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Investigating the Effects of PU-Based Back-Coating with Boric Acid and Titanium Dioxide Additives on Flame Retardancy Levels and Comfort Properties of 100% Cotton Denim Fabric

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Abstract

This study aimed to develop a cost-effective and resource-efficient application to enhance the thermal stability, flame retardancy, self-cleaning, and antibacterial properties of cotton denim fabrics through a single-step, flexible, and simple polyurethane (PU) based back-coating method, ultimately increasing the use of denim fabrics in daily and work clothes thanks to the increased functionality. This method utilizes boric acid (H_3BO_3) and a binary composite of H_3BO_3-titanium dioxide (TiO_2) as functional additives while considering comfort parameters. Limiting oxygen index (LOI) and vertical burning tests were conducted to explore the thermal stability and flame retardancy of the samples, while assessments of air permeability, water vapour permeability, thermal resistance, and thermal absorptivity were performed to investigate the comfort properties. Comparing two kinds of back-coated denim fabrics, H_3BO_3-TiO_2 back-coated cotton fabric showed the best flame retardancy with the lowest char length (45 mm) and highest LOI (27%). The air permeability values of back-coated fabrics decreased by approximately half compared to the untreated denim fabric. Although the water vapour permeability values decreased, they were less affected by the coating. Coating application reduced thermal conductivity and thermal absorbency, resulting in more thermally resistant denim fabric. This study demonstrates the potential utility of a PU-based coating incorporating TiO_2 and H_3BO_3 on traditional cotton denim fabrics to enhance flame resistance while minimizing any adverse effects on the overall thermal comfort of the fabric.

Keywords

Flame retardant, thermophysiological comfort, back coating, denim fabric, boric acid, titanium dioxide.

1. Introduction

Denim stands as a timeless fabric revered for its rich history, widespread usage, enduring fashion appeal, and remarkable adaptability. Originally crafted for the practicality of work attire, denim has evolved to become a staple in high-end fashion circles. Its flexibility is not confined to casual ensembles alone; rather it smoothly integrates into workwear, valued for its comfort and durability. Originally, denim was made from 100% cotton yarn in a twill structure where the warp yarn is dyed and the weft yarn is white [1]. Although denim fabrics are now produced with yarns made from various materials, cotton still dominates this field.

As one of the most versatile fabrics, denims are remarkable not only for their durability and comfort, but also for their functional and innovative aspects [2,3]. In literature, there have been numerous studies on the functionalization of denim fabrics. Enhancing the flame resistance of denim fabrics through various methods is among these studies [2]. Becenen and Erdogan [4] investigated the combined effects of nano-TiO_2 and chitosan on the comfort properties, flame retardancy, and water and air permeability of denim and calico fabrics, aiming to develop environmentally-friendly, sustainable, and protective textile coatings using chitosan biomaterial obtained from crayfish waste shells. Thermogravimetric analysis and vertical burning tests show that chitosan enhances the thermal resistance and flame retardancy of denim fabrics. Residue from thermal degradation of blue dyed denim increased from 16.78% to 34% with chitosan and nano-TiO_2 coating, and mass loss in green calico fabric was reduced from 86.3% to 66.0% Talebi and Montazer [5] conducted a study on in-situ synthesized silica nanoparticles on denim fabric using the Stober method, wherein the alkali solution was derived from a natural material called Keliab. The resulting coated denim fabric exhibited a significantly slower burn rate of 0.075 cm/s and a reduced burn length of only 0.9 cm, compared to the untreated denim fabric, which had a burn rate and burn length of 2.5 cm/s and 10 cm, respectively. Becenen and Eyi [2] found that the addition of small amounts of boric acid, borax, and nano SiO_2 to flame-retardant finish solutions yielded promising results in enhancing the flame retardancy performance of a commercial finish solution which is a halogen and antimony-free finishing solution composed of organic and inorganic nitrogen salts. The effect of the commercial flame-retardant solution was found to increase the most with boric acid addition. According to vertical combustion tests, the combustion process continued for a short period after flame removal in the untreated and with commercial solution treated fabric. The burn progress was halted in the fabrics where boric acid, borax, and nano SiO_2 were added.

Cotton textiles are celebrated for being biodegradable and comfortable, making them ideal for users. Compared with some synthetic polymer fibers, one of the main drawbacks of cotton fibers is their high flammability [2]. They have a low oxygen-limiting index and are highly combustible due to their high carbon and hydrogen content. When exposed to flame, they will ignite rapidly, causing intense heat and producing sparks [6,7]. As a result, these are major issues with regards to cotton fabric, restricting its application in technical applications, workwear, and home textiles [7]. Enhancing the flame retardancy of cotton fabric holds significant practical importance. This involves reducing harmful effects during combustion, minimizing loss of life and property, and broadening the potential applications of cotton fabrics; this holds true for cotton denim fabrics, which have broad and diverse areas of use [8].

It is well known that traditional flame retardants can lead to environmental harm or inflict secondary impacts on human health [9]. As a result, an increasing number of scholars are dedicating their efforts to the development of eco-friendly, halogen-free, and non-toxic flame retardants especially for cotton [8]. Specifically, flame retardants based on metal oxides have garnered attention and are categorized as either inorganic or organic flame retardants. One such metal oxide, titanium dioxide, is regarded as a promising flame retardant due to its low toxicity [10]. Moreover, borate compounds such as borax (sodium borate) and boric acid (boron trihydroxide) have been extensively studied and employed as flame retardants in a variety of textile materials [11–13]. Boric acid is one of the extensively researched additives used to enhance the flame retardancy properties of cotton textiles [11,12]. Borates demonstrate remarkable flame retardancy characteristics as they form impermeable glass coatings upon thermal degradation [14].

Various techniques are employed in the textile industry to enhance the functional properties of cotton fabrics, including flame resistance. These include layer-by-layer assembly [15], chemical grafting [16], plasma treatment [17], and the sol-gel process [18]. Additionally, traditional coating methods such as spray application [19], brush application [20], or roller techniques, as well as back-coating [21,22] using a doctor blade or knife-coating methods have also been utilized. An alternative approach involves immersing the material surface directly into the coating solutions, followed by a drying process to eliminate the solvent [23,24]. Back coating is considered one of the most cost-effective surface treatment methods, particularly for furnishing fabrics. Despite not being a highly discussed topic in research laboratories, its economic advantages make it a preferred choice for enhancing fabric properties [25–27]. The back-coating technique, considered a conventional method, is a straightforward, effective, and cost-efficient process used for modifying the surface of textile materials at low temperatures [25,28]. Polyurethanes (PUs) have been used extensively in the coating industry and are one of the growing segments of it because of their excellent abrasion resistance, low temperature flexibility, and excellent chemical, mechanical and physical properties [29].

The primary aim of this study was to enhance the flame retardancy of 100% cotton denim fabric using the back-coating technique, which incorporates PU along with two distinct functional additives, namely boric acid (H_3BO_3) and titanium dioxide (TiO_2). To the best of our knowledge, there are no existing studies that investigate the combination of H_3BO_3 and TiO_2 in PU-based back-coating for the enhancement of flame retardant properties in cotton denim fabric. A single-step, cost-effective coating technique was employed to functionalize the cotton denim fabric, offering an alternative to conventional flame retardant applications for cotton fabrics. The main challenge of the study was the possibility that the PU-based coating may negatively affect the comfort properties of the fabric in an undesirable way, as the application of a polymer coating has the potential to change the thermal comfort of fabric by hindering the transfer of heat and vapor through the treated fabric. Hence, the primary focus of this study lay in the balance that needs to be established between the efficacy of the flame retardant application by means of the PU based back-coating method and the imperative factor of thermophysiological comfort. By introducing H_3BO_3 and TiO_2 into the back-coating process with PU, the denim fabrics were expected to offer improved thermal stability and flame retardancy, ensuring minimal impact on their comfort properties. The vertical flammability, LOI, air permeability, water vapour permeability, thermal conductivity, thermal resistance, and thermal absorptivity of the denim fabrics were investigated to explore the effects of these functional additives on both comfort and flame retardancy aspects, leading to the development of advanced cotton denim fabrics with wearer satisfaction and enhanced performance.

2. Experimental

2.1. Materials

The technical specifications of the denim fabric utilized in this study are presented in Table 1. H_3BO_3 was purchased from Eti Maden (Turkey) commercially. RUCO-COAT PU 1130 (an anionic, water-based, aliphatic polyether polyurethane dispersion), supplied by Rudolf-Duraner (Turkey), was used as the PU binder. RUCO-COAT FX 8011 and RUCO-COAT TH 5020 were utilized as a crosslinker and thickener, respectively, obtained from Rudolf Duraner (Turkey). TiO_2 nanopowder (~20 nm primary particle size, 99.5% (w/w)) and methanol

	Composition	**Weave**	**Mass per unit area (g/m^2)**	**Weft density (picks/ cm)**	**Warp density (picks/ cm)**
Denim fabric sample	100% CO	3/1 Z	340	22	28

Table 1. Technical specifications of denim fabrics

Code	***Fabric specimen***	***H_3BO_3 solution* (wt%)***	***TiO_2 solution** (wt%)***	***PU based binder (wt%)***	***Thickener solution*** (wt%)***	***Crosslinker agent (wt%)***
UDF	Untreated cotton denim fabric	-	-	-	-	-
B/PU	Cotton denim fabric coated with H_3BO_3 containing back-coating paste	7.5	-	15	2.2	3
BT/PU	Cotton denim fabric coated with H_3BO_3 and TiO_2 containing back-coating paste	7.5	5	16	2.2	3

**dissolved in distilled water (60% (w/v)), **dissolved in methanol (40% (w/v)), ***60% (v/v) solution of thickener*

Table 2. Different concentrations of TiO_2 and H_3BO_3 in back-coating pastes

were obtained from Sigma–Aldrich (USA). The chemicals used were of analytical grade and used without any additional purification.

2.2. Preparation of back-coating formulations

The procedures below were used for the preparation of back-coating formulations:

(I) Functional additives were converted into a dispersion form for use in the coating paste. To accomplish this, TiO_2 nanopowder was dispersed in methanol at a concentration of 40% (w/v), and aqueous dispersion of H_3BO_3 was prepared by mixing H_3BO_3 powder and distilled water at 60% (w/v) concentration. The resulting dispersions were sonicated for a period of 10 min using an ultrasonic probe (Bandelin Sonopuls HD 2070 (20 kHz), Bandelin Electronic GmbH & Co. KG, Berlin, Germany) that operated at 9 kHz frequency with a variable power up to 500 W.

(II) To prepare a stock solution for PU-based back-coating, we dissolved the PU binder, crosslinker agent, and PU-based thickener in distilled water. This was achieved using an ultrasonic probe set to 9 kHz and 500 W of power. After 15 min of ultrasonic mixing, previously prepared TiO_2 and H_3BO_3 dispersions were added to this solution. The resulting solution was mixed for 10 min at 9 kHz frequency and 500 W power for final sonication.

Thus, two distinct coating pastes were acquired, each comprising separate concentrations of TiO_2 and H_3BO_3 (Table 2). The viscosity of the final coating pastes was measured by a Brookfield programmable rheometer (DV-III Ultra) using spindle no. 6 at a speed of 15 rpm. The viscosity of the solutions obtained are in range of 15000-16000 cps. For ease of identification, the denim samples were encoded based on the type of back-coating, as provided in Table 2. B/PU back-coating paste containing 7.5 wt% of H_3BO_3 powder and 15 wt% of PU binder as well as BT/PU back-coating paste including 7.5 wt% of H_3BO_3, 5 wt% of TiO_2 and 16 wt% of binder were obtained.

2.3. Back-coating of denim fabric

The next part of the experiment involved the application of back-coating on denim fabrics using a laboratory type scraping-knife motorized coating machine, with a knife width of 300 mm and roller diameter of 40 mm (Figure 1). The back-coating paste was spread onto the sample fabric, which was fixed in a sample holder, using the back-coating machine at a speed of 5 m/min. The scraping knife angle was adjusted to +10°. The thickness of the back-coating paste applied to the fabric surface was assessed by modifying the distance between the fabric and the scraper using a feeler gauge (0.4 mm). Both denim fabric samples were coated on both sides. Upon coating, the samples were dried in an oven at 150 degrees for 10 minutes.

2.4. Characterization

In this study, TiO_2 and H_3BO_3 were incorporated into PU as back coating materials to improve the thermophysiological comfort and flame retardancy properties of cotton denim fabric. The performance was evaluated by analysing the air permeability, water vapour permeability, thermal resistance, thermal absorptivity, and burning behaviour of the coated denim samples.

The air permeability of textile materials is commonly defined as the capacity of air-permeable fabric to allow the passage of air under specific and well-defined conditions [30]. The air permeability of the textiles was assessed using an SDL Atlas Air Permeability Tester (M021A) at a consistent pressure of 100 kPa over a test area of 20 cm², following the EN ISO 9237:1995 standard, with 10 repetitions. Air permeability, measured in

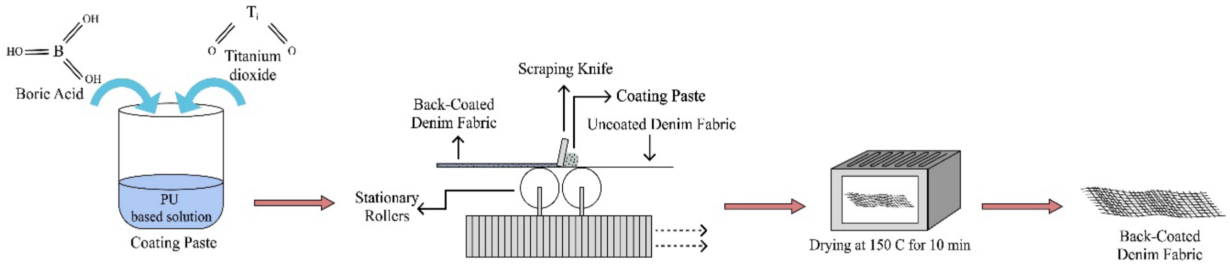


Fig. 1. Schematic illustration of back-coating application of cotton denim fabrics

millimetres per second [mm/s], represents the rate at which air passes through the fabric sample.

The water vapor transmission rates of the fabrics were assessed using an SDL Atlas Water Vapour Permeability Tester (M261) in accordance with ASTM E96-22, the water method, which outlines the standard test methods for the water vapour transmission of materials. Each denim sample underwent 3 tests following this standard procedure. A shallow cup containing approximately 50 ml of distilled water held a circular sample with a diameter of 74 mm, secured by clamping it in place. The assembly, including the cup and sample, was periodically weighed over the course of a day. The weightings determined the rate of vapour movement into the sample from the water in the controlled atmosphere. Calculation of the water vapour permeability (%) was then performed according to Equation (1), where WVP is the water vapour permeability ($g/m^2/day$), G the weight change (g), t the time during which G occurred (h), and A is the test area (m^2) [31]. The coefficient 24 in equation (1) helps to convert the rate into a daily measure, since the unit of water vapor transmission ($g/m^2/day$) indicates how much water vapor passes through a square meter of fabric in a 24-hour period.

$$WVP = (Gx24)/(t \cdot A) \qquad (1)$$

The thermal resistance and thermal absorptivity were assessed using an Alambeta instrument (Sensora, Liberec, Czech Republic), which adheres to ISO 8302 standards and features an upper measuring head designed to simulate human skin. The test involved assessing the heat flow through a sample of material positioned between two metal plates. The upper plate was heated to 35°C, simulating body temperature, while the lower plate maintained ambient temperature. The modified sample was inserted between the plates to allow heat flow through the fabric towards the aerogel layer. The plates were pressed against the sample with approximately 200 Pa of pressure. This test was conducted with 5 repetitions.

The vertical flame test, conducted using a flame control module based on the EN ISO 15025:2016 standard method, was applied to 3 samples in the warp direction and 3 samples in the weft direction for each fabric. The flame was directed towards the lower portion of the vertically placed specimen. Following a 10-second flame exposure, measurements were taken for the after-flame time and char length. To document the process, photographs of the samples were captured using a digital camera (IPhone 13, Apple). The LOI (Limiting Oxygen Index) was assessed by igniting 5 samples measuring 5×10 cm, following the guidelines outlined in ISO 4589-2. The flame was directed towards the upper edge of the samples within a glass tube filled with an O_2/N_2 mixture.

3. Results and Discussion

3.1. Air permeability

The breathability of clothing depends on body geometry, air velocity, fabric breathability, and air gaps between garment layers [30]. Air permeability is closely linked to the fabric's structure, including weight, thickness, and pore structure, which are influenced by fiber type, yarn structure, weft density, and the weaving method. There is a strong correlation between air permeability and porosity, as larger pores increase air flow [32,33]. The decrease in the air permeability of cellulosic fabric obtained by PU coating application is an expected phenomenon, as the breathability of textile materials primarily depends on fabric porosity, including the cover factor and the structure of the fabric [21,22,34]. According to the air permeability results obtained, B/PU and BT/PU exhibit air permeability values that are, respectively, 54% and 61% lower than those of the untreated denim fabric (figure 2). In this investigation, it is observed that the application of a PU-based coating onto denim fabric tends to close the fabric's structural pores. This results in the coated fabric being less porous and, therefore, less breathable. Moreover, the higher surface mass and thicker structure of coated denim fabrics also result in a decrease in air permeability values. Acceptable air permeability limits for denim fabrics can vary depending on factors such as intended use and the target market. For instance, denim fabrics with higher air resistance are deemed suitable for outerwear, as they offer enhanced thermal insulation, particularly in colder climates.

3.2. Water vapour permeability

Water vapour resistance refers to a fabric's capability to permit the transmission of moisture vapour through it. The water vapour permeability of fabrics is one of the main factors that determine comfort of the wearer [1]. As shown in Figure 3, the untreated denim fabric has a water

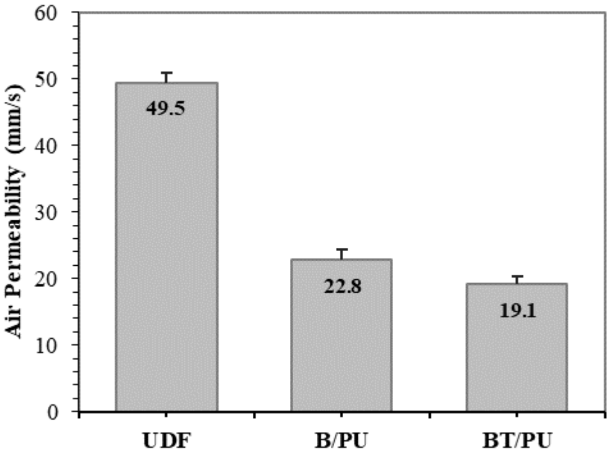


Fig. 2. Air permeability of cotton denim fabric before and after back-coating application

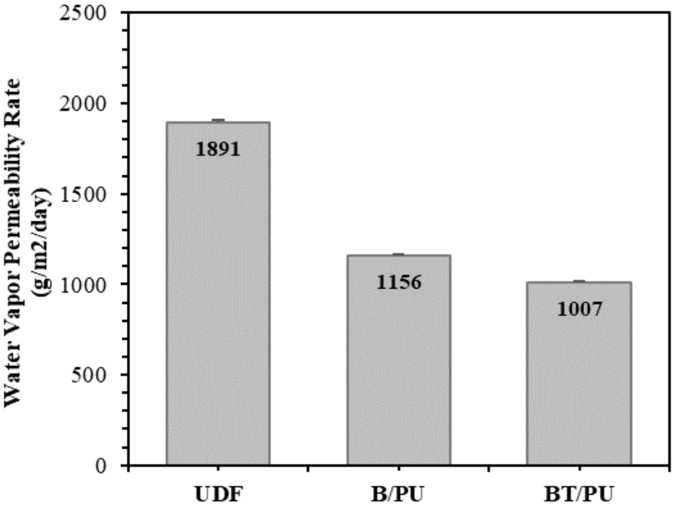


Fig. 3. Water vapor permeability of cotton denim fabric before and after back-coating application

vapour permeability (WVP) value of 1891 g/m^2/day (Exposure conditions: 65% RH; 20°C. Air layer thickness: 10 mm). PU-based coating applications on the same fabric resulted in lower WVP values [34,35]. These outcomes are understandable given that thicker fabrics generally exhibit increased resistance to water/moisture vapour transmission [36]. There exists a significant difference in the WVP rates of B/PU and BT/PU fabrics (t-test P-value: 0.0073), which can be attributed to the greater thickness of BT/PU. Although B/PU and BT/PU exhibit decreases in water vapour permeability by 38% and 46%, respectively, they still maintain a level of permeability that can satisfy the wearer's comfort where the minimum limit for the water vapor permeability value of existing commercial fabrics is ~450 g/m^2/day [37].

3.3. Thermal resistance and thermal absorptivity

The thickness of textile materials is the key factor in determining their thermal resistance, and there is a linear relationship between these two parameters [38]. The thicker the material, the greater its ability to protect against heat loss. The application of coatings resulted in elevated fabric thickness values, generating additional area and air within the fabric structure, consequently enhancing insulation properties. The literature includes studies examining fabrics that exhibit increased thickness and, consequently, enhanced thermal resistance as a result of coating applications [39–41]. Applying a thin layer of functional coating to fabric surfaces can modify thermal conductivity without significantly altering the fibrous structure, porosity, dimensions, or moisture evaporation properties. There are studies focusing on enhancing the thermal insulation capacity of fabrics by reducing their thermal conductivity through the application of coatings [42]. Results of thermal conductivity and thermal resistance obtained for samples are presented in figure 4. The results indicate that the content of H_3BO_3 in the coating layer enhanced the thermal resistance by reducing the thermal conductivity value of the sample fabric. The presence of TiO_2 nanoparticles does not exert a significant influence on the thermophysical properties; namely the thermal conductivity and thermal resistance; of the cotton denim fabric. (The t-test P value for the thermal conductivity results of B/PU and BT/PU is 0.1773).

Thermal absorptivity measures how fabrics feel warm or cool and is linked to surface properties. It is a material's ability to insulate and is affected by conductivity, density, and specific heat capacity [43]. Higher thermal absorptivity ratings indicate that the fabric will feel cool to touch for very short periods of time [44]. Figure 5 shows that untreated denim fabric exhibited the highest thermal absorptivity levels, offering the coolest sensation upon initial contact with the skin. B/PU and BT/PU fabrics, on the other hand, yielded notably lower values, indicating a warmer sensation. There is no statistically significant difference between the thermal absorptivity and thickness values of B/PU and BT/PU (t-test P values are 0.305 and 0.939, respectively). The reduced thermal absorption performance of B/PU and BT/PU can be attributed to the lower thermal conductivity of coated fabrics.

3.4. Flame Retardancy

It is widely recognized within the industry that each specific flammability test presents unique challenges in achieving

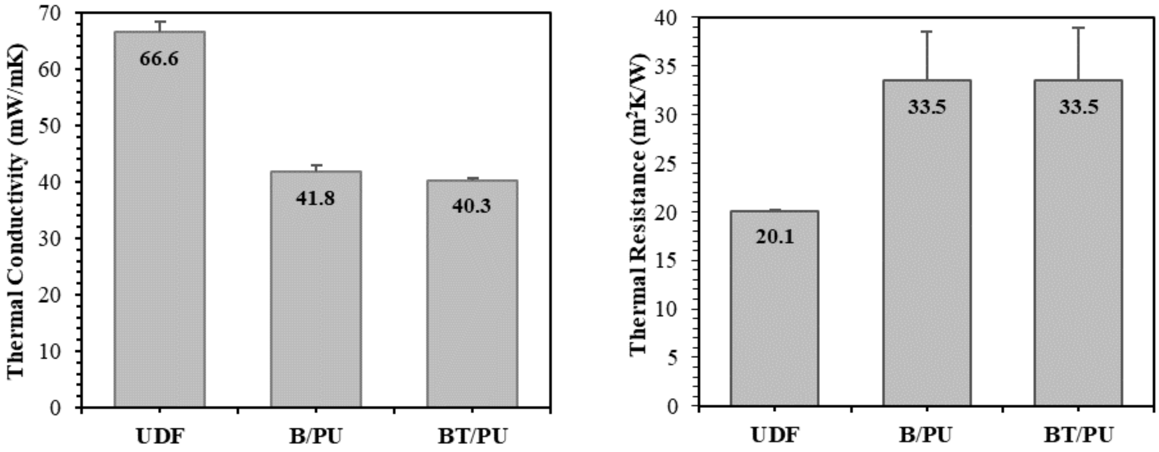


Fig. 4. Thermal conductivity and thermal resistance of cotton denim fabric before and after coating with B/PU and BT/PU

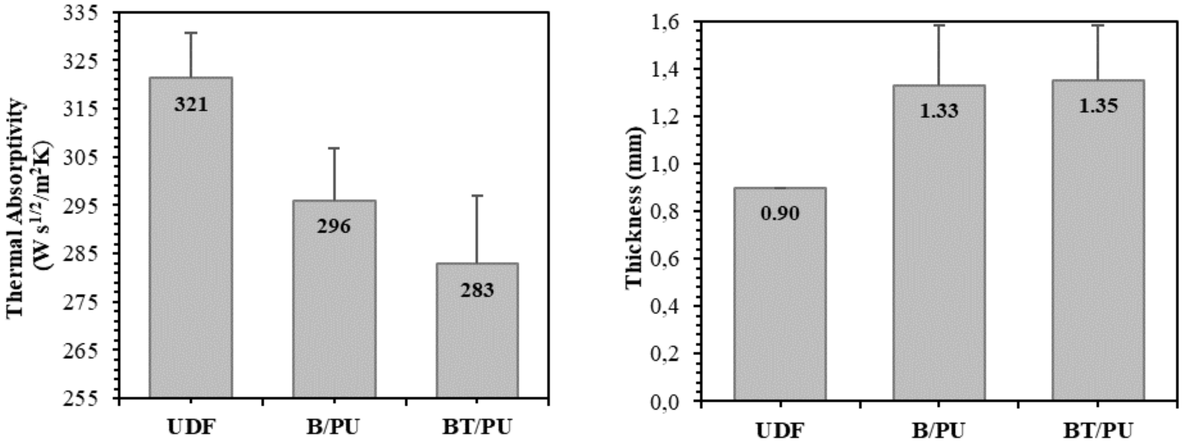


Fig. 5. Thermal absorptivity and thickness of cotton denim fabrics before and after coating with B/PU and BT/PU

a “pass” result. In the vertical flame test based on the EN ISO 15025:2016 standard method, a flame is brought into contact with the edge of the fabric instead of its face. The edge test is particularly challenging to pass because both sides of the fabric are burned simultaneously, making it very difficult to achieve the charring effect. Only highly effective flame retardant treatments can pass this test, which is more commonly applied to work-wear fabrics (over 200 g/m²) [45]. Therefore, a double-sided coating application was performed to enhance the flame resistance of both sides of the resulting fabric.

The flame retardant properties of both untreated cotton and back-coated cotton fabrics were assessed through the vertical flame test, the results of which are presented in Table 3. Both coating applications led to a decrease in after-flame time. Similarly, as observed in Figure 6, in terms of ash content, both coating applications resulted in lower char lengths. Specifically, the after-flame time of BT/PU was realized 30 seconds shorter than that of the untreated fabric, accompanied by an ash length of 45 mm. This phenomenon suggests that the incorporation of TiO_2 additive into the coating formulation (BT/PU) enhances the fabric’s resistance to ignition to a greater degree compared to the H_3BO_3 containing coating formula (B/PU).

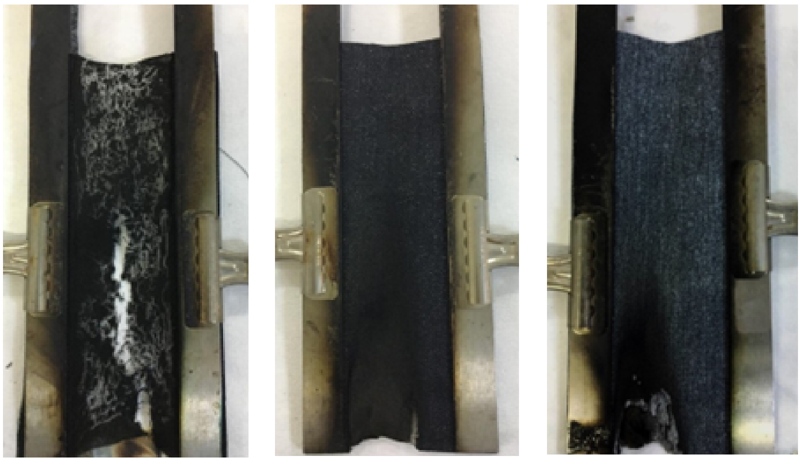
A fabric with an LOI value below 20.95% is classified as flammable, while one falling within the range of 21-28% is categorized as slow-burning, and if it falls within the range of 28-100%, it is classified as self-extinguishing [46]. According to Table 3, the LOI value of UDF is 21.3%, indicating the fabric’s flammable nature. The LOI value of the B/PU increased by 18% compared to the untreated fabric, reaching 25.1%. The LOI value of the BT/PU fabric increased by 26.9% compared to the untreated fabric, demonstrating the best fire resistance performance and reaching a value of 27%, approaching the self-extinguishing threshold (28%).

Borates exhibit excellent flame retardant properties due to the formation of impermeable glass coatings when they undergo thermal degradation. These glass coatings develop on the material’s surface and contribute to the intumescent effect by creating a barrier that excludes oxygen and hinders the

Sample	***Vertical flame test results***				***Limited oxygen index***
	After-flame time (s)		***Char length (mm)***		***LOI (%)***
	Time (s)	***σ****	***Length (mm)***	***σ****	
UDF	60	2.4	200	8.5	21.3
B/PU	45	3.0	75	4.1	25.1
BT/PU	30	2.3	45	3.5	27.0

** σ: Standard deviation of the given average values*

Table 3. Vertical flame results and limited oxygen index (LOI) values



UDF **B/PU** **BT/PU**

Fig. 6. Images of uncoated and B/PU-BT/PU coated cotton denim fabrics following the vertical flame test

spread of combustion. Additionally, through endothermic decomposition, the release of water of hydration not only dilutes the flame but also absorbs the thermal energy, thus providing a cooling effect [14,47]. TiO_2 , a metal oxide, has a high melting temperature during thermal decomposition. The oxides coat the surface of cotton fibers, creating an efficient physical barrier that facilitates the transformation of cotton fibers into carbon through dehydration. This process isolates the cotton fibers from external factors and restricts the spread of flames [8]. TiO_2 can also function as a heat absorber during the flame retardant reaction, aiming to interrupt the combustion cycle of cellulosic fibers [48]. In a comparable study, Bentis et al. [18] investigated the modification of cotton fabric surfaces using the sol-gel method with titanium-based sol and boric acid as an additive, finding that the coated fabrics exhibited good flame retardancy properties, and thermal studies by thermogravimetric analysis and differential scanning calorimetry demonstrated increased thermal stability due to the synergistic effect of Ti and B. The vertical flame resistance and LOI results of the BT/PU fabric indicate the synergistic effect of H_3BO_3 and TiO_2; these findings are consistent with those reported by the referenced study. Overall, it can be stated that TiO_2 and H_3BO_3 demonstrate an additional impact on the thermal stability and flame retardancy levels of the cotton denim fabric (BT/PU) obtained in this study.

4. Conclusion

The aim of this study was to enhance the flame retardancy and thermal stability properties of cotton denim fabric using a PU-based coating method, with a limited impact on the overall thermal comfort level of the denim fabric. Two types of back-coating pastes were obtained by employing H_3BO_3 and H_3BO_3-TiO_2 as paired additive materials. A scraping-knife motorized coating machine was used to apply the coating onto the fabric surface. The back-coated fabrics were tested for vertical flammability, LOI, air permeability, water vapor permeability, thermal conductivity, thermal resistance, and thermal absorptivity to determine their thermal stability, flame resistance, and comfort properties. According to the results, both types of coatings enhanced the thermal stability and flame resistance properties of the cotton denim fabric. The fabric coated with H_3BO_3-TiO_2 exhibited the best after-flame time (30 s), shortest char length (45 mm), and highest LOI (27%) value. However, both coated fabrics showed a decrease in air permeability values by 54% and 61%, respectively, compared to the untreated fabric. Additionally, water vapor permeability values decreased by 39% and 47%, correspondingly. The coating application resulted in lower thermal conductivity and thermal absorptivity, thereby ensuring a more thermally resistant denim fabric.

The study demonstrated an enhancement in the flame retardancy properties of denim fabrics coated with TiO_2 and H_3BO_3 additives, along with an increase in thermal resistance in the context of comfort properties. These characteristics could potentially render coated denim fabrics advantageous for use in workwear, outdoor apparel, and cold-season garments through a relatively inexpensive and straightforward method known as the back-coating technique. The halogen-free flame retardant coating applied in this study may serve as a significant alternative for finishing processes of flame retardants applied to cotton fabrics.

The use of naturally occurring H_3BO_3-TiO_2 additives and the absence of aqueous processes in the coating application make this study environmentally friendly, which could be considered in future research efforts in this field. Scientists are using various surface finishing techniques to apply thin flame-retardant coatings to polymers and textiles, but special attention must be paid to enhancing coating durability and improving current coating techniques for commercial production. Different types of flame retardants, including inorganic and nanoparticle variants, exhibit strong synergistic effects. However, further research is required to improve interfacial compatibility, and it is crucial to consider the potential effects of using nanoparticle-sized materials on the environment and human health. In addition, within the realm of enhanced flame-retardant fabrics, bio-based flame retardants attract considerable interest from chemists due to their favorable environmental impact and safety for human health. Moreover, improving the wash durability of flame retardants in garments and maintaining a balance with other fabric properties, such as comfort, while adding flame-retardant features are major challenges in the field.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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