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Systematic pad dry cure technique for augmenting the flame resistance functionality of jute fabric

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A R T I C L E I N F O

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A B S T R A C T

Applying flame retardant finish on jute makes flame protective jute products that can be another diversified use of it. The target of this experiment is to observe the flame retardancy improvement of the fabric properties after finishing treatment with various flame retardant chemicals. The untreated (raw) and H_2O_2 bleached jute fabrics having plain weave were used in this experiment. Borax, diammonium phosphate (DAP) and thiourea were used as flame retardant chemicals. The combinations of these chemicals were applied to the fabrics by the pad-dry-cure method with various concentrations. Vertical flammability, breaking load percentage, and weight gain percentage were performed on all samples to observe the change in fabric properties. Significant improvement was found for all chemical combinations compared to untreated fabrics. Here, the flame spread time and weight gain percentage increase, but the breaking load percentage decreases for every combination. Among all combinations, the borax and DAP combination especially at 6% concentration shows the 305% improvement of flame spread time for raw jute and 276% for bleached jute fabric. In contrast, the borax and thiourea combination showed the progress of weight gain percentage. Besides, better wash durability was reported for all samples after five washing cycles. These flame-retardant jute fabrics have prospective industrial applications as brattice cloth in mines and many other potential fields of applications such as flame-retardant kitchen aprons, furnishings for a public hall, theater and hospitals.

1. Introduction

Nowadays, functional materials, especially flame-retardant textiles, have attracted much attention and increased public awareness of safety (Barbalini et al., 2020). Worldwide, a large number of people die and lose fortunes in fire accidents due to the easy ignition of textiles every year (Zhang et al., 2019). Therefore, it is urgent to impart textiles with less flammability or non-flammability.

Today's challenges of textile industries are to make new developments in clothing, especially protective clothing. In continuation of this, there are some innovations in developing heat-resistant fibres and flame retardant clothing (Horrocks et al., 2005; Zhang et al., 2020). Flame retardancy does not mean to prevent the materials from igniting; rather it minimizes the rate of flame spread. To develop a flame retardant material, a compound or composition is added to materials that increase resistance to combustion (Yasin, 2017; Patankar et al., 2021). There are textiles, for example, aramids, which are inherently flame retardant. But the production of inherently flame-retardant textile materials is expensive to process (Sohail et al., 2016). Instead of using inherently flame-retardant textiles, natural fibres like jute can be the cheapest source for developing flame protective clothing. It can also be environmentally friendly (Papaspyrides et al., 2009). Jute and jute-based products are becoming popular in the domestic and international fields due to their eco-friendliness and biodegradable

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characteristics (Samanta and Bhattacharya, 2015). The flame retardant treated product can be a diversified use of jute. Though much research has been done on the flame retardancy of cotton, a few works have been existed on jute (Khatton et al., 2019). Jute is a lignocellulosic fibre having hemicellulose (22–24%), α-cellulose (58–60%), and lignin (12–14%) as the key constituents with other minor constituents as well (Jamshaid et al., 2018). The burning characteristics of the jute fibre depend on cellulose and lignin. In the presence of flame, cellulose begins to burn and forms a higher levoglucosan, a highly flammable compound. Besides, the thermal decomposition of jute fibre depends on the containing a certain amount of lignin (Roy et al., 2018). A lower amount of lignin can improve the flame resistance of jute fibre. Various durable and non-durable finishing treatments can also make the cellulosic fibre (jute) flame retardant (Samanta et al., 2015). Flame retardant compounds which are most commonly used, are based on phosphorous, sulfur and other acid-forming materials that cause dehydration by producing water and char at the expense of flammable tars in the jute fabrics (Mohamed and Hassabo, 2015). In recent research, different inorganic salts (Basak and Ali, 2017), diammonium phosphate (Basak et al., 1993), nitrogen-based compound (Atakan et al., 2019; Samanta et al., 2011a), urea (Basak et al., 2014), organic sulphate (Basak and Ali, 2017), borax and boric acid (Samanta et al., 2011b) have been applied on jute to observe the changing properties of the jute fabric on behalf of these flame retardant compounds. But containing higher chemicals add-on, noticeable strength loss, stiffness of jute fabrics has been found after being treated with these flame retardant compounds (Basak and Samanta, 2019; Shahinur et al., 2013). Our previous work has investigated the flame retardancy behavior of jute fabric using a single chemical such as borax, DAP and thiourea (Repon et al., 2021). Flame retardancy was found to pointedly upsurge using the simple flame-retardant finishing agents. However, there is a lack of investigations in the field of the flame resistance functionality of jute fabric employing combined chemicals used for fire protection purposes published in the literature. Moreover, the durability of fire protective materials has to be improved to avoid performance changes during several washings.

One of the most efficient ways to increase the thermal resistance of jute to ignition and provide a higher degree of flame retardancy efficiency in the final product is to use flame resistant (FR) chemicals. The primary goal of using flame retardants is to give people more time to escape a fire and thereby minimize death and injuries. In this study, the combination of various flame retardant chemicals: borax, di-ammonium phosphate (DAP), and thiourea are applied with three different varieties to observe the development of flame resistance properties of raw and bleached jute fabric. The flame spread time was evaluated to observe the thermal behavior and the breaking load percentage was assessed to know the effect of chemical treatment on the strength of the jute fabric. The weight gain percentage of the FR treated fabrics was determined as well. The wash durability was also investigated to justify the feasibility of the application, which is very important and desired. This research aimed to develop flame resistant jute fabric in an economical way using commercially available FR chemicals, going through the pad-dry-cure process.

2. Experimental

2.1. Reagents and materials

Plain woven jute fabric was used for the study, which is commonly known as Hessian cloths having an areal density of 241 g per square meter (GSM) using 210.54 tex yarn in both warp and weft. The warp and weft densities were 6.2 ± 0.2 and 5.2 ± 0.2/cm of the fabric used. Fig. 1 indicates the jute plant, fibre, yarn and fabric used in this study. The breaking load of the raw and bleached jute fabric was 32 and 25 kg in the warp direction and 30 and 23 kg in the weft direction accordingly. The areal density of bleached jute fabric was 232 g/m^2. Borax ($Na_2B_4O_7.10H_2O$), diammonium phosphate (DAP) $(NH_4)_2HPO_4$, and thiourea (CH_4N_2S) were collected from Tradesia International Pvt. Ltd., Singapore. Other essential chemicals, particularly hydrogen peroxide (H_2O_2), sodium silicate (Na_2SiO_3), sodium carbonate (Na_2CO_3) and acetic acid (CH_3COOH), were procured from Redox Chemical Ltd., Srilanka. All reagents were laboratory grade and were used without further purification.

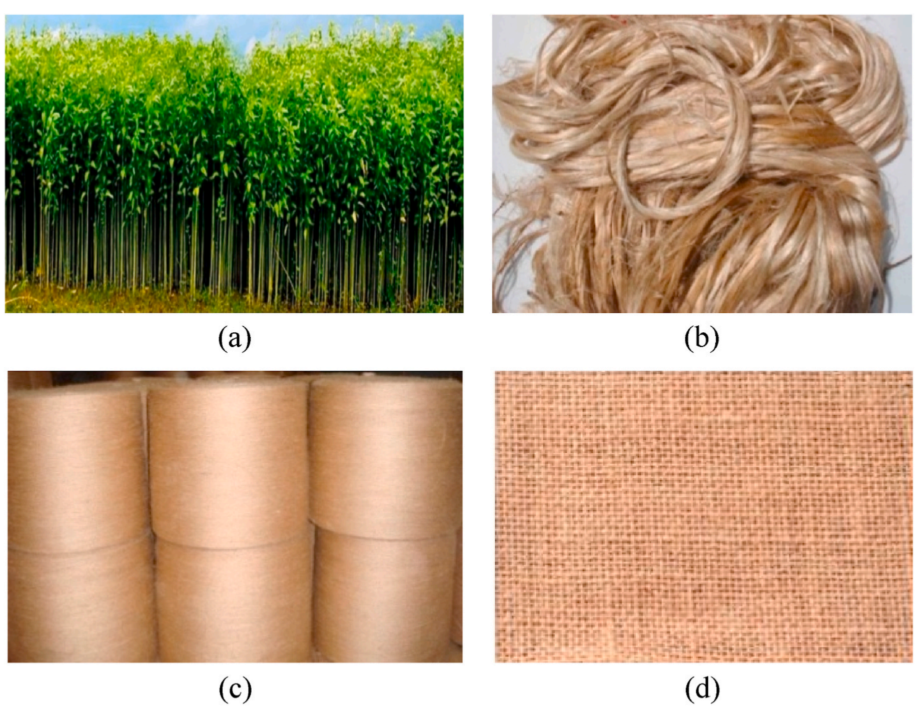

Fig. 1. Jute: (a) plant (b) fibre (c) yarn and (d) fabric used.

2.2. H_2O_2 treatment

The bleaching process was performed according to our previous work (Repon et al., 2021). In brief, H_2O_2 treatment was done maintaining the recipe of hydrogen peroxide: 1.5 g/L, sodium silicate: 3 g/L, sodium carbonate: 3 g/L, wetting agent: 1 g/L, material to liquor ratio: 1:40 and pH: 11. This process was performed at 85 °C for 60 min using an infrared lab dyeing machine (Xiamen Rapid, China). After bleaching, a cold wash was done at room temperature for 10 min and the fabric was neutralized with 0.5 g/L acetic acid.

2.3. Flame retardant finishing treatment

The flame retardant finishing treatment was conducted according to our previous work (Repon et al., 2021). In brief, the raw and bleached jute fabric samples were padded with the flame retardant combined chemicals in different concentrations in the padding bath of two bowl horizontal padding machines. The samples were followed by drying at 100 °C for 5 min after padding and curing at 120 °C for 5 min. The combinations and formulations of flame protective functional finishing chemicals were mentioned in Table 1. Fig. 2 indicates the modification of jute fabric through flame retardant finishing treatment.

$$\text{Pick up }(\%) = \frac{\text{Wet weight of the sample} - \text{Dry weight of the sample}}{\text{Dry weight of the sample}} \times 100 \quad (1)$$

2.4. Testing and evaluation

The testing and evaluation processes were shown in detail in our previous work (Repon et al., 2021). In brief, the vertical flammability testing was done followed by the standard test method of ASTM D6413 (ASTM, 2015). The selected untreated and treated jute fabric specimens of specified dimensions were exposed to a standard flame for a limited time and were allowed to burn. The breaking strength was determined followed by the standard method of EN ISO 13934-2 (ISO 13934-2, 2014). The weight gain of the samples was measured by using equation (2) and expressed as a percentage.

$$\text{Weight gain} = \frac{W2 - W1}{W1} \times 100 \quad (2)$$

where, W_1 and W_2 indicate the oven-dry weight of the untreated and treated fabric samples.

The jute fabrics were conditioned for 48 h in a standard testing atmosphere *i.e.*, 65 ± 2% relative humidity (RH%) and 27 ± 2 °C temperature to perform the tests. Fig. 3 demonstrates the schematic diagram of the jute fabric combustion cycle.

2.5. Fabric encrypting

The raw jute fabric and bleached jute fabric samples were identified as RJF (Raw jute fabric) and BJF (Bleached jute fabric) before applying flame retardant finishing agents. The fabric samples are recognized as stated in Table 1 depending on the combinations and formulations of flame retardant functional finishing chemicals.

Table 1
List of chemical formulations and identification of the tested sample.

Fabric type	Chemical compositions	Chemical concentrations with sample code			
		2%	3%	4%	6%
Raw jute fabric (RJF)	Borax + DAP	RA1	RA2	RA3	RA4
	Borax + Thio-urea	RB1	RB2	RB3	RB4
	DAP + Thio-urea	RC1	RC2	RC3	RC4
Bleached jute fabric (BJF)	Borax + DAP	BA1	BA2	BA3	BA4
	Borax + Thio-urea	BB1	BB2	BB3	BB4
	DAP + Thio-urea	BC1	BC2	BC3	BC4

3. Result and discussion

3.1. Flame retardant performance of jute fabric

Jute is a highly combustible material. A vertical flammability test was used to evaluate the combustion properties of jute fabrics padded with flame retardant functional finishing agents and corresponding data summarized were presented in Fig. 4 and Fig. 5. The effects of flame retardant treatments on raw jute fabric are shown in Fig. 4 and on bleached jute fabric are shown in Fig. 5.

The raw jute fabrics catch fire and burn within 18 s while samples are treated with no flame retardant single/combined chemicals. It is evident from Fig. 4 that the flame spread time increased after the flame retardant finishing treatment.

At a concentration of 2%, the order of the sample was found as RA1>RB1>RC1, and the flame spread time increased 105.56%, 94.44% and 88.89% for RA1, RB1 and RC1 compared to untreated raw jute fabric (Fig. 4). At 3% concentration, the sample order was uncovered as RA2>RB2>RC2 and flame spread time showed 166.67%, 150% and 144.44% higher for RA2, RB2 and RC2. The sample order was retrieved RA3>RB3>RC3 and flame spread time indicated 205.56%, 200% and 188.89% higher for RA3, RB3 and RC3 at 4% concentration. At 6% concentration, the sample order came down with RA4>RB4>RC4 and flame spread time revealed 305.56%, 294.44% and 261.11% higher for RA4, RB4 and RC4 accordingly (Fig. 4).

The increasing tendency of chemical concentration has an impact on increasing the flame spread time and borax and DAP combination showed better results on flame retardancy compared with borax and thiourea, and DAP and thiourea combinations. At different concentrations, borax and DAP show better results because it is known that borax releases water and at high temperature melts to form sodium borate coating. Borax can react with the primary hydroxyl group of cellulose polymers and give borate ester that blocks the release of flammable gases. Besides, DAP forms phosphoric acid at a high temperature which causes the material to char and provides a barrier between the material and the heat source by forming a thick glassy layer of carbon. The combination of both chemicals, borax and DAP improves the non-flammability of the raw jute fabric. Thio-urea releases inert nitrogen gases that inhibit the chain reaction leading to combustion. When borax and thio-urea are combined, as well as DAP and thio-urea, the flammability is reduced, although not as much as when borax and DAP are combined (Fig. 4).

At the different percentage of chemical concentrations, the order of samples treated with the borax and DAP combination was found as RA4>RA3>RA2>RA1 and RB4>RB3>RB2>RB1 was found for the samples treated with borax and thiourea, and RC4>RC3>RC2>RC1 was found for the samples treated with DAP and thiourea combinations. The flame spread time was increased and observed to be 105.56%, 166.67%, 205.56%, and 305.56% higher while treated with borax and DAP combined chemicals at 4%, 6%, 8%, and 12% concentrations. At the same chemical concentrations, the flame spread time showed 94.44%, 150%, 200%, and 294.44% higher when samples were treated with borax and thiourea and 88.89%, 144.44%, 188.89%, and 261.11% higher when samples were treated with combinations of DAP and thiourea (Fig. 4).

The bleached jute fabrics catch fire and burn within 21s while samples are treated with no flame retardant single/combined chemicals. From Fig. 5, it is depicted that the flame spread time of bleached jute fabric treated with combined chemicals was increased with the increase of loading of chemicals. The order of flame spread time of treated samples at 2%, 3%, 4% and 6% chemical concentration were found as BA4>BA3>BA2>BA1, BB4>BB3>BB2>BB1 and BC4>BC3>BC2>BC1

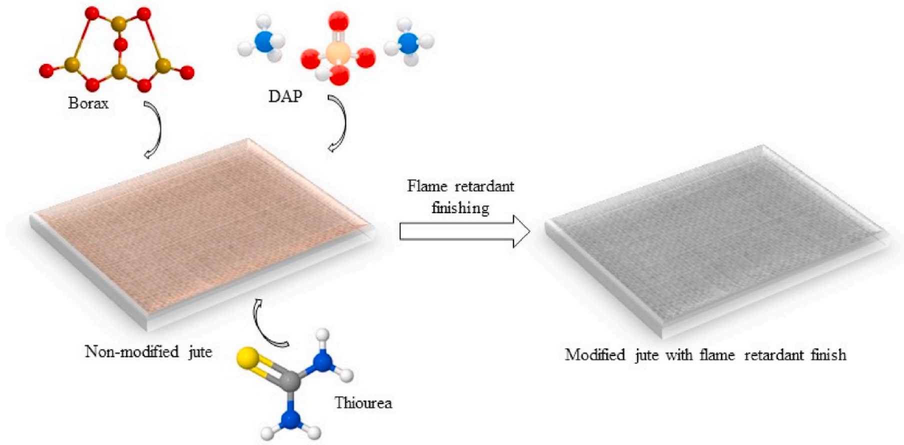

Fig. 2. Modification of jute fabric through flame retardant finishing treatment.

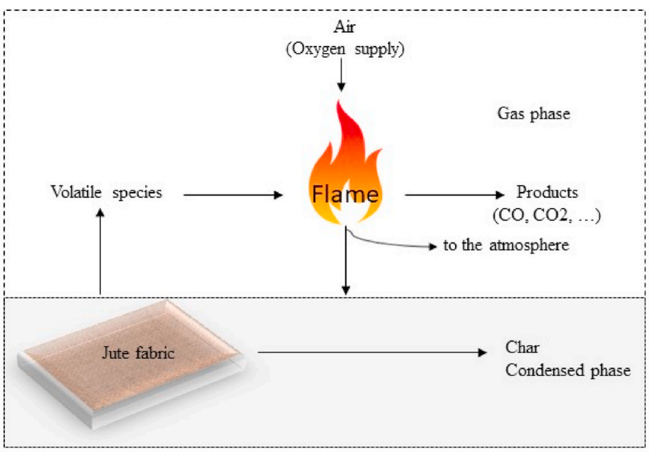

Fig. 3. Schematic of the jute fabric combustion cycle.

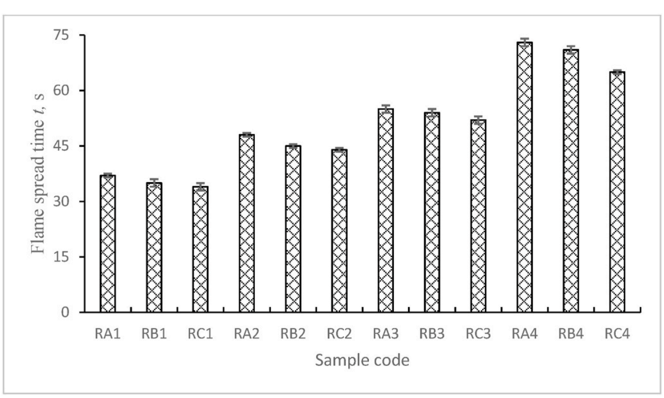

Fig. 4. Impact of combined flame retardant finish and chemical loading on flame spread time of raw jute fabric.

while treated with borax and DAP, borax and thiourea and DAP and thiourea respectively. Compared to untreated bleached fabric, it is 90.5%, 161.9%, 219.1% and 276.2% higher for BA1, BA2, BA3 and BA4 samples which are treated with borax and DAP combinations. Similarly, the flame spread time was 76.2%, 133.3%, 190.5% and 252.4% higher for samples BB1, BB2, BB3 and BB4 treated with Borax and Thio-urea. On the other hand, DAP and Thio-urea treated bleached fabrics showed 71.4%, 123.8%, 171.4% and 223.8% higher for BC1, BC2, BC3

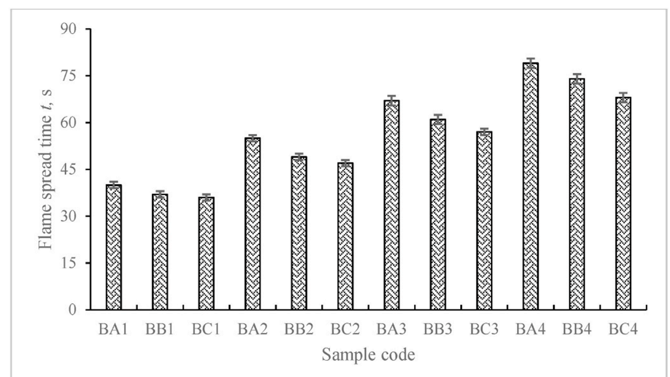

Fig. 5. Impact of combined flame retardant finish and chemical loading on flame spread time of bleached jute fabric.

and BC4 (Fig. 5).

At 2% concentration, the sample order of flame spread time was found as BA1>BB1>BC1 and it is 90.5%, 76.2% and 71.4% higher for BA1, BB1 and BC1. At 3% concentration, the sample order was found as BA2>BB2>BC2 and it was 161.9%, 133.3% and 123.8% higher for BA2, BB2 and BC2. At 4% concentration, the sample order is BA3>BB3>BC3 and it is 219.1%, 190.5% and 171.4% higher for BA3, BB3 and BC3. At 6% concentration, the sample order was found to be BA4>BB4>BC4 and it is 276.2%, 252.4% and 223.8% higher for BA4, BB4 and BC4 (Fig. 5). After all, tantamount behaviour has been observed by raw and bleached samples. As far as the flammability test is considered, all the treated jute samples showed enhanced flame retardancy.

The flame spread time of the sample treated with a combination of flame retardant chemicals was shown better than the sample treated with the same chemicals separately for both H_2O_2 treated and raw jute samples (Repon et al., 2021).

3.2. Impact of F-R finish on breaking load

After treating raw and bleached jute fabric with combined chemicals, the breaking load changes were observed and shown in Figs. 6 and 7. Fig. 6 illustrates the breaking load changes of raw jute treated fabrics and Fig. 7 explains the differences in the breaking rate of bleached jute treated materials in both warp and weft directions.

From Fig. 6, the samples order was found as RA1>RB1>RC1 in the warp direction and RA1>RB1>RC1 in the weft direction at 2% chemical concentration while the chemical combinations were borax and DAP, borax and thiourea and DAP and thiourea. At 3% concentration, the

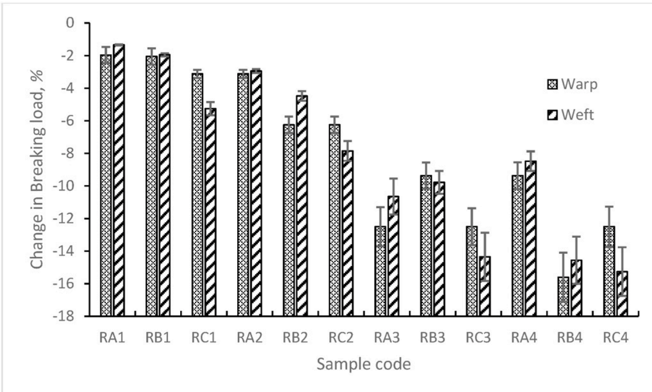

Fig. 6. Impact of combined flame retardant finish and chemical loading on breaking load of raw jute fabric.

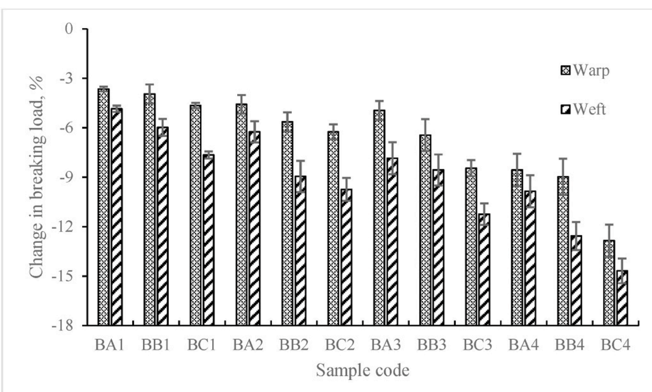

Fig. 7. Impact of combined flame retardant finish and chemical loading on breaking load of bleached jute fabric.

sample order was RA2>RB2 = RC2 in the warp direction and RA2>RB2>RC2 in the weft direction for the same combination. At 4% concentration, the sample order was found as RB3>RA3 = RC3 in the warp direction and RB3>RA3>RC3 in the weft direction accordingly. At 6% concentration, the sample order is RA4>RC4>RB4 in the warp direction and RA4>RB4>RC4 in the weft direction consequently (Fig. 6).

At 2% concentration, the breaking load was observed 1.97%, 2.05% and 3.12% lower in the warp direction and 1.34%, 1.95% and 5.26% lower in the weft direction for samples RA1, RB1 and RC1, respectively compared with untreated (raw) jute fabric. At 3% concentration, the breaking load was found 3.12%, 6.25% and 6.25% lower in the warp direction and 2.95%, 4.48% and 7.85% lower in the weft direction for RA2, RB2 and RC2 while compared with the same manner. The breaking load was found at 4% concentration, 12.5%, 9.37% and 12.5% lower in the warp direction and 10.65%, 9.78% and 14.35% lower in the weft direction for RA3, RB3 and RC3. At 6% concentration, the breaking load was found 9.37%, 15.6% and 12.5% lower in the warp direction and 8.48%, 14.56% and 15.26% lower in the weft direction for RA4, RB4 and RC4 (Fig. 6).

At 2%, 3%, 4% and 6% of the chemical concentrations, it has been observed that the orders of the samples were RA1>RA2>RA4>RA3, RB1>RB2>RB3>RB4 and RC1>RC2>RC3 = RC4 in the warp direction while specimens were treated with the chemical combinations of borax and DAP, borax and thiourea, and DAP and thiourea respectively and it was found as RA1>RA2>RA4>RA3, RB1>RB2>RB3>RB4 and RC1>RC2>RC3>RC4 in the weft direction. The breaking load of samples treated with borax and DAP combination were found to be 1.97%, 3.12%, 12.5% and 9.37% lower in the warp direction and 1.34%, 2.95%, 10.65% and 8.48% lower in the weft direction for RA1, RA2, RA3 and RA4 respectively compared with untreated raw jute fabric while chemical loading was 2%, 3%, 4% and 6% accordingly. The breaking load of samples treated with borax and thiourea was observed to be 1.95%, 4.48%, 9.78% and 14.56% lower in the weft direction and 2.05%, 6.25%, 9.37% and 15.6% lower in the warp direction for RB1, RB2, RB3 and RB4. The breaking load of samples treated with DAP and thiourea was found 5.26%, 7.85%, 14.35% and 15.26% lower in the weft direction and 3.12%, 6.25%, 12.5% and 12.5% in the warp direction for RC1, RC2, RC3 and RC4 respectively compared with untreated raw jute fabric while chemical loading was 2%, 3%, 4% and 6% accordingly (Fig. 6).

From Fig. 7, it was found that the samples order depending on the changes of breaking load percentage of treated bleached jute fabric was BA1>BB1>BC1, BA2>BB2>BC2, BA3>BB3>BC3 and BA4>BC4>BB4 in the warp direction while samples were treated with 2%, 3%, 4% and 6% chemicals combinations of borax and DAP, borax and thiourea and DAP and thiourea respectively. Similar orders of samples were found in the weft direction as well. At 2% concentration, the breaking load was found as 3.65%, 3.95% and 4.65% lower in the warp direction and 4.85%, 5.98% and 7.65% lower in the weft direction for the samples BA1, BB1 and BC1 when chemicals combinations were borax and DAP, borax and thiourea and DAP and thiourea correspondingly. At 3% concentration, the breaking load was found as a rate of 4.58%, 5.65% and 6.25% lower in the warp direction and 6.25%, 8.95% and 9.74% lower in the weft direction for BA2, BB2 and BC2. At 4% concentration, the breaking load was found as 4.95%, 6.45% and 8.45% lower in the warp direction and 7.85%, 8.56% and 11.24% lower in the weft direction for BA3, BB3 and BC3. At 6% concentration, the breaking load was found 8.56%, 8.98% and 12.85% lower in the warp direction and 9.85%, 12.56% and 14.68% lower in the weft direction for BA4, BB4 and BC4 compared with untreated bleached fabric (Fig. 7).

Depending on chemical loading, it was observed for treated bleached jute fabric that the orders of samples were found as BA1>BA2>BA3>BA4, BB1>BB2>BB3>BB4 and BC1>BC2>BC3>BC4 in the warp direction while treated with borax and DAP, borax and thiourea and DAP and thiourea respectively and BA1>BA2>BA3>BA4, BB1>BB3>BB2>BB4 and BC1>BC2>BC3>BC4 orders were found in the weft direction. The breaking load of samples treated with borax and DAP was found to be 3.65%, 4.58%, 4.95% and 8.56% lower in the warp direction and 4.85%, 6.25%, 7.85% and 9.85% lower in the weft direction for BA1, BA2, BA3 and BA4. The breaking load of samples treated with borax and thiourea was found to be 3.95%, 5.65%, 6.45% and 8.98% lower in the warp direction and 5.98%, 8.95%, 8.56% and 12.56% lower in the weft direction for BB1, BB2, BB3 and BB4. The breaking load of samples treated with DAP and Thio-urea was found to be 4.65%, 6.25%, 8.45% and 12.85% lower in the warp direction and 7.65%, 9.74%, 11.24% and 14.68% in the weft direction for BC1, BC2, BC3 and BC4 compared to untreated bleached jute fabrics (Fig. 7). It is mentioned that the decreasing of breaking load percentage was observed lower for bleached jute samples than that of raw jute fabrics. From Figs. 6 and 7, it is depicted that the breaking load percentage was decreased with the increase of concentration of combined flame retardant chemicals. This is because mild acidic hydrolysis changes the chemical structure of jute and, consequently, the breaking load decreases.

The percentage of breaking load of the sample treated with a combination of flame retardant chemicals and the sample treated with the same chemicals separately was observed in a similar fashion in both warp and weft directions, as well as for the H_2O_2 treated and raw jute sample (Repon et al., 2021).

3.3. Impact of combined F-R finish on fabric weight

The weight gain percentage of raw and bleached jute fabrics was measured after treating with different combinations of flame retardant finishing agents such as borax and DAP, borax and thiourea, and DAP and thiourea at different concentrations and results are presented in Fig. 8 and Fig. 9.

The impacts of flame retardant finish on raw jute fabrics are stated in Fig. 8 and the data presented were analyzed accordingly. At 2% concentration, the sample order was found as RB1>RC1>RA1 and the weight of the samples was 1.74%, 3.85%, 2.45% higher for RA1, RB1, RC1 while compared to the untreated raw fabrics. At 3% concentration, the order of sample was found to be RB2>RC2>RA2 and the weight of the samples was 1.90%, 3.98%, 2.89% higher for RA2, RB2, RC2. At 4% concentration, the order of samples was found to be RB3>RC3>RA3 and the weight of the samples was 2.12%, 5.98%, 3.54% higher for RA3, RB3, RC3. At 6% concentration, the sample order was found to be RB4>RC4>RA4 and the weight of the samples was 3.14%, 8.21%, 5.78% higher for RA4, RB4, RC4 (Fig. 8).

Depending on the chemical loading amount, the order of samples was found as RA4>RA3>RA2>RA1 when specimens were treated with Borax and DAP, RB4>RB3>RB2>RB1 was found during treated with borax and thiourea and RC4>RC3>RC2>RC1 was found during treated with DAP and thiourea. The weight was increased 9.2%, 21.8% and 80.5% for the samples RA2, RA3 and RA4 compared with RA1. The weight was increased by 3.37%, 40.3% and 113.25% for the samples RB2, RB3, RB4 compared to RB1. The weight was increased 17.9%, 44.5%, 135.9% for samples RC2, RC3, RC4 while compared with RC1. Again, compared to untreated raw jute fabric, the weight of the borax and DAP treated samples was found to be 1.74%, 1.90%, 2.12% and 3.14% higher for RA1, RA2, RA3 and RA4. The weights of the borax and thiourea treated samples were found to be 3.85%, 3.98%, 5.98% and 8.21% higher for RB1, RB2, RB3, and RB4. The weight of the DAP and thiourea treated samples was found to be 2.45%, 2.89%, 3.54% and 5.78% higher for RC1. RC2, RC3 and RC4 (Fig. 8).

Fig. 9 represents the weight gain percentage of bleached jute fabrics treated with the flame retardant finish. At 2% concentration, the sample order was found as BB1>BC1>BA1 and the weight of the samples was 2.05%, 3.10% and 2.18% higher for BA1, BB1 and BC1 than untreated bleached jute fabrics. At 3% concentration, the order of samples was found as BB2>BA2>BC2 and the weight of samples was 2.14%, 4.88%, 1.84% higher for BA2, BB2, BC2. At 4% concentration, the order of samples was found BB3>BA3>BC3 and the weight of samples was 4.48%, 7.12%, 3.92% higher for BA3, BB3, BC3. At 6% concentration, the sample order was BB4>BA4>BC4 and the weight of the samples was 6.78%, 7.56%, 5.14% higher for BA4, BB4, BC4. Besides, compared with sample BA1, the rate of increasing weight was 51.2% for sample BB1 and 6.3% for BC1. The weight was increased 128.03% for BB2 but decreased 14.01% for BC2 while compared with BA2. The weight of the BB3 and BC3 samples compared to BA3 increased 58.9% and decreased 12.5%, respectively. Compared with BA4, the weight was increased 11.5% for

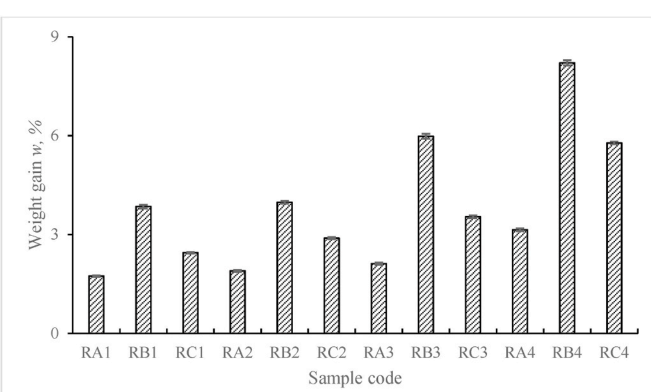

Fig. 8. Impact of combined flame retardant finish and chemical loading on weight gain percentage of raw jute fabrics.

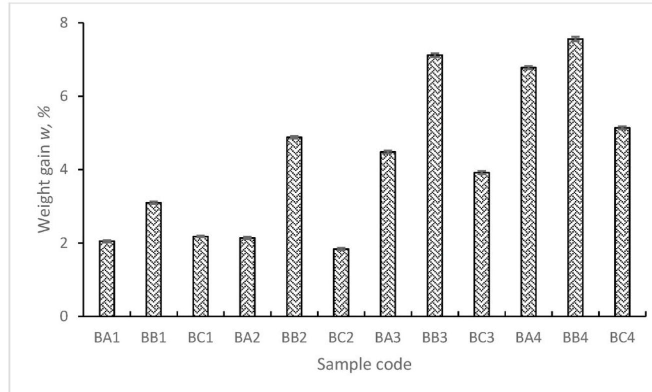

Fig. 9. Impact of combined flame retardant finish and chemical loading on weight gain percentage of bleached jute fabrics.

sample BB4 and decreased 24.2% for BC4 (Fig. 9).

The orders of samples were found BA4>BA3>BA2>BA1 while treated with borax and DAP, BB4>BB3>BB2>BB1 for borax and thiourea and BC4>BC3>BC1>BC2 for DAP and thiourea during the increasing the concentration of flame retardant finishing agent from 2 to 6%. The weight was increased 4.4%, 118.5% and 230.7% for the samples BA2, BA3 and BA4 compared with BA1. The weight increased 57.4%, 129.7%, and 143.87% for the BB2, BB3, BB4 samples compared to BB1. The weight decreased 15.6% for sample BC2 and increased 44.5% and 135.9% for samples BC3 and BC4 compared to BC1. Again, compared with untreated bleached jute fabric, the weight of borax and DAP treated samples was found 2.05%, 2.14%, 4.48% and 6.78% higher for BA1, BA2, BA3 and BA4. The weight of the borax and thiourea treated samples was found to be 3.10%, 4.88%, 7.12% and 7.56% higher for BB1, BB2, BB3, and BB4. The weight of the DAP and thiourea treated samples was found 2.18%, 1.84%, 3.92% and 5.14% higher for BC1. BC2, BC3 and BC4 (Fig. 9).

Figs. 8 and 9 describe the weight gain percentage for both raw and bleached jute fabrics treated with different combinations of flame retardant finish. The main reason behind this can be created by an insulating layer on the fabrics by the reaction of combined chemicals.

The weight gain percentage of the sample treated with a combination of flame retardant chemicals and the sample treated with the same chemicals separately were noted in a mostly identical manner for both H_2O_2 treated and raw jute samples (Repon et al., 2021).

3.4. Flame retardant performance during washing

Conventional flame retardant finishes lose their effectiveness during washing. The flame retardant finish should be fast to five wash cycles as flame retardant jute fabrics are seldom washed (not more than once in a year). Moreover, an excellent flame retardant finish for textile applications must be reasonably fast to wash and cost-effective. After several washing cycles, the durability of flame retardant treated samples of raw and bleached jute fabrics was evaluated and the changes of flame spread time are presented in Fig. 10.

As it can be seen from the results presented in Fig. 10, the wash of the treated fabric harms the flame retardancy; however, the flame retardancy dynamics during the washing has a similar character in both raw-treated and bleached-treated fabric. It was found that the flame spread time decreased 16.4%, 23.3% and 35.6% at 1st, 3rd and 5th wash cycles for the RA4 sample. Accordingly, for RB4 it was found 16.9%, 30.9% and 40.8%, and for RC4-21.5%, 24.6% and 41.5%. The tendency of flame retardancy between specimens in groups of raw-treated and bleached-treated samples is very similar to the situation after washing. Again, in bleached-treated groups, the flame spread time decreased 13.4%, 25.3% and 37.9% at 1st, 3rd and 5th wash cycles for sample BA4.

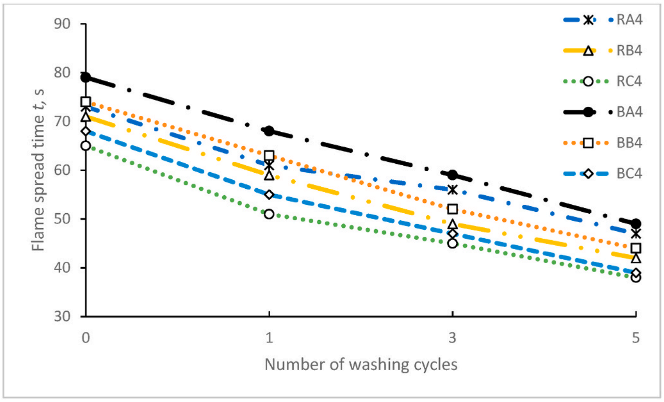

Fig. 10. Washability evaluation of raw and bleached jute fabrics treated with the combined flame retardant finish at different washing cycles.

Consequently, the flame spread time decreased 14.8%, 29.7% and 40.5% for BB4, for BC4-19.1%, 30.8% and 42.6% (Fig. 10). The explanation for this decrease is that the five-cycle washing process slightly damages the chemical coating on the surface of the treated fabrics. After all, comparatively, the wash durability of the bleached treated sample was better than that of the raw jute treated sample. The formation of the flame retardant coatings on the jute fabric surface was confirmed by the flame spread time after several wash cycles.

The flame spread time was observed in decreasing pattern after each washing cycle and a higher spread time was detected for H_2O_2 treated sample than the raw jute sample. The wash durability of the sample treated with a combination of flame retardant chemicals was revealed better than the sample treated with the same chemicals separately (Repon et al., 2021).

The pursuit of sustainable development is one of the driving forces behind the growing interest in fire retardant materials made from natural fibres. Fire retardant jute fabrics can be used in a variety of applications, including industrial workwear, firefighter costumes, and professional motor racing clothing to protect the wearer from fires and electrical arcs.

4. Conclusion

The study shows the effect of applying combined flame retardant finishes on jute fabric. The result of flame spread time of jute fabric has improved highly after applying combined flame retardant chemicals. The flame spread time increases with the increase of chemical percentage and shows the highest result for borax and diammonium phosphate combinations: 73 s for RA4 and 79 s for BA4. With the increase of chemical concentration, the breaking load of treated jute fabric decreases. The study shows that the combined application of borax, diammonium phosphate and thiourea improves the flame retardant properties of jute fabric and opens the further scope of using these chemicals for flame retardant finishing of jute fabric. The proposed jute fabric treated with a combined flame retardant finishing agent designed for industrial fire protection application has an advantage as the easily available flame retardant finishing agents are used. As it was expected, the highest flame retardancy was detected for the specimens with higher concentrations of the combined chemicals in the process - in this research.

All the presented jute fabric can be used for fire protective clothing; however, the higher flame retardancy of the jute fabric requires a higher concentration of flame retardant to reach the required level. It was obtained that the washing of the specimen has a negative effect on flame retardancy.

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Authors' contributions

Md. Reazuddin Repon: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualization; Writing-Original draft preparation; Writing - review and editing. **Halima Tus Sadia**: Data curation; Investigation; Writing - Original draft preparation. **Tarikul Islam**: Project administration; Writing - review and editing. **Mohammed M. Rahman**: Supervision; Writing - review and editing. **Md. Rezaul Karim**: Resources; Writing - review and editing.

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 paper.

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