Hindawi
Journal of Chemistry
Volume 2023, Article ID 1619577, 11 pages
https://doi.org/10.1155/2023/1619577

Research Article

Investigation on the Flammability and Washing Durability of Trevira CS and Its Blends with Cotton, Modal, and Acrylic Fabrics

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Received 17 March 2023; Revised 6 July 2023; Accepted 7 July 2023; Published 31 July 2023

Academic Editor: Frederic Dumur

The aim of this study was to develop flame-retardant textile materials and study their aspects to durability against several washing cycles. Since the conventional textile substrates are flammable and combustible, the development of flame-retardant apparel from pure Trevira CS fabrics as well as its blends with cotton, modal, and acrylic in certain proportion was carried out in this study. Furthermore, in addition to demonstrating necessary flame-retardancy characteristics, flame-retardant garments must provide a minimum degree of comfort to the wearer, and it is thought of as blending. The productions of yarn were made with ring spinning systems, and knitted fabrics also were produced from this pure Trevira CS and its blends yarn. Flammability test was carried out for the spun yarn and for the fabrics manufactured separately. Limiting oxygen index (LOI) tests were carried out for the sample fabrics. The result indicates that most of the fabrics are flame resistant except the T/C (80 : 20) fabric which show low LOI values, but by treatment with finishing agents, it can be improved. In order to study the durability against washing cycles, LOI values of all sample fabrics were determined. LOI values of all the four types of knitted fabrics in gray, finished, and washed states were evaluated and compared. The pure Trevira-spun knitted fabric exhibits very good flame retardancy in gray state and hence may not require any flame-retardant finishing treatment. Upon imparting the wash resistant, flame-retardant finish Pekoflam DPN, it was observed that the LOI of all the treated samples showed a significant increase. It was revealed also that upon washing (after 10 washes), the LOI values of the fabrics have been considerably reduced; however, no appreciable reduction in flame retardancy is noticed upon further washing of fabrics, after 20 and 30 washes, respectively. Even after 30 washes, the flame retardancy of most of fabrics are very good and one sample showed good result. Finally, the knitted fabrics from pure Trevira-spun yarns and the FR-treated T/C (80 : 20), T/M (80 : 20), and T/A (80 : 20) ones qualify very well for the production of flame-retardant garments for various applications in different forms.

1. Introduction

The majority of flame retardant treatments, formulations, and additives were discovered between 1950 and 1980 [1, 2], and those of contemporary commercial interest have just lately been examined [3]. Since then, growing concerns about the toxicological and environmental consequences of using such chemical species on textile substrates with high specific surface areas and close contact with the skin have created a barrier to new chemistry development and application. As a result, in the last 20 years or so, in response to these concerns and the perceived need for improved flame retardant performance at a reasonable cost, both research scientists and industry have considered improving the efficiency of currently used retardants, replacing those where concerns exist with other existing formulations or repurposing known chemistry in novel ways [1].

Innovative fashion and technology have developed smart and integrated wearable textiles with multidimensional values in areas such as sports, fashion, defense, healthcare and safety, entertainment, and industry in the twenty-first century. Technical advancements, on the other hand, have had a significant impact on the realm of wearable materials and textiles thus far. They are not only better than natural or synthetic fibres in terms of functionality, but they also outperform them in a variety of new and growing textile industries [4].

Smart textiles can be divided into two main groups: (i) aesthetic enhancing type: refers to the textiles that scattered and shined appearance with color changing and (ii) performance enhancing type [4]. One of the most appropriate functional aspects of smart textiles is flame retardant finish, which delivers high-performance characteristics to textiles. As a result, new technologies, products, and materials have been developed in the field of flame retardancy to address the difficulties and needs of the contemporary period [4, 5].

Textiles are common materials in our everyday lives, and they have been extensively employed in both homes and industry [6–9].

Natural polymers such as wool, silk, and cellulose, as well as synthetic polymeric units such as nylon, polyester, and polypropylene, and semi-synthetics such as rayon, have been used to produce textile substrates, which are ubiquitous in our daily lives. These materials are used to make high-value home appliances (apparel and typical interior products such as upholstered furniture, curtains, carpets, and bedding). Most of these items are very flammable and combustible, necessitating the desired demand for the quality and safety of textile materials, with the goal of preventing fires and loss of life. In this case, flame retardant chemicals must be utilized. Floor coverings, upholstery, drapery, home, and the aviation industry, for example, utilize flame retardant treatments to protect textile substrates against fire, which is required by firemen and emergency workers. The most important criteria for a commercially acceptable flame retardant are little or no bad effects on the physiological and aesthetic qualities of textile materials, simplicity of application, and durability against harsh washing, cleaning, and drying cycles [4, 5].

Flame retardants provide an important source of enhancing the material protection. Safety and protection of human lives and valuable are strong factors in the consumption of flame retardant (FR) and flame retardant textiles [10, 11].

Textiles are now one of the most common product categories in which flame retardants are used. Garments, protective wear, children's clothing, work wear, mobile technology, and furniture are all examples of essential textile-based products. To obtain desired effectiveness in textiles and pass any standard requirement, flame retardants are necessary [10].

Due to its exceptional characteristics, cotton fabrics have been extensively applied in both military and civilian applications [12–14]. The drawbacks and limits of cellulose fibers in the development of high-performance fire-protective textile products include their low thermal stability, simple ignition, and rapid combustion [15].

To achieve fire resistance, textile materials are typically treated with fire-resistant resistant chemicals. Inorganic salts (e.g., aluminum or magnesium hydroxides), organohalogens (e.g., chloroparaffins, bromobiphenyl ether, and bromobisphenols), and formaldehyde-based compounds, for example, are all efficient flame retardants [4, 15-16]. The use of halogenated and formaldehyde-based flame retardant compounds has been outlawed due to their severe toxicity. As a result, various halogen- and formaldehyde-free alternatives, such as polyphosphates, organic phosphates, and nitrogenous-based agents, have been commercialized [15–17]. Because of their PN synergistic impact and valued uses, nitrogen and phosphorus-based compounds are far more attractive in this aspect [18].

Compositions based on aluminum trihydrate (ATH), antimony oxides, bromine, chlorine, organophosphorus (for example, tetrakis (hydroxymethyl) phosphonium salt, and alkyl-substituted, and N-methylolphosphonopropionamide), and others are being employed as major flame retardants. Bromine-based flame retardants were largely used, although there are serious environmental issues about the chemicals emitted [10, 19].

Several studies on organo phosphorus flame retardants or flame retardants (FRs) in broad, include analyses of phosphorus compounds' mechanisms [20–22]. Fire inhibition, heat reduction, surface change by phosphoric acid-containing containing compounds, and char formation are all effects of phosphorus-based FRs in both the condensed phase and the flame [23–25]. According to the scientific research, phosphorus is mostly retained in the char, which shields the primary material from heat and flame [26, 27]. Also, it is recognized that compounds containing other flame retardant components improve the efficiency of phosphorus. When phosphorus is mixed with silica gel [28] or nitrogen [29, 30], the resulting combinations increase the flammability and/or thermal stability of treated fabrics, as well as diminish exothermicity.

A sol-gel method [31, 32], layer-by-layer (LbL) assembly [33, 34], plasma treatment [35, 36], flame-retardant finishing technology [37, 38], dip coating technology [6, 39], and surface grafting treatment [40] have been used to improve flame retardancy.

To address the challenge and needs of ever-changing safety regulations, numerous new substituted technologies, finishing agents, and active materials are being developed with current flame retarding materials. It is a multidisciplinary project involving a variety of scientific and engineering instruments.

However, in this study an attempt were made to develop flame retardant fabrics and their aspects to sensitization and durability against several washing cycles. The effects of washing cycles on the limited oxygen values were studied and discussed.

Having this in mind, this investigation presents the development and characterization of flame-retardant apparel. The flame-retardant apparel has to provide a minimum degree of comfort to the wearer besides exhibiting essential flame-retardancy characteristics, and it is a thought of blending Trevira CS with other commodity fibres, such as cotton, modal, and acrylic. As cotton and modal fibres are well-known for their comfort and aesthetic properties and extensively used in apparel and innerwear, these are blended in certain proportions with Trevira CS fibres to produce yarns and knitted fabrics for exploring the feasibility of development of flame-retardant apparel. It is believed that when Trevira CS fibres are blended with cellulosic fibres, the former with the high heat of combustion supports the cellulosic fibres, which have a relatively lower heat of combustion and thus the pyrolysis of cellulosic fibres is enhanced.

The characteristics of pure Trevira CS yarns, blended yarns, and of the resultant fabrics are investigated and assessed to suggest a suitable type of yarn and fabric composition for the economic production of flame-retardant apparel. A study is also undertaken to improve the flame-retardant properties of fabrics produced from the blends mentioned above, through application of a durable flame-retardant finish Pekoflam DPN, popularly used for cellulosic and their blended materials. The characteristics of the pure Trevira CS and blended fabrics are investigated and assessed to suggest the suitable type of fabric for the production of flame-retardant garments for various applications.

In this study, a product named pekoflam is applied in Trevira CS and its blend with cotton, modal, and acrylic fabrics in the form of flame retardant finish. The flame retardant treatment carried out with a phosphorus-based compound, i.e., the Pekoflam DPN. Phosphorus-based flame retardants act mainly in the solid phase of burning polymeric materials and cause the polymer to char, thus inhibiting the pyrolysis process necessary to feed the flames.

The purpose of this research work is to explore the flame retardant action of Trevira CS and its blends. The flame retardant characteristics of pure Trevira CS fabrics, Trevira/cotton, Trevira/acrylic, and Trevira/modal fabric blends in specific proportions were investigated and assessed. The effect of consequent washing on the performance of flame retardant fabric will be studied and compared. The suitable type of yarn and fabric composition for the economic production of flame-retardant apparel for different applications were suggested and revealed.

2. Materials and Methods

2.1. Materials. Trevira CS flame retardant fibres are procured from Rajasthan Spinning and Weaving Mills Ltd. Also, cotton (DCH 32), modal and acrylic fibres were collected from nearby spinning mills to produce Trevira blended yarns.

2.2. Chemicals. The Trevira/cotton knitted fabric sample was scoured with NaOH and then bleached with H_2O_2. The pure Trevira, Trevira/modal and Trevira/acrylic knitted fabric samples are given finishing treatment with Pekoflam DPN. Phosphoric acid as a catalyst was used. Detergent used to wash the sample fabrics.

2.3. Equipment/Apparatus and Machineries. The laboratory model G 5/1 ring-frame is used to produce ring-spun yarn. The laboratory model fabric analysis knitter is used for knitting of the yarn samples. Apparatus required for LOI test are test chimney, test specimen holder, gas supplier, gas measurement and control devices, timing device, soot, fumes, and heat-extraction system. A padding mangle is used for uniform distribution of Pekoflam DPN finish. An oven is used for curing of the Pekoflam DPN finished sample fabrics.

2.4. Preparation of Yarn Samples. The yarn samples of 30 Ne are spun from pure Trevira CS fibres and from its blends with other fibres. The 30 Ne pure Trevira yarns are spun on ring spinning systems. The 30 Ne ring-spun yarns from blends of Trevira/cotton (80/20), Trevira/scrylic (80/20), and Trevira/modal (80/20) are produced. The ring yarns are spun on a laboratory model G 5/1 ring-frame. Ring-spun yarns are produced to investigate the influence of all these yarn structures on the flammability of fabrics produced from them. The yarn spinning plan and the process parameters used are given in Table 1.

2.5. Determination of Flammability of Yarns. The flammability of yarn samples is determined using an in-house test method, wherein a yarn specimen of 300 mm is held vertically in a stand with suitable clamps. The flame is applied at the bottom of the specimen for a period of 2 seconds and then withdrawn. The length of specimen melts/burnt is recorded. At least 10 readings are taken to compute the average melt/burnt length for each sample. The test is carried out in a controlled draught-free condition.

2.6. Production of Knitted Fabric Samples. The yarn samples are knitted on a laboratory model fabric analysis knitter (FAK-tube knitter) of 3.5″ diameter. The 30 Ne yarns are knitted on 24-gauge cylinder with 220 needles and a single feeder to produce single jersey tubular fabric. In order to develop flame-retardant textile products, the four types of yarns 30 Ne pure Trevira ring-spun, 30 Ne T/C (80 : 20), 30 Ne, and T/M (80 : 20) 30 Ne T/A (80 : 20) were knitted separately on 16″diameter knitting machine (PMW make). Four samples of single jersey fabrics were produced using a 24-gauge cylinder with a positive feeder.

2.7. Determination of Flame-Resistance of Knitted Fabric Samples. The flame-resistant characteristics of conditioned knitted fabric samples are determined using the vertical flame test (Method A) as described in the IS: 11871-standard. The flame-resistance of fabric samples, in an inclined configuration, is determined using the procedure described in ASTM D 1230 method. The flammability of all the samples is also measured using a limiting oxygen index method as per the procedure described in IS: 13501 method (1992). The details of these test methods are described as follows.

2.7.1. Vertical Strip Test. A conditioned, strip of fabric sample is suspended vertically and ignited at the base by flame impinging on both sides in a standard manner. After igniting the specimen for a specific period of time, the char length, after-flame, and afterglow characteristics are noted.

Table 1: Particulars of yarn sample preparation.

Sl. no	Ring spun yarns	Spindle speed (r/min)	Break draft	Twist multiplier	Traveller
1	30 Ne Trevira CS	15000	1.25	3.6	5/O
2	30 Ne T/A (80 : 20)	15000	1.25	3.6	5/O
3	30 Ne T/C (80 : 20)	15000	1.25	3.6	5/O
4	30 Ne T/M (80 : 20)	15000	1.25	3.6	5/O

T/A: Trevira/acrylic; T/C: Trevira/cotton; T/M: Trevira/modal.

The test specimen is 315 mm long × 50 mm wide. Six specimens, three in course direction and three in wales direction, are prepared.

2.7.2. Inclined Strip Test. A conditioned strip of fabric sample is kept at an angle of 45° and ignited at the base by flame impinging on both sides in a standard manner. After igniting the specimen for a specific period of time, the char length, after-flame, and after-glow characteristics are noted.

The test specimens are about 150 mm in length × 50 mm length. Six such fabric samples, three in course direction and three in wales direction are prepared.

2.7.3. Limiting Oxygen Index Method. A small test specimen is supported vertically in a mixture of oxygen and nitrogen flowing upwards through a transparent chimney. The upper end of the specimen is ignited. The minimum concentration of oxygen and nitrogen flowing upward in a test chimney that will just support combustion is measured under equilibrium conditions of burning. The equilibrium is established by the relation between the heat generated from the combustion of the specimen and the heat lost to the surroundings as measured by one or the other two arbitrary criteria, namely, the period for which the burning continues, or the length of the specimen burnt. This point is approached from both sides of the critical oxygen concentration in order to establish the oxygen index.

A specimen of length 140 ± 5 mm × 52 ± 0.5 mm is used. It is ensured that the specimens are clean and free from flaws. The edges of the specimen are relatively smooth and free from fur or bur of material left from the machining.

The flame is applied for up to 30 seconds, removing it for every 5 seconds for just sufficient time to observe whether or not the entire top surface of the specimen is burning. The oxygen concentration used as the volume percent is recorded. The limiting oxygen index (LOI) is determined by using the following equation:

$$\mathrm{LOI} = \left[\frac{(O_2)}{(O_2 + N_2)} \right] \times 100, \qquad (1)$$

where O_2 = the volumetric flow of oxygen in $\mathrm{cm}^3/\mathrm{sec}$.

2.8. Processing of Knitted Fabrics. The Trevira/cotton knitted fabric sample is scoured, bleached, and finished with Pekoflam DPN. The pure Trevira, Trevira/modal, and Trevira/acrylic knitted fabric samples are plain washed and given finishing treatment with Pekoflam DPN.

2.8.1. Scouring. The Trevira/cotton grey fabric is scoured with 4% of alkali (NaOH) and 0.5% of wetting agent for 90 minutes using the material-to-liquor ratio of 1 : 20 and the temperature of 85–90°C.

2.8.2. Bleaching. The scoured material is bleached with 1% of H_2O_2 using the material-to-liquor ratio of 1 : 20 and the temperature of 85–90°C for 90 minutes.

2.8.3. Finishing. The bleached T/C fabric, plain washed T/M and T/A fabrics are finished separately using Pekoflam DPN and phosphoric acid as a catalyst, making use of the recipe given as follows. The uniformity of finish is obtained by using a padding machine. The sample is dipped in the solution and padded. The finished fabric is cured in oven at a temperature of 90–100°C for 5 minutes.

The knitted sample fabrics were finished by treatment with 400 gpl Pekoflam DPN using the material-to-liquor ratio of 1 : 20. 20 gpl of phosphoric acid was used as a catalyst.

Pekoflam DPN, a widely available FR agent, was utilized in this study to provide fabrics a long-lasting flame-retardant finish. DPN Pekoflam Trivera CS and its blends with cotton, modal, and acrylic are permanently flame-retardant finished with Pekoflam® DPN, an organic phosphorus compound. Depending on the cross linker system, it offers great wash resistance. It has a low yellowing rate and meets Oko-tex Class IV specifications.

A flame retardant reagent often works in one of two ways: either by reducing the amount of energy lost during burning or by raising the amount of energy required for the fiber to reach the burning stage. A basic strategy for reducing the amount of energy lost during the pyrolysis process is to manage the burning process such that fewer combustible products are produced, hence reducing the amount of heat lost during the burning process [41]. This is also how the organic phosphorous-based fireproofing material known as Pekoflam DPN functions.

2.8.4. Washing. The finished sample is given for 10, 20, and 30 consequent washes. The amount of material used for each consequent wash is 0.5 m. The washing method is carried out using detergent at a temperature of 40°C for 20 minutes.

2.9. Testing of Fabrics

2.9.1. Analysis of Constructional Parameters. The four types of fabrics have been relaxed, conditioned, and analysed for important constructional parameters such as course per inch

(CPI), wales per inch (WPI), and areal density (GSM), both in gray state and finished state.

2.9.2. Determination of LOI Value. The limiting oxygen index of all the four types of fabric samples in a gray state, finished state, and after-washed state (after 10 washes, 20 washes, and 30 washes) is determined using the standard test procedure described in IS 13501 : 1992.

3. Result and Discussion

3.1. Flammability of Yarns. The flammability values of yarns are given in Table 2 and Figure 1. It can be seen that among the four samples the 30 Ne T/C (80 : 20), ring-spun yarns exhibited longer melt length followed by the 30 Ne T/A (80 : 20) ring-spun and 30 Ne T/M (80 : 20) ring-spun. The pure 30 Ne Trevira ring-spun yarn showed minimum melt length. This shows that the Trevira yarns has flame retardancy property as compared to others.

Table 2: Flammability values of yarns.

Sl. no	Yarn code	Yarn description	Melt length (mm)
1	*A*	30 Ne Trevira ring-spun	166
2	*B*	30 Ne T/A (80 : 20) ring-spun	180
3	*C*	30 Ne T/C (80 : 20) ring-spun	227
4	*D*	30 Ne T/M (80 : 20) ring-spun	178

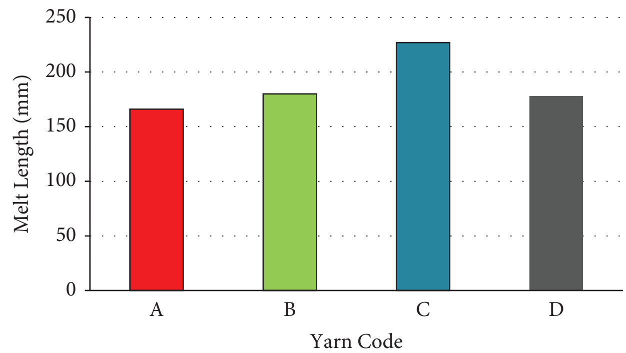

Figure 1: Flammability values of yarns.

3.2. Flame-Resistance Characteristics of Knitted Fabric Samples

3.2.1. Vertical Strip Test Results. It can be observed from Table 3 that there is no discernible difference between the flame-resistance characteristics of fabric samples A and B as their melt-lengths values (in fabric state) are the same. The fabric produced from T/M (80 : 20) blended yarn has flammability characteristics that are similar to those exhibited by the fabrics produced from pure Trevira-spun yarns. The fabric C produced from T/C (80 : 20) yarns performed worst in regard to their flame-resistance as the entire test length of the fabric was burnt.

3.2.2. Inclined Strip Test Results. As per the inclined strip test (Table 4), all the fabrics, especially *A*, *B,* and *D* are rated as Class I as regards their flame-resistance and hence it can be concluded that these fabrics can be readily used to produce flame-retardant apparels. Furthermore, as per the test results, the fabrics *C* may not qualify to produce flame-retardant apparel.

3.2.3. LOI Values of Fabric Samples. Table 5 shows the LOI values of all the four different types of fabrics. It can be observed that among the four types (*A*–*D*) of fabrics produced from 30 Ne pure Trevira-spun yarns and its blends, that the fabric A produced from 30 Ne pure Trevira ring-spun has highest LOI value (40). The fabric B produced from 30 Ne T/A (80 : 20) ring-spun yarn with an LOI value of 32 well qualifies itself for the production of flame-retardant apparels, sweaters, knitwear, etc.

The fabric *D* produced from 30 Ne T/M (80 : 20) ring-spun yarn has a LOI value of 26, which is above the minimum LOI value of 25 (Figure 2) required by a flame-retardant fabric. Hence, it qualifies itself for the production of comfortable flame-retardant apparel. Fabrics *C* produced from T/C (80 : 20) yarns show very low LOI values and hence they are not suitable to produce comfortable flame-retardant apparel.

3.3. Characteristics of Gray, Finished and Washed Knitted Fabric Samples. The important constructional parameters and the LOI values of all the four types of knitted fabrics in gray, finished, and washed states are given in Table 6. It can be observed from Table 6 that the constructional particulars of all the fabrics vary from gray through finished to after-washed states. Overall, there is an increase in the areal density of fabrics caused due to a general increase in the CPI and WPI in all cases caused by the chemical treatments, which clearly indicate certain shrinkage in the fabrics. Furthermore, it is clearly noticeable that there is an almost 10% increase in the areal density of gray fabrics due to application of flame-retardant finish, Pekoflam DPN.

It is clear from Table 6 and Figure 3 that in a gray state, amongst all the four fabrics (F_1, F_6, F_{11}, and F_{16}), F_1 produced from pure Trevira-spun yarn exhibits the highest LOI of 40, followed by F_{16}, F_{11}, and F_6 in the decreasing order. The flame retardancy of F_1 is considered to be very good, that of F_{16} is medium, and those of F_{11} and F_6 are below the minimum range (indicated by the red line in Figure 2) as required by a standard flame-retardant textile material.

Upon imparting the wash resistant, flame-retardant finish Pekoflam DPN, it is observed that the LOI of all the four treated samples (F_2, F_7, F_{12}, and F_{17}) is significantly increased with the result that F_2, F_7, and F_{12} exhibit a very high LOI in the range of 49-50, while F_{17} has a value of 45. This clearly shows that the Pekoflam DPN has a great effect in improving the flame retardancy of cellulose and its blended fabrics, and Pekoflam DPN may not have a similar effect on other fibrous materials like Acrylic, which is depicted in Figure 4. The phosphorous

Table 3: Flame-resistance values of fabrics in vertical strip test.

Sl. No	Fabric code	Fabric description	*Vertical strip test* Average melt length (mm)	Time in seconds after flame	Time in seconds after glow
1	*A*	30 Ne Trevira ring-spun yarn fabric	125	0	0
2	*B*	30 Ne T/A (80 : 20) ring-spun yarn fabric	125	0	0
3	*C*	30 Ne T/C (80 : 20) ring-spun yarn fabric	Burnt entire length	—	—
4	*D*	30 Ne T/M (80 : 20) ring-spun yarn fabric	130	0	0

Table 4: Flame-resistance values of fabrics in inclined strip test.

Sl. no	Fabric code	Fabric description	*Inclined strip test* Average time in seconds for flame spread	Class
1	*A*	30 Ne Trevira ring-spun yarn fabric	Did not ignite	I
2	*B*	30 Ne T/A (80 : 20) ring-spun yarn fabric	Did not ignite	I
3	*C*	30 Ne T/C (80 : 20) ring-spun yarn fabric	Did not ignite	—
4	*D*	30 Ne T/M (80 : 20) ring-spun yarn fabric	Did not ignite	I

Table 5: LOI values of fabric samples.

Sl. no	Fabric code	Fabric description	LOI (%)
1	*A*	30 Ne Trevira ring-spun yarn fabric	40
2	*B*	30 Ne T/A (80 : 20) ring-spun yarn fabric	32
3	*C*	30 Ne T/C (80 : 20) ring-spun yarn fabric	23
4	*D*	30 Ne T/M (80 : 20) ring-spun yarn fabric	26

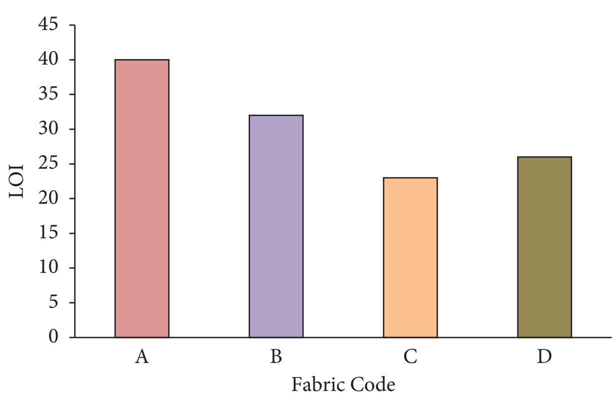

Figure 2: Limiting oxygen index values of fabrics.

compound present in Pekoflam DPN, after pyrolysis takes away the heat supplied to the fibre by external means and chars, thereby forming a barrier to the propagation of flame caused by the combustible substances. The flame retardancy of all the four fabrics F_2, F_7, F_{12}, and F_{17} is rated to be very good.

Furthermore, Table 6 reveals that upon washing (after 10 washes), the LOI values of the fabrics F_3, F_8, F_{13}, and F_{18}, have been considerably reduced, however, no appreciable reduction in flame retardancy is noticed upon further washing of fabrics, viz. F_4, F_9, F_{14}, and F_{19} after 20 washes and F_5, F_{10}, F_{15}, and F_{20} after 30 washes, respectively. These effects can be clearly seen in Figures 5–7. Even after 30 washes the flame retardancy of fabrics F_5, F_{10}, and F_{15} is very good and that of the fabric F_{20} is good.

Overall, it can be stated that the pure Trevira-spun knitted fabric exhibits very good flame retardancy in gray state and hence may not require any flame-retardant finishing treatment. The knitted fabrics produced from T/C (80 : 20) and T/M (80 : 20) yarns are not at all suitable for flame-retardant application in gray state, however, upon application of the wash resistant, flame-retardant finish Pekoflam DPN, their LOI values exceeded beyond 40 and even after 30 washes, they show very good flame-retardancy effect. The T/A (80 : 20) knitted fabric has medium flame retardancy in its virgin form, upon flame-retardant finishing its LOI is increased beyond 40 and upon continuous washing it still registers a good flame-retardancy effect. Hence, the knitted fabrics from pure Trevira-spun yarns and the FR treated T/C (80 : 20), T/M (80 : 20), and T/A (80 : 20) ones qualify very well for the production of flame-retardant garments for various applications in different forms.

3.4. Effect of Consequent Washing of Knitted Fabrics on LOI Value. LOI values of all the four types of knitted fabrics in the pure Trevira CS, T/C (80 : 20), T/M (80 : 20), and T/A (80 : 20) in a gray, finished, and washed states were given in Tables 7–10, and the effect of washing cycles on flame-retardancy performance were discussed.

From Table 7 and Figure 8, it was observed that in the pure Trevira CS fabrics, amongst all the five fabrics (S_1, S_2, S_3, S_4, and S_5), S_2 produced from pure Trevira finished exhibits the highest LOI of 50, followed by S_3, S_4, S_5, and S_1 in the decreasing order. The pure Trevira in a gray state showed very good LOI value and also when it was treated with Pekoflam DPN finishes the LOI value increased to 50. Upon

Table 6: Characteristics of gray, finished, and washed knitted fabric samples.

Sl. no	Fabric description	Fabric code	Courses per inch CPI	Wales per inch WPI	Areal density (g/m^2)	LOI (%)
1	Trevira gray	F_1	50	34	152	40
2	Trevira finished	F_2	52	34	168	50
3	Trevira finished-10 washes	F_3	54	36	176	43
4	Trevira finished-20 washes	F_4	56	38	184	43
5	Trevira finished-30 washes	F_5	58	40	192	42
6	T/C gray	F_6	46	34	158	23
7	T/C finished	F_7	47	36	171	50
8	T/C finished-10 washes	F_8	48	36	175	43
9	T/C finished-20 washes	F_9	48	38	183	42
10	T/C finished-30 washes	F_{10}	50	38	190	41
11	T/M gray	F_{11}	46	34	160	26
12	T/M finished	F_{12}	46	36	175	49
13	T/M finished-10 washes	F_{13}	48	36	179	45
14	T/M finished-20 washes	F_{14}	50	36	184	42
15	T/M finished-30 washes	F_{15}	50	38	191	40
16	T/A gray	F_{16}	46	36	146	32
17	T/A finished	F_{17}	46	36	160	45
18	T/A finished-10 washes	F_{18}	48	36	165	37
19	T/A finished-20 washes	F_{19}	50	38	174	36
20	T/A finished-30 washes	F_{20}	50	38	174	35

LOI: 25–29: Below minimum; LOI: 30–34: Medium. LOI: 35–39: Good; LOI: 40 and above: very good.

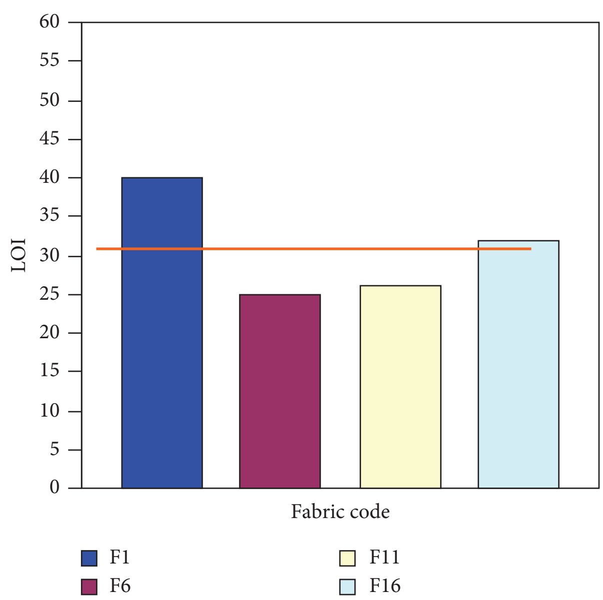

Figure 3: LOI of gray fabrics.

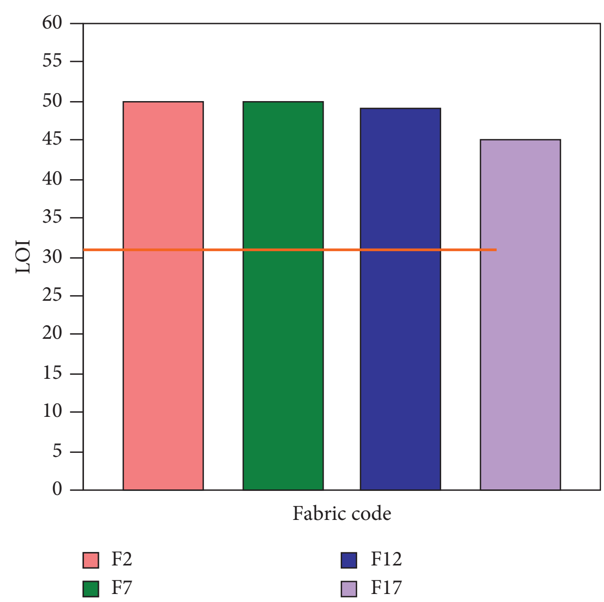

Figure 4: LOI of finished fabrics.

imparting washing resistant, flame-retardant finish Pekoflam DPN, it is revealed that the LOI of all the four treated samples (S_2, S_3, S_4, and S_5) is significantly increased with the result that S_2, S_3, S_4, and S_5 exhibit a very high LOI value. This clearly shows that the Pekoflam DPN has a great effect in improving the flame retardancy of Trevira and its blended fabrics.

Upon washing (after 10 wash), the LOI value showed a considerable reduction but still the LOI value is very good. Even after 20 wash the LOI value is similar to that of the after 10 wash. This indicates that after 20 wash the flame resistance of fabrics has not been changed or affected. Even upon after 30 wash the flame-resistancy of the fabric has not shown an appreciable reduction and the LOI value is still very good.

In Table 8 and Figure 9, it can be observed amongst all the five T/C (80 : 20) fabrics (S_6,S_7,S_8,S_9, and S_{10}) that the S_7 produced from Trevira/cotton blend (80 : 20) shows the highest LOI value of 50 followed by S_8,S_9,S_{10}, and S_6 in the decreasing order. The flame retardancy of S_7,S_8,S_9, and S_{10} is considered to be very good, while that of S_6 are below the minimum range (indicated by the red line in Figure 9) as required by a standard flame-retardant textile material.

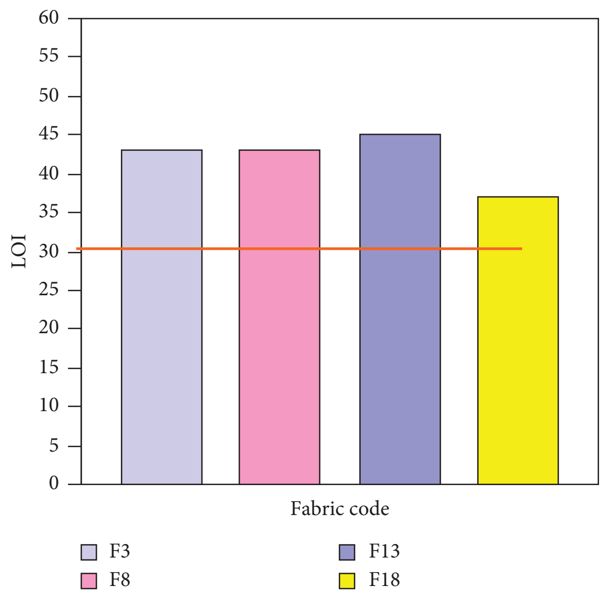

Figure 5: LOI of fabrics: after 10 washes.

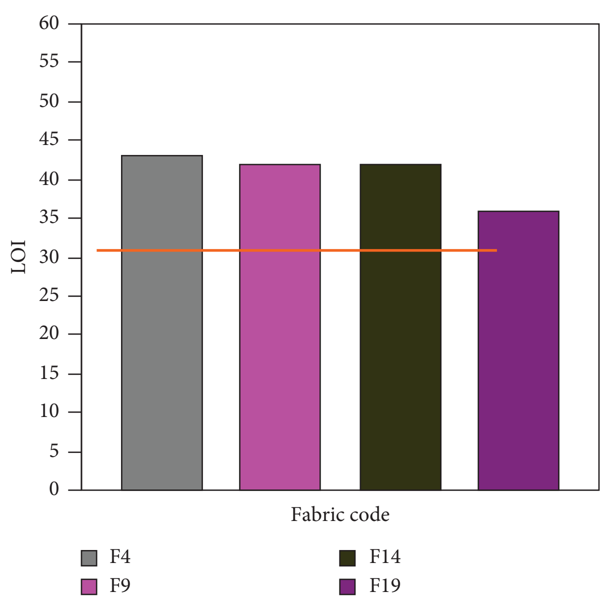

Figure 6: LOI of fabrics: after 20 washes.

Upon imparting wash resistant, flame-retardant finish Pekoflam DPN, it was observed that the LOI of all the four treated samples (S_7, S_8, S_9, and S_{10}) is significantly increased with the result that S_7, S_8, S_9, and S_{10} exhibit a very high LOI in the range of 41–50. It was revealed that upon wash (after 10 wash), the LOI values of the fabric S_3 showed a significant reduction; however, no appreciable reduction in flame retardancy is noticed upon further washing of fabrics S_9 after 20 washes and S_{10} after 30 washes, respectively.

From Table 9 and Figure 10, it was observed amongst all the five T/M (80 : 20) fabrics (S_{11}, S_{12}, S_{13}, S_{14}, and S_{15}) that the S_{12}, produced from Trevira/modal (80 : 20) blend exhibited the highest LOI value of 49 followed by S_{13}, S_{14}, S_{15},

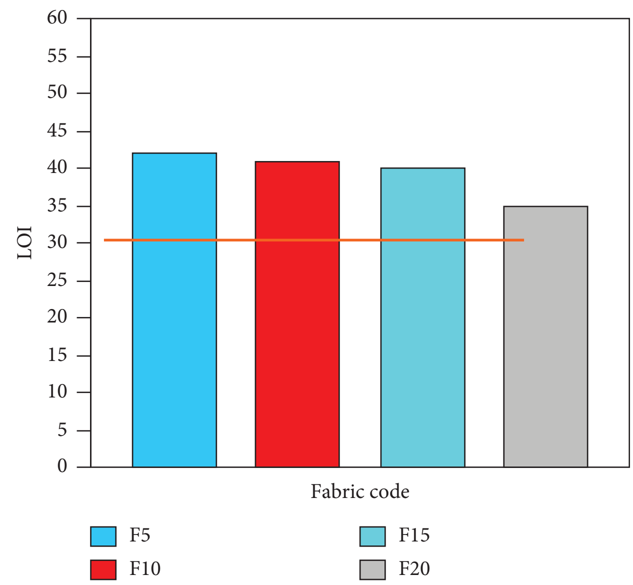

Figure 7: LOI of fabrics: after 30 washes.

Table 7: Effect of washing of Trevira fabric on LOI.

Sl. no	Fabric description	Fabric code	LOI (%)
1	Trevira gray	S_1	40
2	Trevira finished	S_2	50
3	Trevira finished: 10 washes	S_3	43
4	Trevira finished: 20 washes	S_4	43
5	Trevira finished: 30 washes	S_5	42

Table 8: Effect of washing of T/C blend fabric on LOI.

Sl. no	Fabric description	Fabric code	LOI (%)
1	T/C gray	S_6	23
2	T/C finished	S_7	50
3	T/C finished: 10 washes	S_8	43
4	T/C finished: 20 washes	S_9	42
5	T/C finished: 30 washes	S_{10}	41

Table 9: Effect of washing of T/M blend fabric on LOI.

Sl. no	Fabric description	Fabric code	LOI (%)
1	T/M gray	S_{11}	26
2	T/M finished	S_{12}	49
3	T/M finished: 10 washes	S_{13}	45
4	T/M finished: 20 washes	S_{14}	42
5	T/M finished: 30 washes	S_{15}	40

Table 10: Effect of washing of T/A blend fabric on LOI.

Sl. no	Fabric description	Fabric code	LOI (%)
1	T/A gray	S_{16}	32
2	T/A finished	S_{17}	45
3	T/A finished: 10 washes	S_{18}	37
4	T/A finished: 20 washes	S_{19}	36
5	T/A finished: 30 washes	S_{20}	35

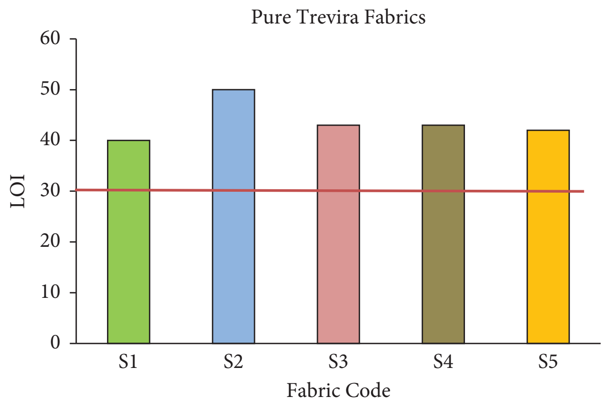

Figure 8: Effect of washing of Trevira fabric on LOI.

Figure 9: Effect of washing of T/C blend fabric on LOI.

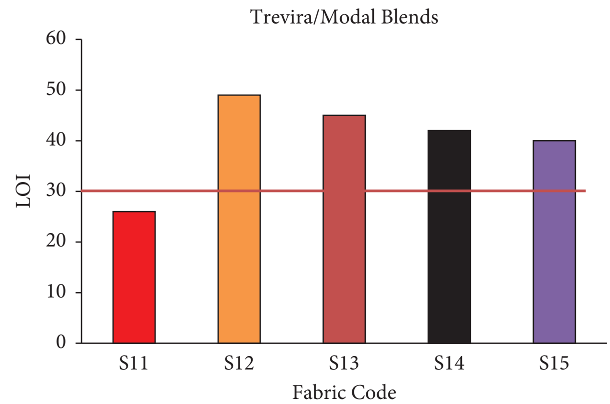

Figure 10: Effect of washing of T/M blend fabric on LOI.

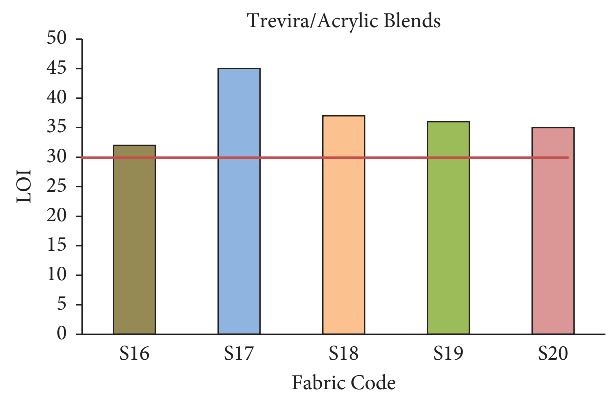

Figure 11: Effect of washing of T/A blend fabric on LOI.

and S_{11} in the decreasing order. The flame retardancy of S_{12}, S_{13}, S_{14}, and S_{15} is considered to be very good, while that of S_{11} are below the minimum range (indicated by the red line in Figure 10) as required by a standard flame-retardant textile material.

Upon imparting wash resistant, flame-retardant finish Pekoflam DPN, it was observed that the LOI of all the four treated samples (S_{12}, S_{13}, S_{14}, and S_{15}) is significantly increased with the result that S_{12}, S_{13}, S_{14}, and S_{15} exhibit a very high LOI in the range of 40–49. It was revealed that upon wash (after 10 wash) the LOI values of the fabric S_{13} showed a considerable reduction, however, no appreciable reduction in flame retardancy is noticed upon further washing of fabrics S_{14} after 20 washes and S_{15} after 30 washes, respectively.

From Table 10 and Figure 11, it was observed amongst all the five T/A (80 : 20) fabrics ($S_{16,}S_{17,}S_{18,}S_{19}$, and S_{20}) that the $S_{17,}$ produced from Trevira/Acrylic (80 : 20) blend exhibited the highest LOI value of 45 followed by $S_{18,}S_{19}$, S_{20}, and S_{16} in the decreasing order. The flame retardancy of S_{17} is considered to be very good, that of $S_{18,}S_{19}$, and S_{20} are good, and that of S_{16} is medium.

Upon imparting wash resistant and flame-retardant finish Pekoflam DPN, it was observed that the LOI of all the four treated samples ($S_{12,}S_{13,}S_{14}$, and S_{15}) is significantly increased with the result that $S_{12,}S_{13,}S_{14}$, and S_{15} exhibit a very high LOI in the range of 40–49. It was revealed that upon wash (after 10 wash) the LOI values of the fabric S_{13} showed a considerable reduction, however, no appreciable reduction in flame retardancy is noticed upon further washing of fabrics S_{14} after 20 washes and S_{15} after 30 washes, respectively.

4. Conclusions

The following conclusions are drawn from the present work: the fabric produced from 30 Ne Trevira/modal (80 : 20) ring-spun yarn shows an LOI value of 26, which is above the minimum LOI value of 25 required for the production of comfortable flame-retardant apparel. The fabrics produced from Trevira/cotton (80 : 20) yarns show very low LOI values and hence they are not suitable for production of comfortable flame-retardant apparel.

The constructional particulars of all the knitted fabrics studied vary from gray through finished to after-washed states. Overall, there is an increase in the areal density of fabrics caused due to a general increase in the CPI and WPI in all cases caused by the chemical treatments, which clearly indicate certain shrinkage in the fabrics. Furthermore, there is an almost 10% increase in the areal density of gray fabrics due to application of flame-retardant finish, Pekoflam DPN.

In gray state, amongst all the four fabrics (F_1, F_6, F_{11}, and F_{16}), F_1 produced from pure Trevira-spun yarn exhibits the highest LOI of 40, followed by F_{16}, F_{11}, and F_6 in the decreasing order. The flame retardancy of F_1 is considered to be very good, that of F_{16} is medium, and those of F_{11} and F_6 are below the minimum range required by a standard flame-retardant textile material. Upon treatment with wash resistant FR finish Pekoflam DPN, the LOI of all the four samples (F_2, F_7, F_{12}, and F_{17}) is significantly increased with the result that F_2, F_7, and F_{12} exhibit a very high LOI in the range of 49–50, while F_{17} has a value of 45. The Pekoflam DPN has a great effect in improving the flame retardancy of cellulose and its blended fabrics, and a slightly inferior effect on other fibrous materials like acrylic. It is found that after 10 washes, there is a considerable reduction in the LOI values of all the treated fabrics; however, no appreciable reduction in flame retardancy is noticed upon further washing of fabrics. Nevertheless, even after 30 washes the flame retardancy of fabrics F_5, F_{10}, and F_{15} is very good and that of the fabric F_{20} is good.

Overall, it can be stated that the pure Trevira-spun knitted fabric exhibits very good flame retardancy in gray state and hence may not require any flame-retardant finishing treatment. The knitted fabrics produced from T/C (80 : 20) and T/M (80 : 20) yarns are not at all suitable for flame-retardant application in gray state, however, upon application of the wash resistant, flame-retardant finish Pekoflam DPN, their LOI values exceeded beyond 40 and even after 30 washes, they show very good flame-retardancy effect. The T/A (80 : 20) knitted fabric has medium flame retardancy in its virgin form, upon flame-retardant finishing its LOI is increased beyond 40 and upon continuous washing it still registers a good flame-retardancy effect.

From the above-given theory, one can conclude that Trevira CS fibres can be successfully used to produce flame-retardant apparel, knitwear, sweaters, drapes, curtains, cover, and bed fabrics. The comfort of Trevira CS products may be enhanced through blending Trevira CS with a small proportion of cotton fibres (10–20%), modal fibres (10–20%), and acrylic fibres (10–20%) without sacrificing the flame-retardant characteristics. This results in economic production of flame-retardant apparel from Trevira CS and its selected blends in small proportions. Finally, the knitted fabrics from pure Trevira-spun yarns and the FR treated T/C (80 : 20), T/M (80 : 20), and T/A (80 : 20) ones qualify very well for the production of flame-retardant garments for various applications in different forms.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

The authors thank the Kombolcha Institute of Technology (KIOT), Wollo University, Kombolcha, Ethiopia. And Defence Research and Development Organisation, New Delhi, India.

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