of prepared extract solutions on to the selected fabric, the burning behavior of the control and treated fabric samples have been evaluated as per the standard methods. Cotton fabric without any treatment could not pass the flammability test and was completely burnt, suggesting on cotton poor fire retardancy. *Punica grantum* treatment to the cotton fabric imparted good flame retardancy and burning of the fabric was stopped after removing burning source.

3.1 Vertical Flammability test

Vertical flammability test method was used to evaluate the behaviour of control and treated fabric samples. In this test, different parameters were measured according to ISO 900 method[5]. As per this method, the fabric sample (250mm X 40mm) has been ignited with the flame of

38mm height for 12 sec. Before testing, all the samples have been conditioned at 65% R.H and 27^0C. While testing the efficacy of modified fabric samples it was noticed that the untreated or control cotton fabric easily caught fire during the vertical burning test with a robust flame on the specimen; the fabric sample was destroyed and fully consumed within 12 s (the ignition time) leaving only traces of residue on the sides. Table 1 shows the photographs of the modified unwashed cotton fabric samples after vertical burning test and Table 2 shows the photographs of the modified washed cotton fabric samples (5 wash cycles) after vertical burning test. In both tests modified cotton fabrics stopped the flame propagation after the removal of flame source and self-extinguished, showing no after-flame or after-glow activity.

Table 1. Vertical burning test values of modified unwashed cotton fabric samples

Control sample	Modified fabric samples			
				
	20% ext.	30% ext.	40% ext.	50% ext.
	L = 175 mm	L = 140 mm	L = 105 mm	L = 90 mm
12 s (ignition time)	(5.5)	(7.1)	(8.8)	(10.2)
	Add on (%) = 7.9 %			

Table 2. Vertical burning test values of modified washed cotton fabric samples

Control sample	Modified fabric samples			
				
	20% ext.	30% ext.	40% ext.	50% ext.
	L = 181 mm	L = 170 mm	L = 135 mm	L = 110 mm
12 s (ignition time)	(4.9)	(6.2)	(7.8)	(9.4)
	Add on (%) = 7.08 %			

As shown in Table 1 and Table 2, the test values of unwashed fabric samples and 5 cycle washed fabric samples treated with selected bio-resource decrease as the extract concentration rises the fabric samples that have been altered with a 50% extract concentration exhibit the best flame-retardant qualities.

3.2 Limiting oxygen index (LOI)

The values of LOI and add-on of treated unwashed and treated washed cotton fabric samples modified with pure *Punica grantum* extract solution are given in the Table 3.

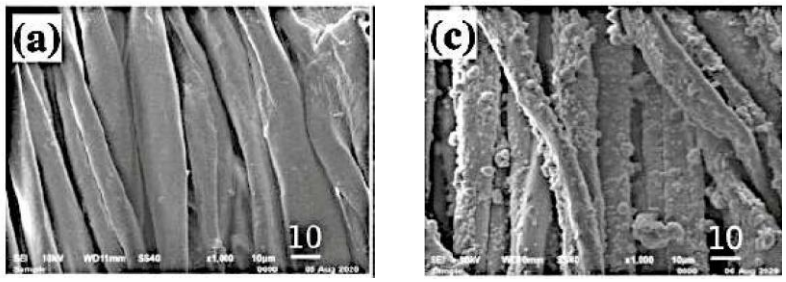
Table 3. Limiting Oxygen Index (LOI) test values of treated unwashed and treatedwashed fabric samples

Combinations and Concentrations	Add-on		Limiting Oxygen Index (LOI)	
	Before wash	After wash	Before wash	After wash
Punica 20% *grantum*	5.9 6.7	4.9 5.8	18.9	-
30%			21.0	-
40%	7.3	6.7	24.7	24.0
50%	8.2	7.6	27.0	26.6

It can be observed that add-on weight consistently rises with increase in concentration of particular bio-resource. As shown in the chart there is no significant change between the addon values of before and after-washed treated fabric samples. This implies the better crosslinking between developed extract and cellulose material. Treated after wash fabric sample shows no LOI value for first two concentrations (i.e. 20% and 30%). It can be deduced that there were no significant difference between the LOI test values of washed and unwashed fabric samples in the above data. Above figure also shows that all treated fabric samples after subjecting to laundering retard very low LOI values seen in treated washed samples as compared to that of treated-unwashed samples which shows the durability of the treatments on the fabrics. Further it is also noticed that this efficiency of flame- retardants does not diminish on washing for last two concentrations thus assuring the maximum efficiency of the flame retardants.

3.3 SEM assessment

To observe the surface morphology of the cotton fabric, SEM test was performed. Figure 3 shows the SEM images of the control (untreated) cotton and cotton fabric samples treated with selected bio-resource *Punica grantum*. With a flat, ribbon-weave structure made of winding, thin cotton fibers, the control fabric's surface was observed to be clean and smooth. The bubble char structure (Fig. 3) which has a continuous outer surface and a porous, swelling structure, prevents the cellulose from degrading and acts as a barrier to heat transfer, as well as insulating the oxygen source. This suggests even further that it may be possible to stop the flames from spreading. The bubble structure on the surface of the char residue improved in flame retardance as the extract concentration increased[6].



Control fabric Modified fabric

Fig 3. SEM analysis

3.4 Mechanical strength

Tensile strength was evaluated according to standards ASTM D461 (Computerized fabric strength tester). The effect of *Punica grantum* on the mechanical property of treated samples were studied after comparing the results between control fabric sample and treated fabric samples.

Table 4: Effect of *Punica grantum* on tensile strength of fabric

Sample	Concentrations	Unwashed	Washed
Pure 'b'	20%	188.7	3.2
	30%	195.5	4.9
	40%	224.2	6.6
	50%	248.9	8.9

It can be seen from Table 4 that the application of flame- retardant finish has no significant adverse effect on the tensile strength of *Punica grantum* treated sample.

4. Conclusions

This study demonstrates the effectiveness of pomegranate peel extract as a sustainable and ecofriendly fire-retardant finish for textiles. The treated fabrics exhibited significant improvements in flame resistance, as confirmed by successful results in the vertical burning test, where the flame spread was considerably reduced. Additionally, the limited oxygen index (LOI) test showed an increased threshold for combustion, indicating enhanced fire retardancy. Beyond flame resistance, the treated textiles maintained good mechanical properties, ensuring that the application of the natural finish did not compromise fabric strength or durability. Furthermore, wash durability tests revealed that the flame-retardant effect remained intact even after multiple laundering cycles, highlighting the long-term stability of the treatment. Unlike conventional synthetic flame retardants, which pose environmental and health risks, the use of pomegranate peel extract provides a biodegradable, non-toxic, and renewable alternative. The findings suggest that agricultural waste materials can be successfully repurposed for functional textile applications, aligning with sustainable development goals and circular economy principles. Further research on optimizing application methods and exploring synergistic effects with other natural flame retardants can help advance this approach for commercial use. Overall, this study contributes to the growing field of green textile chemistry, offering a viable pathway toward safer, high-performance, and environmentally responsible fire-retardant treatments.

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