Egyptian Journal of Chemistry

http://ejchem.journals.ekb.eg/

Enhancement of Fire Resistance in Cotton/Polyester and Cotton/Linen Blends Using Sol-Gel Derived Silicate/Phosphate Coatings

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Abstract

This research provides an overview of studies conducted on the usage of a novel composition containing sodium silicate, urea, and sodium hydrogen phosphate using sol-gel technology. The composition was designed to impart fire-retardant properties, to cotton based textiles (cotton/polyester (60/40) and cotton/linen (70/30)) using sol-gel technology. The factors affected the fire-retardant properties were investigated such as how temperature, heat treatment time, and starting component concentration. The fire-retardant properties of cotton-based fabrics are shown to alter at temperatures of 500, 600, and 750°C. The three different types of heat treatment are investigated. The cotton-based fabrics treated with a fire-retardant compound had better fire-retardant characteristics than the untreated fabrics. When tested for flammability with a 15-second ignition time, untreated fabrics completely burns after 60 seconds. In fabrics treated with a fire retardant, a 15-second ignition period resulted in a minor smoldering duration. After modifying the surface of the treated cotton-based fabrics (cotton/polyester 60/40 and cotton/linen 70/30), scanning electron microscopy (SEM) and energy dispersive micro-analysis (EDX) provide that the untreated fabric contains 57.90% carbon and 42.10% oxygen while the treated fabrics provide containing sodium, silicon (4.44 and 2.79%), and phosphorus (9.96 and 4.84%) for both fabric respectively. In addition, cellulose materials that have been changed with compositions comprising sodium silicate, urea, and sodium hydrogen phosphate have better fire resistance. The recommended compositions provide greater fire resistance may be done using ordinary finishing without needing for a high-temperature fixing step.

Keywords: fire retardant properties, textile materials, sodium hydrogen phosphate, sodium silicate, urea, sol-gel technology

1. Introduction

Textile fabrics composed of cotton, polyester, and linen exhibit remarkable versatility and can be utilized in several applications, including curtains, draperies, and furniture upholstery. They are utilized in bedding, specialized protective apparel and items, as well as ornamental finishes for rooms serving various utilitarian purposes. These materials are also present in technology, public infrastructure, and transportation. Nevertheless, they are easily ignited and provide a considerable risk in the occurrence of a fire. Moreover, they facilitate the propagation of flames, and upon combustion, they emit substantial quantities of smoke and fumes, posing a significant threat to human life. Both individuals and the environment are vulnerable to considerable harm from fires that emit substantial quantities of smoke and toxic gases. Evacuations are necessary, and substantial environmental consequences will ensue due to the poisonous air pollutants generated by large-scale fires. Consequently, implementing preventative measures to mitigate the risk of fire in the home may be the most efficacious approach to reduce the incidence of fire-related incidents and fatalities in the future. Currently, specific improvements have been made in the field of fire-resistant textile fabrics. To enhance the flame-retardant properties of both natural and synthetic materials, several studies are being conducted across various countries, [1-15] and synthetic fibers. [7, 16-22] Scientists also present the most recent advancements in the development of fire-resistant biocomposites. [14, 15, 23-27] The works thoroughly examine the application of eco-friendly and cost-effective additives to fire retardants in the manufacturing of fire-resistant materials. [28-32]

Durable fire-retardant coatings for polyester fabrics are achieved using a nanocoating composed of chitosan and ammonium polyphosphate, [33] ammonium polyphosphate and carbon microspheres, [34] phosphorus, nitrogen, and silicon, by layer-by-layer assembly of colloidal silicon dioxide and polyphosphates. [35]

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Receive Date: 19 July 2025, Revise Date: 15 September 2025, Accept Date: 16 September 2025

DOI: 10.21608/ejchem.2025.405495.12069

Layer-by-layer assembly technologies are garnering heightened interest in the creation of fire-resistant coatings. [36-38]

Recently, several modern technologies have been employed, including ultraviolet curing technology, plasma technology, and physical and chemical vapor deposition technology. [22, 39-42] The authors investigated the concurrent grafting and polymerization of flame retardant monomers onto textile materials subjected to argon plasma treatment. [43-45] The utilization of plasma and other modern technologies in industrial settings necessitates a specialized installation with a complex design, hence complicating the technological process of textile material processing and elevating the end product's cost.

Currently, sol-gel technology is extensively employed for the novel treatment of textile materials. [36, 46-53] The primary advantage of the sol-gel approach compared to alternative techniques is its capacity to regulate the structure of the resultant materials, including particle size, pore dimensions and volume, as well as film surface area, thereby facilitating the acquisition of materials with specific qualities. This process does not necessitate specialized equipment or costly initial reagents, making it a comparatively economical synthesis approach. The sol-gel method results in the creation of self-organized (nano) layers on the fiber surface, producing new coatings with a high degree of molecular homogeneity and enhanced physicochemical qualities. [54-64]

This project aims to acquire cellulose materials (polyester and cotton) endowed with flame retardant qualities by sol-gel technology.

2. Experimental

The fabric used during this study was (cotton/polyester (60/ 40), 153 g/m^2) and (cotton/linen (70/30), 185 g/m^2) which supplied by Auf for textile industry, Egypt were used.

Liquid glass - aqueous alkaline sodium silicate solution $Na_2O(SiO_2)n.nH_2O$ supplied by MERK, Germany. disodium hydrogen phosphate (Na_2HPO_4 Mwt.: 141.96 g/mole)) is an inorganic compound and Urea ($CO(NH_2)_2$. Mwt.: 60.06 g/mole) supplied by LOBA Co. India

2.1. Methods

2.1.1. Treatment process

Samples of blended fabrics comprising 60 percent cotton and 40 percent polyester, together with 70 percent cotton and 30 percent linen, were measured at 200 × 170 millimeters. The exact mass of the samples was determined using an analytical balance prior to immersion in a bath containing silicate for one minute at a spin rate of 90 percent. The treated fabric was subsequently dried for eight to ten minutes at a temperature of 75–85°C, rinsed thoroughly with distilled water, and then dried again. During the second phase of the process, the specimens were subjected to a treatment involving sodium silicate. Subsequently, they were submerged for one minute in a solution of sodium hydrogen phosphate and urea dissolved in water. Subsequently, they were diminished to ninety percent of their original size through compression. Subsequently, they were desiccated at a temperature of 75°C for three minutes in an air oven. They were subsequently rinsed with distilled water and air-dried at ambient temperature.

2.2. Measuerments

Tests of the fire-retardant effectiveness of the developed compositions were carried out in accordance with GOST R 50810-95, which establishes a method for determining the ability of textile materials (fabrics, non-woven fabrics) to resist ignition, stable combustion, as well as assessing their fire-retardant properties. The standard applies to all flammable decorative textile materials supplied to the consumer.

The tensile characteristics of the materials were determined using a tensile testing machine MT-150, GOST 3813–72 (company and country).

Electron microscopic examination of the samples was carried out using a low-vacuum scanning electron microscope JSM-6510LA (company and country).

3. Results and its discussion

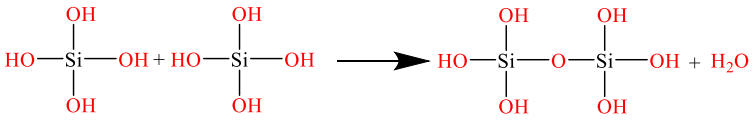
The sol-gel method is a cutting-edge chemical finishing technology that adds functional qualities to fabrics without changing their look or feel too much. These properties include antibacterial, flame-retardant, water-repellent, UV-resistant, and self-cleaning effects. The first step is to make a sol, which is a colloidal suspension produced from metal alkoxides like tetraethoxysilane (TEOS) or metal chlorides in an alcohol-based solvent. Depending on the required qualities of the fabric, functional additives such nanoparticles of TiO_2, ZnO, or Ag are added. The textile is then soaked in the sol or treated using a pad-dry-cure method, where it is put in a sol bath and pressed between rollers to control how much it absorbs. After soaking, the fabric is dried to get rid of the solvents and start the gel forming process. This fixes the particles to the fiber surface. A final heat treatment (curing) at high temperatures (typically 120–180°C) finishes the condensation and polymerization reactions, creating a strong inorganic-organic network that is attached to the fabric. With this process, you can make uniform nanoscale coatings that are quite strong and can be used for many things.

Some common uses are antibacterial fabrics (with silver nanoparticles), UV-protective fabrics (with ZnO or TiO_2), water- and oil-repellent surfaces (with fluorinated silanes), flame-retardant coatings (with silica), and self-cleaning fabrics (with photocatalytic TiO_2).

The application of the sol-gel method in the chemical finishing of textiles and fabrics involves the soaking of textile fibers in a sol-gel solution, followed by drying and heat treatment under suitable circumstances. In the sol-gel process, the initial step is hydrolysis, which is then followed by a condensation reaction that results in the creation of –Si-O-Si bonds. The aqueous solution of sodium silicate undergoes a hydrolysis reaction that follows the pattern detailed below:

$$Na_2SiO_3 + 3H_2O \rightarrow Si(OH)_4 + 2NaOH$$

The silicic acid released as a result of hydrolysis contains silanol groups capable of polycondensation to form polymer acids.



The hydroxyl groups and the sol-gel composition are responsible for the construction of a three-dimensional network on the surface of the cellulose fiber during the second stage. This network forms as a result of the creation of hydrogen, ionic, and coordination linkages. The highest weight increase results, as shown in Table 1, provide evidence of the presence of a silica coating that has a high degree of fixing.

Table 1: Weight of fabric samples before and after treatment with fire retardant

Sample	$CO(NH_2)_2$ (g/l)	Na_2HPO_4 (g/l)	Weight of fabric (g)			
			Cotton/polyester (60/40)		Cotton/linen (70/30)	
			Before treatment	After treatment	Before treatment	After treatment
1	5	15	12.15	21.75	11.15	16.39
2	10	25	12.07	16.35	11.15	14.78
3	10	20	12.41	18.72	11.20	15.80
4	10	30	12.30	17.91	11.17	16.05

Table 2 provides a detailed comparison of the tensile strength, length of charred area, and smoldering time for two types of fabric—cotton/polyester (60/40) and cotton/linen (70/30)—as they undergo treatment with various concentrations of urea ($CO(NH_2)_2$) and sodium hydrogen phosphate (Na_2HPO_4) at three different treatment temperatures (50°C, 60°C, and 75°C).

The results showcase how the fire-retardant treatment dramatically influences the smoldering time and char length of the fabrics, with minimal reduction in tensile strength. The data highlights: a) Better fire-retardant performance with increased concentrations of the fire-retardant compound, and b) Optimal flame resistance achieved at 75°C for higher concentrations of Na_2HPO_4 and $CO(NH_2)_2$.

The major findings and observations for the treated cotton/polyester (60/40) fabric show that adding chemicals, especially in higher amounts, greatly improves the fabric's flame-retardant characteristics while keeping its strength. The tensile strength stays quite stable, going down only a little from 345 N in untreated fabric to 328 N at the highest additive concentration (10 g/l $CO(NH_2)_2$ and 30 g/l Na_2HPO_4) and 75°C. This shows that the fabric strength doesn't change much. The length of the burnt region drops dramatically, from 220 mm in untreated samples to only 25 mm in treated samples, no matter the temperature. The time it takes for the fabric to smolder also goes down from 60 seconds to as little as 3–4 seconds when the same high concentration of additives is used, showing a big improvement in flame resistance.

For the cotton/linen (70/30) fabric, the tensile strength stays very much the same, going from 345 N in untreated fabric to 320 N after treatment, which is the same as the cotton/polyester fabric. The burned region stays the same length in untreated samples (220 mm), but in treated fabrics, it gets much shorter, going down to 28–29 mm at the highest additive concentration and 75°C. The time it takes for untreated fabrics to smolder is always 60 seconds. However, at 75°C and with the highest concentration of additives, the time it takes to smolder is cut down to an average of 25–28 seconds. This is noticeably longer than the cotton/polyester samples, which means that this fabric blend is not as good at stopping flames from spreading.

Furthermore, analysis of the finding data provides that:

a) Fire Retardant Efficiency: The data shows that both textiles are much more fire resistant when they are treated with increasing amounts of Na_2HPO_4 and $CO(NH_2)_2$ at 75°C. These treatments seem to work better on cotton/polyester, which has shorter smoldering times (as low as 3 seconds) and smaller char lengths (down to 25 mm) than cotton/linen.

b) Little Loss in Tensile Strength: - The small drop in tensile strength (less than 5% for most samples) shows that the sol-gel fire-retardant coating doesn't damage the fabric's mechanical integrity. This is a good quality for keeping cloth strong after treatment.

c) Fabric Variability: Cotton/polyester (60/40) is always better at stopping flames than cotton/linen (70/30). The larger polyester content may be to blame for this discrepancy, as it interacts better with the sol-gel coating, or it could be due to changes in fiber structure that affect chemical absorption.

d) Treatment Temperature: The best temperature for treatment is 75°C, as shown by the big drops in char length and smoldering duration compared to lower temperatures (50°C and 60°C). This experimental evidence corroborates the effect of elevated temperatures in augmenting the bonding and activation of fire-retardant additives.

Finally, the table shows that sodium silicate, sodium hydrogen phosphate, and urea-based sol-gel coatings work well to make textiles less flammable. The best results are seen when the concentrations of the additives are at their highest ($CO(NH_2)_2$ = 10 g/l and Na_2HPO_4 = 30 g/l) and the treatment temperature is at its highest (75°C). Cotton/polyester mixes are better for these treatments since they are more flame-resistant while still being strong enough. In general, these results provide a useful and cost-effective way to make flame-retardant materials that meet both safety and environmental goals in the textile sector.

Table 2: Effect of treatment temperature on the properties of both investigated fabrics upon treatment

Fabric type	$CO(NH_2)_2$ (g/l)	Na_2HPO_4 (g/l)	Treatment temperature (°C)								
			Tensile strength (N)			Length of charred area (mm)			Smoldering time (sec)		
			50	60	75	50	60	75	50	60	75
Cotton /polyester (60/40)	Blank		345	345	345	220	220	220	60	60	60
	5	15	340	340	340	220	220	210	148	145	150
	10	20	335	335	330	220	220	220	150	150	160
	10	25	340	340	340	220	220	210	80	80	72
	10	30	330	330	328	25	26	25	3	3	4
Cotton /linen (70/30)	Blank		345	345	345	220	220	220	60	60	60
	5	15	330	330	325	220	220	220	168	168	170
	10	20	320	325	320	220	220	220	168	170	160
	10	25	318	318	318	220	220	220	125	130	127
	10	30	320	320	320	28	28	29	25	27	28

Figures 1 and 2 visually depict the results of the vertical flame tests or different compositions of treated and untreated textile samples. These images include: Figure 1 displays the flame test results on cotton/polyester (60/40) fabric and Figure 2displays the flame test results on cotton/linen (70/30) fabric.

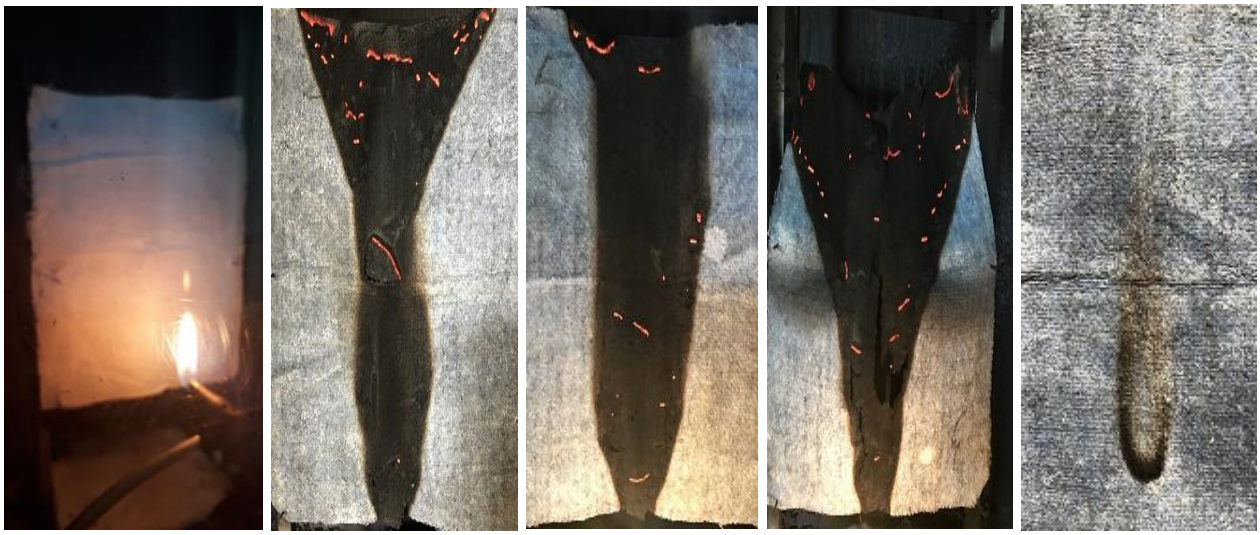
Each figure shows how the flammability characteristics change with increasing concentrations of urea ($CO(NH_2)_2$) and sodium hydrogen phosphate (Na_2HPO_4) in the fire-retardant treatment, as well as the differences between untreated samples and treated samples under varying additive concentrations.

Figure 1 shows the vertical flame test of cotton/polyester (60/40) fabrics. It shows how the fire resistance gets better as the amount of sol-gel additives increases. The untreated sample (Image A) displays a lot of burning, which leaves behind a big, brittle char that illustrates how flammable the blend is. When treated at moderate levels (Image B: $CO(NH_2)_2$ 5 g/l and Na_2HPO_4 15 g/l), the fabric's structural integrity is better and the flame spread is less. Images C and D ($CO(NH_2)_2$ 10 g/l, Na_2HPO_4 20–25 g/l) show even more improvement. The fact that the char is stable shows that it is partially self-extinguishing. When the additives are at their greatest levels (Image F, $CO(NH_2)_2$ 10 g/l, Na_2HPO_4 30 g/l), the cloth is most resistant, with very little charring, smoke, and vertical flame spread. These results show that raising the concentration of the additive significantly improves flame retardancy. The best treatment gives cotton/polyester blends great fire resistance.

Figure 2 shows the vertical flame test of cotton/linen (70/30) fabrics. The results are comparable to those of cotton/polyester, but the flame-retardant effects are a little less strong. The untreated sample (Image A) burns a lot and leaves a big charred residue, which shows how flammable the combination is. With lesser quantities of additives (Image B, $CO(NH_2)_2$ 5 g/l and Na_2HPO_4 15 g/l), the flames move more slowly, although charring and smoldering are still visible. Images C and D ($CO(NH_2)_2$ 10 g/l, Na_2HPO_4 20–25 g/l) show better resistance. The production of stable char and lower vertical char length suggest that the material can partially self-extinguish. The fabric shows the biggest improvement at the greatest additive concentration (Image F, $CO(NH_2)_2$ 10 g/l, Na_2HPO_4 30 g/l), with little flame spread and limited charring. Overall, the cotton/linen mix shows a big improvement in flame resistance at greater levels of additives, although it still doesn't work as well as the cotton/polyester blend examined in Figure 1.

A comparison of Figures 1 and 2 shows that both cotton/polyester (60/40) and cotton/linen (70/30) fabrics become much more flame-resistant as the amounts of Na_2HPO_4 and $CO(NH_2)_2$ increase. Both mixes show less flame spread and better fabric integrity at greater doses of the additive, but cotton/polyester works better, especially in Image F of Figure 1, where there is less charring and shorter smoldering periods. On the other hand, cotton/linen, while significantly improved, still has slightly larger burned areas and longer smoldering

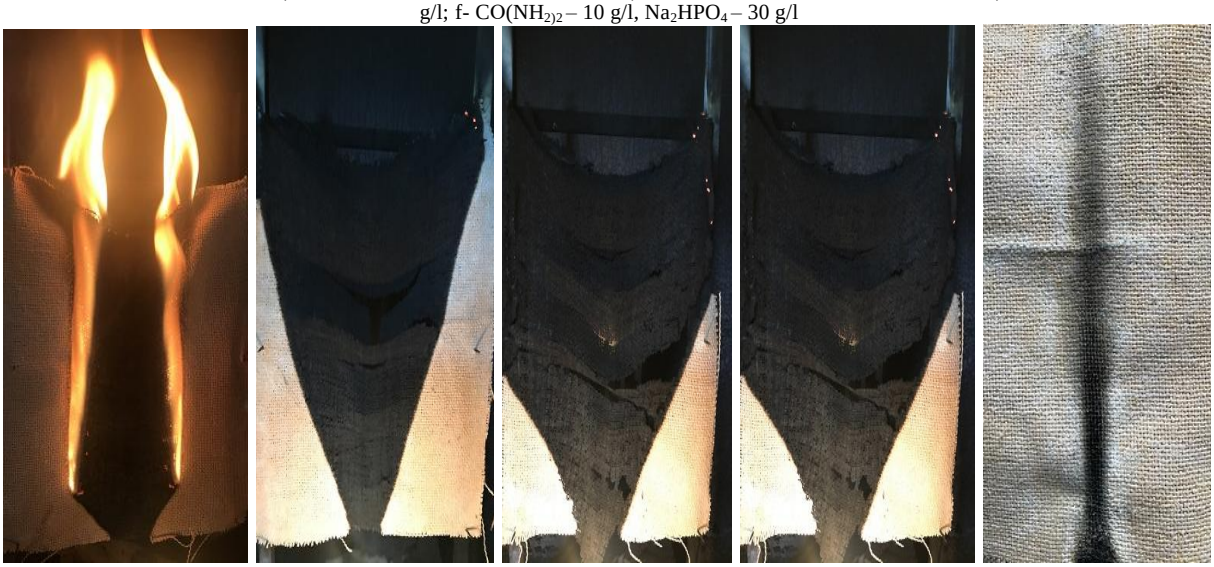
times, which means it is less effective at putting out flames. In general, both statistics show that higher concentrations of additives are very important for improving fire resistance, with cotton/polyester being the best at doing so.



A B C D F

Figure 1: Photos showing fabric (cotton 60% polyester 40%) with vertical flame test

a - original sample, b - $CO(NH_{2})_2$ – 5 g/l, Na_2HPO_4 – 15 g/l; c- $CO(NH_{2})_2$ – 10 g/l, Na_2HPO_4 – 20 g/l; d - $CO(NH_{2})_2$ – 10 g/l, Na_2HPO_4 – 25 g/l; f- $CO(NH_{2})_2$ – 10 g/l, Na_2HPO_4 – 30 g/l



A B C D F

Figure 2: Photos of fabric (cotton 70% linen 30%) with vertical flame test

a - original sample, b - $CO(NH_{2})_2$ – 5 g/l, Na_2HPO_4 – 15 g/l; c- $CO(NH_{2})_2$ – 10 g/l, Na_2HPO_4 – 20 g/l; d - $CO(NH_{2})_2$ – 10 g/l, Na_2HPO_4 – 25 g/l; f- $CO(NH_{2})_2$ – 10 g/l, Na_2HPO_4 – 30 g/l

Figures 1 and 2 clearly show that sol-gel fire-retardant treatments work to make textile blends more flame-resistant. Higher amounts of Na_2HPO_4 and $CO(NH_2)_2$ make a big difference. The protective effect is stronger in cotton/polyester fabrics than in cotton/linen fabrics. This is probably because the fibers are made up of different materials and soak up chemicals differently after treatment. When the levels of additives are higher, the treated fabrics stay stronger and don't char or spread flames as much. The numbers back up the text's findings and show that sol-gel-based treatments are a useful way to make different types of fabric more fire-resistant.

Figure 3 shows the morphological and elemental surface analysis of fabrics that have not been treated and those that have been treated. It shows how the sol-gel fire-retardant treatment affects the structure and chemistry of the fabrics. Images a and b of the untreated fabric show a smooth, even fiber surface under SEM with no protective layers. EDX demonstrates that carbon and oxygen are the sole primary constituents, which is consistent with the natural cellulose structure. The treated cotton/polyester mix (Images c and d), on the other hand, has a thin, even coating layer over the fibers that makes a silica-phosphate protective network. The EDX results show that silicon (4.44%), phosphorus (9.96%), and sodium (9.96%) are all present. This con-

firms that flame-retardant elements were deposited, which improves thermal stability. The treated cotton/linen mix (Images e, f) also has a coating layer, but it is not as even. This is probably because the fibers have different textures and porosities. EDX found reduced amounts of silicon (2.79%), phosphorus (4.84%), and salt (6.47%). These results show that cotton/polyester fibers soak up the sol-gel treatment better than cotton/linen fibers, which makes them better at stopping flames.

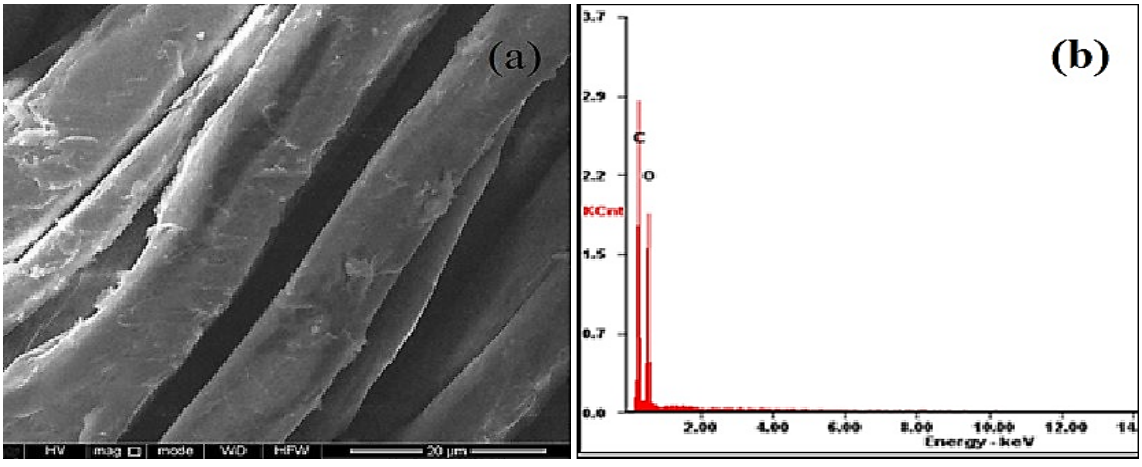
Table 4 summarizes the elemental composition of untreated and treated fabrics, confirming the successful integration of flame-retardant elements through sol-gel processing. The untreated cotton fabric consists mainly of carbon (57.9%) and oxygen (42.1%), characteristic of cellulose fibers with no inherent fire resistance. After treatment, the cotton/polyester blend has a lot more silicon (4.44%), sodium (9.96%), and phosphorus (9.96%), and a lot less carbon (41.69%) and oxygen (38.76%). This shows that an inorganic layer has formed that protects the fabric and makes it more stable in heat. In comparison, the treated cotton/linen blend also contains silicon (2.79%), phosphorus (4.84%), and sodium (6.47%), though in lower amounts, reflecting reduced uptake of the sol-gel coating due to the linen component. The relatively higher carbon and oxygen contents in the cotton/linen sample further suggest less effective integration of flame-retardant material, explaining its slightly lower performance compared to the cotton/polyester blend.

The comparison of fabric types demonstrates that the cotton/polyester (60/40) combination holds more silicon, phosphorus, and sodium, which means it absorbs the flame-retardant coating better. The polyester part is probably what makes it stick better. It makes the surface smoother, which helps the sol-gel layer stick better. On the other hand, the cotton/linen (70/30) blend benefits from the treatment, but it has lower elemental incorporation. This suggests that the porous and uneven structure of linen fibers makes it harder to form a uniform coating and makes the overall flame-retardant less effective than the cotton/polyester blend.

Figure 3 and Table 4 show a clear link between visual and numerical proof that the sol-gel therapy works. Figure 3's SEM photos reveal that treated fabrics have smooth, inorganic coating layers on their surfaces. Untreated samples, on the other hand, don't have any such protective film. The EDX spectra and elemental data in Table 4 back up what we can see with our eyes. They show that the amount of carbon has gone down while the amounts of silicon, phosphorus, and sodium have gone up. These results demonstrate that a silicate-phosphate hybrid layer was successfully deposited, which supports the idea that the sol-gel technique can improve flame retardancy.

Figure 3 and Table 4 show that sol-gel treatments work well to make flame-retardant coatings on cotton/polyester and cotton/linen blends by adding important elements including silicon, phosphorus, and sodium. The cotton/polyester blend has a greater elemental incorporation and a more even coating. This shows how the content of the fibers and the structure of the surface affect how well the treatment works, making this blend better for generating better fire resistance. From a practical point of view, the combination of SEM, EDX, and elemental data gives us a good foundation for improving sol-gel formulations and pretreatments. This lets us use diverse methods that improve coating uniformity and uptake on different types of fabric.

The SEM images and EDX analysis in Figure 3 and Table 4 show that the sol-gel coating does indeed create an effective protective layer. The cotton/polyester blend has more silicon and phosphorous in it, which makes it better at stopping flames. The cotton/linen blend, on the other hand, has slightly less but still useful advantages. These results show that sol-gel technology is useful for improving fire resistance and that the type of fiber used can affect how well the treatment works.



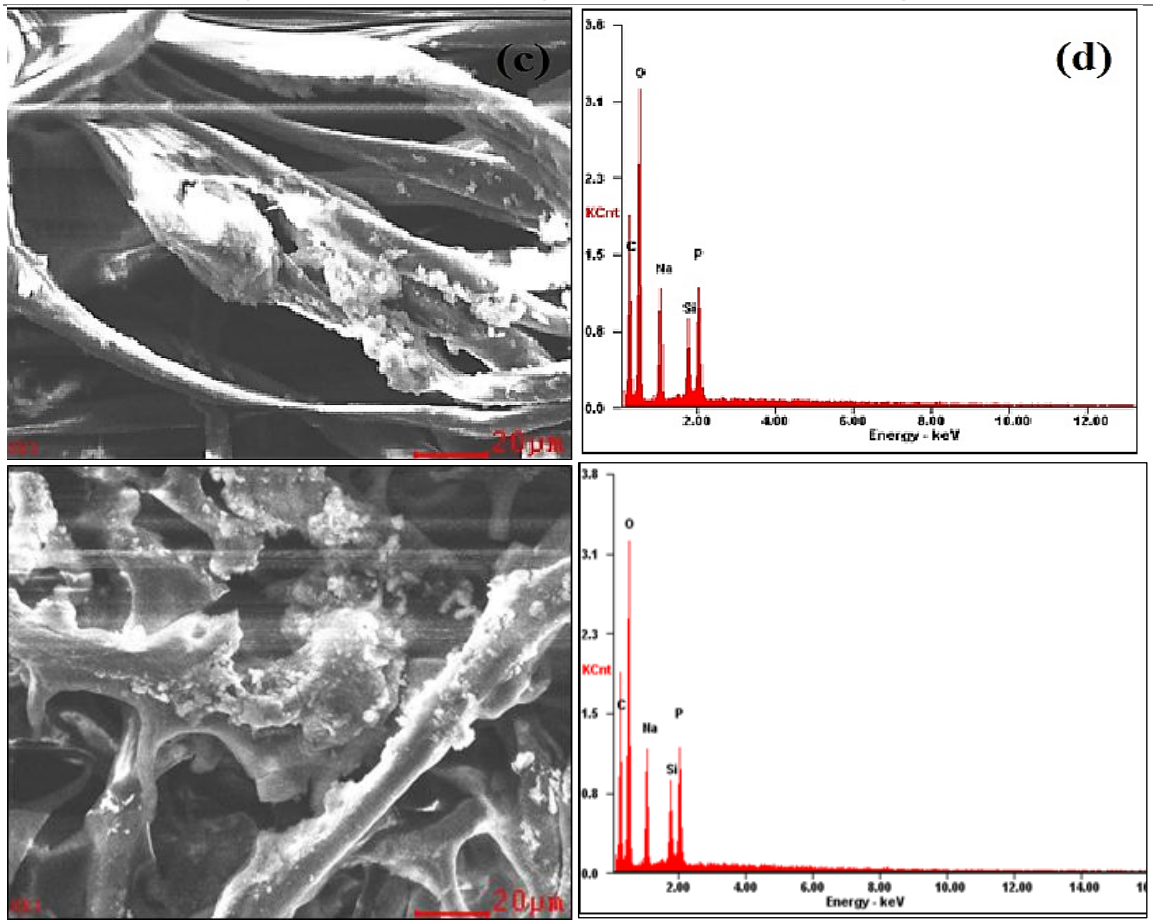


Figure 3: Scanning Electron microscopic images (SEM) and energy dispersive microanalysis (EDX) of the untreated and treat6ed fabrics
(a, b) original sample, (c, d) modified cotton 60% polyester 40%: and (e) modified cotton 70% linen 30%

Table 3: Average elemental composition of untreated and modified fabric, obtained based on the results of energy-dispersive microanalysis

Sample	Mass fraction, %					Atomic fraction, %				
	C	O	Na	Si	P	C	O	Na	Si	P
Original fabric: cotton 100%	57,90	42,10				64,69	35,31			
Treated fabric (cotton 60% and polyester 40%)	41,69	38,76	9,96	4,44	9,96	52,18	36,42	6,52	2,38	2,50
Treated fabric (cotton 70% linen 30%)	43.85	42.05	6.47	2.79	4.84	53.56	38.56	4.13	1.46	2.29

4. Conclusion

This work effectively created a sol-gel-based fire-retardant coating for cotton-polyester (60/40) and cotton-linen (70/30) blended fabrics, utilizing sodium silicate, urea, and sodium hydrogen phosphate to enhance flame resistance significantly. Compared to untreated samples, treated materials had far shorter smoldering times and less burned regions. The cotton-polyester blend showed the biggest improvement, going from 60 seconds to just 3–4 seconds. The treatment kept the fabric's strength, with only a small drop in breaking load from 345 N to 328 N. SEM and EDX tests showed that a thin, even coating containing silicon (up to 4.44%) and phosphorous (up to 9.96%) had formed. This proved that the sol-gel method worked. The process was also cost-effective, good for the environment, and easy to use because it didn't need any special tools or high-temperature fixing. Overall, the results show that this sol-gel treatment is a potential, long-lasting way to make cotton-based blends more fire-resistant while keeping their mechanical integrity. This makes it good for everything from everyday clothes to industrial and protective textiles.

The flammability of textile materials such as cotton, polyester, and linen remains a significant challenge due to their tendency to ignite easily and propagate flames rapidly, producing smoke and toxic gases. In this study, sol-gel technology was employed to enhance the flame retardancy of mixed fabric compositions (cotton/polyester and cotton/linen) by treating them with a combination of sodium silicate**,** sodium hydrogen phosphate (Na_2HPO_4)**,** and urea ($CO(NH_2)_2$)**.**

Weight Gain and Coating Efficiency: The sol-gel process enabled the formation of a silica-based hybrid network on the fiber surface through hydrolysis and condensation reactions. As shown in **Table 1**, a substantial increase in fabric mass after treatment indicates the effective deposition of inorganic coatings. The highest weight gain was observed in sample 1 (Na_2HPO_4 – 15 g/L and urea – 5 g/L), with post-treatment weights of 21.75 g and 16.39 g for cotton/polyester and cotton/linen blends, respectively. This confirms the formation of a solid inorganic matrix anchored onto the cellulose-rich fiber surfaces via silanol-polymer interactions.

Fire Retardant Performance: Data from **Tables 2** demonstrate a significant improvement in flame resistance following treatment. Untreated fabrics exhibited long smoldering times (60 s) and large charred areas (220 mm), consistent with the high flammability of natural and synthetic fibers After treatment, the smoldering time was reduced dramatically to as low as **3–4 seconds** for the cotton/polyester blend and **25–28 seconds** for the cotton/linen blend at the highest additive concentrations and 75°C heat treatment.

This reduction in flammability can be attributed to the combined action **of** phosphorus and nitrogen-based flame retardants, which promote char formation and dilute flammable gases. Phosphates promote dehydration of cellulose and inhibit the release of combustible volatiles, while urea contributes to non-flammable gas evolution (NH_3, CO_2), creating a protective barrier layer.

The flame spread images in Figures 1 and 2 corroborate the tabulated data, showing visually reduced charring and carbonization for treated samples compared to the original. The suppression of vertical flame propagation, especially in samples treated with higher concentrations of Na_2HPO_4 and urea, visually demonstrates the effectiveness of the treatment.

Mechanical Integrity: Importantly, the fire-retardant treatment had minimal impact on the mechanical strength of the fabric. A.s indicated in **Tables 2**, the breaking load decreased only slightly from 345 N in untreated samples to a minimum of 328 N after treatment. This finding is consistent with previous reports where inorganic sol-gel coatings offered enhanced fire resistance without compromising tensile strength significantly.

Morphological and Elemental Analysis: Scanning electron microscopy (SEM) revealed the formation of a **thin, uniform coating** over the fibers in treated samples, which is absent in the original fabric (Figure 3). This observation aligns with the self-organizing behavior of sol-gel coatings. Furthermore, energy-dispersive X-ray spectroscopy (EDS) confirmed the presence of Si and P elements on the treated fabric surface, with Si reaching up to 4.44% and P up to 9.96% by mass (Table 3). These elemental changes validate the successful integration of silicate and phosphate networks into the fabric matrix.

The lower concentrations of Si and P in the cotton/linen fabric compared to the cotton/polyester blend may be due to differences in fiber surface energy or porosity, which affect chemical uptake during sol-gel treatment.

The application of sol-gel technology using sodium silicate, Na_2HPO_4, and urea resulted in textiles with enhanced flame resistance and preserved mechanical properties. These results demonstrate a cost-effective and environmentally benign method of producing flame-retardant fabrics without requiring specialized equipment or toxic chemicals, consistent with the sustainability goals in textile engineering

5. Consent for publication

All authors read and approved the final version of the manuscript.

6. Data Availability Statement

All data was provided in this paper.

7. Ethics approval

Not applicable.

8. Credit authorship contribution statement

All authors equally participated in the conceptualization, design of the methodology, validation procedures, data collection, statistical analysis, result interpretation, and the drafting and revision of the manuscript.

9. Funding

No fund was received.

10. Acknowledgments

Not applicable

11. Conflicts of Interest

No conflict of interest was reported by all authors.

12. References

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