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ORIGINAL RESEARCH

Development of sustainable and cost efficient textile foam-finishing and its comparison with conventional padding

Muhammad Mohsin · **Shaheen Sardar**

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Abstract Conventional padding is a non-sustainable textile processing technique, which consumes excessive water, chemicals and energy. To support the survival of the textile processing industry, researchers have identified the foam technology for application of dyes and finishes. Foam technology is more eco-friendly than the conventional padding. However, the successful foam generation for different finishes is a challenging task. In addition, it is more difficult and complicated task to effectively apply the foam on the fabrics and get the results which should be comparable with the conventional padding. This paper compares the pad-finishing with foam-finishing on the basis of sustainability, cost, productivity, and performance using 11 different non-toxic and sustainable finishes including cross-linkers, oil and water repellents, softeners, and fire retardant on the cotton fabric samples. Cost, productivity, performance and sustainability were estimated through the specific methods. The paper organizes the problem as analytic hierarchy process model and solves the model using super decisions software. The results reveal that the foam-finishing technique is more preferable in terms of cost, productivity and sustainability, if optimized properly. In addition, the successful foam-finishing recipes have been generated and the performance of foam-finishing has been comparable with pad-finishing. For instance, if all the criteria were given the same priority, the foam-finishing recipe with less quantity of chemical was 84.61% better than the pad-finishing. The optimized foam-finishing recipe was 84.55% better than the pad-finishing. In addition, the optimized foam-finishing recipe indicated better finishing performance in term of some important tests as compared to padding.

Keywords Padding · Foam coating · Analytic hierarchy process · Textile finishing · Sustainable processing

Introduction

In the textile processing industry, conventional padding has disturbed the natural environment due to the extensive use of water, chemicals and energy as well as generation of huge wastewater (Elbadawi and Pearson 2003; Zhou et al. 2019; Tang et al. 2019). In order to decrease these consumptions, researchers have developed some cost effective and ecofriendly

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M. Mohsin (✉) · S. Sardar
Textile Engineering Department, University of Engineering and Technology, Faisalabad Campus, Lahore, Pakistan
e-mail: mohsinmalikntu@yahoo.com

technologies such as foam-coating (Samanta et al. 2019). Foam-coating can offer several benefits such as low cost, water saving, energy saving, chemical saving, improved productivity, less waste release, and better physical properties (Kumar and Yaashikaa 2018; Song et al. 2013). Foam technology has been reported to improve the cost and efficiency of the textile production (Jokisch and Scheibel 2017; Chen et al. 2017; Hou and Wang 2017). However, there is a lack of implementation in the processing industry due to the issues such as foam generation and application difficulties, incompatibility of chemicals with fabrics, and difficulty to achieve required performance.

The research on the foam technology is increasing gradually (Palamutcu 2017). The textile processing industry is willing to implement the foam technology due to the availability of fewer natural resources, development of foam coating machinery, and higher motivations from customers and social organizations (Yu et al. 2014). The conventional padding uses wet pickup of 60–90% and foam coating uses wet pickup of 10–20%. The volume of foam solution is 7–10 times higher than the padding, resulting in more fabric treatment with less chemicals and heat (Gopalakrishnan et al. 2019; Rather et al. 2019). As a result, the foam-coating saves approximately 50% water related to pick-up compared with the conventional padding. This saves 30% energy related to drying (Van der Walt and Van Rensburg 1986). Substantial energy saving in the drying process is due to the use of air instead of water in the finishing solution (Chen et al. 2017). In addition, chemical saving can be achieved due to the application of chemicals only on the fabric surface, and the more fabric can be processed with less chemical solution. Similarly, the recipe application time in foam-coating is less than the conventional padding, which increases the production speed.

Many studies address the certain foam-finishing problems using cotton fabrics. The existing literature compared the certain foam-finishing with traditional padding and showed the considerable cost saving, comparable performance, and environmental benefits (Bhavsar et al. 2017; Song et al. 2013; Liu et al. 2012; Li et al. 2011; Wadsworth and Wey 1988; Bryant 1984; Gregorian et al. 1983). For instance, Yang et al. (1989) compared pad-finishing and foam-finishing on cotton fabrics with toxic formaldehyde based DMDHEU resin based finishing agents. In foam application, the finish uniformity and wrinkle recovery angle were better than the traditional padding. Sarwar et al. (2017) applied the resin based on dihydroxy ethylene urea (DHEU) on the stretch denim fabrics and achieved better performance in foam application with reference to padding. Rowland et al. (1983) studied the durable press performance and the distribution of resin based on toxic DMDHEU on the cotton. Nevertheless, the treated fabrics exhibited the performance comparable with the conventional padding. Gonzales and Reinhardt (1986) performed foam finishing on cotton fabrics using toxic formaldehyde, zinc nitrate at 40% wet pickup. Li et al. (2014) applied the crease resistant finishes on the cotton samples using resin based on toxic dimethyl dihydroxylethylene-urea (DMDHEU) as a cross-linking agent. It was concluded that when the quantity of cross-linker increased, the wrinkle recovery angle increased while the tear strength and breaking strength decreased.

The above literature motivates the implementation of foam-finishing technology in the textile processing industry. Despite its cost effectiveness and environmental sustainability, the foam technology has several issues such as foam stability. However, the previously reported research work on textile foam finishing is limited to mostly toxic chemicals like carcinogenic formaldehyde based DMDHEU cross-likers (Rather et al. 2019). Hence, there is a need to use ecofriendly chemicals in the foam coating process (Jokisch and Scheibel 2017).

To address these issues, this paper uses 11 different non-toxic finishes including formaldehyde-free cross-linkers like citric acid (a bio-based product), maleic acid, similarly C6 based oil and water repellent instead of C8 based oil and water repellent as well as halogen and formaldehyde free fire retardant. This paper differentiates the padding and foam application with respect to the productivity, cost, sustainability, and performance.

Materials and methods

This paper uses the cotton fabric samples with grams per square meter (GSM) as 180 and 3/1 weave. The fabric was pre-scoured and bleached. Foam was generated for 11 finishes using optimized quantity of the commercial foaming agent, Unifroth 450. Foam stability, foam half-life, and quantity of foaming agent were optimized for each finish. The half-life of foam determines the foam stability. Half-life is the period of time in which the foam volume reduces to half as compared to the original full foam volume. For each finish, the half-life of more than 180 s was achieved which is typically required for successful foam application on the textile fabrics, by using 100 ml of water, blow ratio of 1:8, and stirring of 1200 revolutions per minute for five minutes. Therefore, above conditions were used for each foam finishing recipe. In this research first the foam is generated for each finish recipe and then it was applied through foam coating machine.

The prepared foam was applied on the fabric using the lab-coating machine, MU572C. Pad-finishing was performed using the mini padding machine with model number PAD VH 350 GD. Pad-finishing and foam-finishing were compared for the 11 finishing recipes as given in Table 1. The three alternatives were compared, which include "pad-finishing (pf)", "foam-finishing with recipe-one (Ff1)", and "foam-finishing with recipe-two (Ff2)". The finish quantity of padding and foam-finishing with recipe-one (Ff1) were kept same. For foam-finishing with recipe-two (Ff2), the number of trials were carried out by raising the finish quantity to ensure its performance of comparable to padding. In case of most of the foam finish recipes containing 3.5 times the finish % as compared to padding demonstrated the similar performance. Therefore, for foam-finishing with recipe-two (Ff2), each finish % was raised to 3.5 times the finish % as that of padding or foam-finishing with recipe-one (Ff1).

The finishing chemicals dihydroxy ethylene urea (DHEU with commercial name Arkofix NZK Liq), dimethylol dihydroxy ethylene urea (modified DMDHEU with commercial name Fixapret F-ECO Liq), catalyst magnesium chloride ($MgCl_2$ with commercial name CATALYST F-M), oil and water repellent (C6 based with commercial name Nuva N), fatty acid softener (Cepreton), polyethylene softener (Ceralube), and silicon softener (SOLUSOFT) were donated by Archroma. The sodium hypophosphite (SHP) was used as catalyst with citric acid and maleic acid. Diammonium hydrogen phosphate (DAHP) along with citric acid and SHP catalyst was used as halogen and formaldehyde free fire retarding agent as per the author previous published paper (Qutab et al. 2019).

Finishing performance was assessed in terms of (CRA) crease recovery angle using AATCC 66-2003, oil and water repellency (AATCC test method 118-2002 for oil and water drop), shower test (AATCC 22 spray test), fire retardancy, tear strength (ASTM D1424), air permeability (ASTM D737), and bending length (ASTM D3886). The shower test is a water repellency test according to standard test method (AATCC 22 spray test). In this method, a rating between 0 and 5 is given to the fabric.

Table 2 shows the data used for calculating the productivity, cost, and sustainability. Cost included the chemical, water, and energy costs. Productivity included the quantity of fabric processed and production time. Sustainability included the consumptions for water, energy, and chemicals. All the calculations were performed based on the formulas developed by the same researchers and reported in a research article for foam dyeing (Mohsin and Sardar 2019).

Much literature exists on the understanding and application of analytic hierarchy process (AHP). The reader may refer to a research article for the key literature and the detailed implementation of AHP methodology in the foam dyeing problem (Mohsin and Sardar 2019). AHP can be applied manually or using spreadsheets. To simplify the mathematical calculations, several software packages such as Super Decisions have been developed for AHP modeling. In this paper, the AHP methodology was implemented in the foam finishing problem using Super Decisions software package. A comprehensive book is available to implement AHP using Super Decisions software package (Mu and Pereyra-Rojas 2016). The problem hierarchy was created as per following steps.

Goal/objective: "Select the best process for the finishing".

Level-one criteria: Sustainability, cost, performance, and productivity.

Level-two criteria: It was defined as follows.

- Chemical cost: Connected to the cost of each finish.
- Water and energy costs connected to the alternatives directly.
- Water, energy, and chemical usage connected to the alternatives directly.
- Production time period and quantity of fabric produced connected to the alternatives directly.

Table 1 Three alternative recipes for 11 finishes used in this research

Finish name	Recipe name	Finish quantity (g)	Foaming agent (g)	Half-life (seconds)	Catalyst (g)	Other chemicals (g)
1. DHEU	pf	5	N/A	N/A	0.5 g $MgCl_2$	No
	Ff1	5	1.5	216	0.5 g $MgCl_2$	No
	Ff2	17.5	3.5	270	1.75 g $MgCl_2$	No
2. Modified DMDHEU	pf	5	N/A	N/A	0.5 g $MgCl_2$	No
	Ff1	5	1.5	220	0.5 g $MgCl_2$	No
	Ff2	17.5	3.5	300	1.75 g $MgCl_2$	No
3. Citric acid	pf	5	N/A	N/A	4 g SHP	No
	Ff1	5	1.5	255	4 g SHP	No
	Ff2	17.5	3.5	310	14 g SHP	No
4. Maleic acid	pf	5	N/A	N/A	4 g SHP	No
	Ff1	5	1.5	200	4 g SHP	No
	Ff2	17.5	3.5	330	14 g SHP	No
5. Oil and water repellent alone	pf	2	N/A	N/A	No catalyst	No
	Ff1	2	1.5	200	No catalyst	No
	Ff2	6	3.5	335	No catalyst	No
6. Oil and water repellent + citric acid	pf	2	N/A	N/A	4 g SHP	5 g citric acid for each finishing option
	Ff1	2	1.5	215	4 g SHP	
	Ff2	6	3.5	305	4 g SHP	
7. Oil and water repellent + maleic acid	pf	2	N/A	N/A	4 g SHP	5 g maleic acid for each finishing option
	Ff1	2	2	215	4 g SHP	
	Ff2	6	3.5	305	4 g SHP	
8. Fire-retardant (DAHP)	pf	15	N/A	N/A	8 g SHP	10 g citric acid for each finishing option
	Ff1	15	1.5	200	8 g SHP	
	Ff2	45	3.5	210	8 g SHP	
9. Silicon softener	pf	1	N/A	N/A	No	No
	Ff1	1	1.5	210	No	No
	Ff2	3	1.5	206	No	No
10. Polyethylene softener	pf	1	N/A	N/A	No	No
	Ff1	1	1	300	No	No
	Ff2	3	1	210	No	No
11. Fatty acid softener	Pf	1	N/A	N/A	No	No
	Ff1	1	1.5	306	No	No
	Ff2	3	1.5	206	No	No

N/A indicates that this entry is not applicable

Table 2 Calculation data

Quantity of the fabric lot (m)	15,000
Dry sample weight for fabric lot (g)	9
Wet sample weight for the fabric lot (g)	For padding = 15.3, For foam application = 9.9
Cost for the fresh water per liter (US$)	0.00233
Cost for the water treatment per liter (US$)	0.002
Post pickup percentage of water drainage per lot	15% (for individual finishing choice)
Fabric GSM	180
Application/drying speed (m/min)	For pad-finishing = 30, For foam-finishing = 70
Power usage for application/drying machine (W)	3000
Working time for foam making machine (h)	0.083 h (5 min)
Power usage for foam making machine (W)	140
Kilowatt hour cost (US$)	10
Aqueous solution weight (g)	100
Cost/g for the foaming agent (US$)	0.0014
Cross-linker 1 Cost/g (US$)—DHEU (Arkofix NZK Liq)	0.00198
Cross-linker 2 Cost/g (US$)—Modified DMDHEU (Fixapret F-ECO Liq)	0.00072
Cross-linker 3 Cost/g (US$)—citric acid	0.0006
Cross-linker 4 Cost/g (US$)—maleic acid	0.0022
Oil and water repellent Cost/g (US$)—C6, Nuva N	0.01013
Fire retardant Cost/g (US$)—diammonium hydrogen phosphate	0.0025
Softener 1 Cost/g (US$)—silicon (SOLUSOFT)	0.00288
Softener 2 Cost/g (US$)—polyethylene (Ceralube)	0.00142
Softener 3 Cost/g (US$)—fatty acid (Cepreton)	0.00168
Catalyst (magnesium chloride) catalyst F-M Cost/g (US$)	0.00065
Catalyst Sodium hypophosphite Cost/g (US$)	0.0013

- For performance, the 11 finishes connected to the performance properties of each finish.

Level-three criteria: Chemical cost of each finish and performance properties of each finish connected to the alternatives.

Alternatives: "Pad-finishing (Pf)", "foam-finishing with recipe-one (Ff1)", and "foam-finishing with recipe-two (Ff2)".

The above hierarchy of the problem was modeled in Super Decisions software (Fig. 1). The abbreviations used in Fig. 1 are given in Table 3. AHP methodology makes pairwise comparisons between different elements to derive priories with respect to their parent node. This paper uses the Super Decision software to perform pairwise comparisons and to derive priorities.

Results and discussion

Table 4 summarizes the results based on calculations and referred methods. The three alternatives have been compared in AHP language. Then, the three different cases have been designed to evaluate AHP model.

Comparison based on sustainability and cost

Concerning the chemical cost for any finish, the trend Pf > Ff2 > Ff1 can be observed, Fig. 2. For DHEU cost, the following statements can be observed, Table 4.

- "Foam-finishing with recipe-one" is 3.33 times preferable than the "foam-finishing with recipe-two".
- "Foam-finishing with recipe-two" is 1.75 times preferable than the pad-finishing.

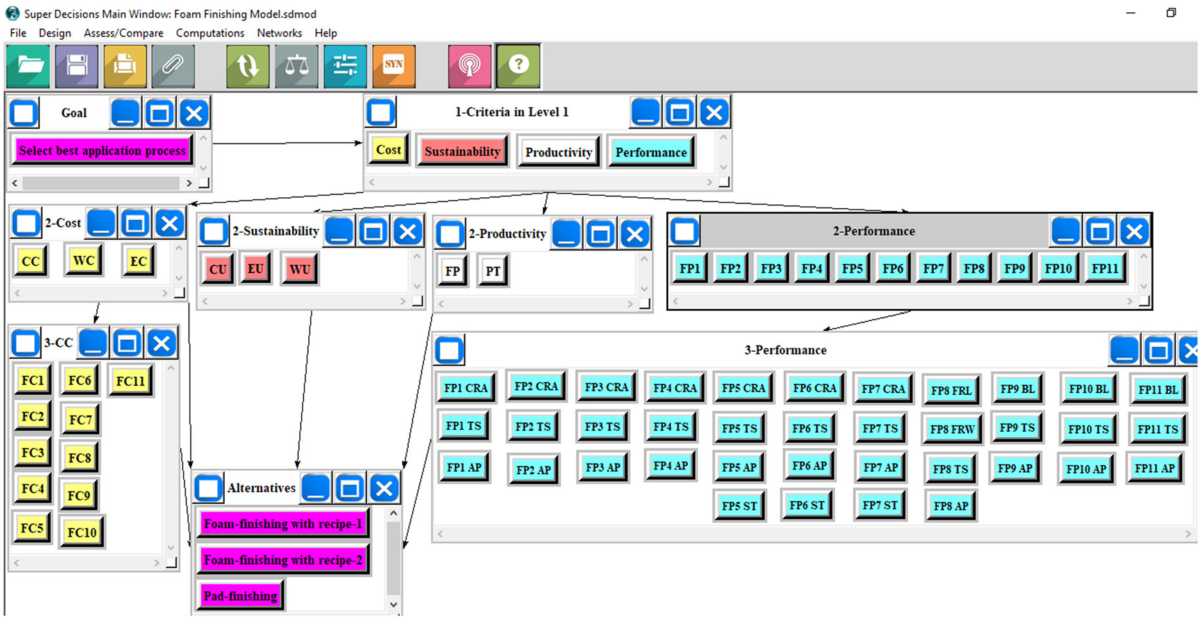


Fig. 1 Analytic hierarchy process model using super decisions software

Table 3 Interpretation of the abbreviations used in AHP model development

CC = Chemical cost	FC1 = DHEU cost	FP1 = DHEU performance
WC = Water cost	FC2 = Modified DMDHEU cost	FP2 = Modified DMDHEU performance
EC = Energy cost	FC3 = Citric acid cost	FP3 = Citric acid performance
CU = Chemical used	FC4 = Maleic acid cost	FP4 = Maleic acid performance
WU = Water used	FC5 = Repellent (alone) cost	FP5 = Repellent (alone) performance
EU = Energy used	FC6 = Repellent + citric acid cost	FP6 = Repellent + citric acid performance
TS = Tear strength	FC7 = Repellent + maleic acid cost	FP7 = Repellent + maleic acid performance
AP = Air permeability	FC8 = Fire retardant cost	FP8 = Fire retardant performance
CRA = Crease recovery angle	FC9 = Silicon softener cost	FP9 = Silicon softener performance
ST = Shower test performance	FC10 = Polyethylene softener cost	FP10 = Polyethylene softener performance
FRW = Fire retardancy (width)	FC11 = Fatty acid softener cost	FP11 = Fatty acid softener performance
FRL = Fire retardancy (length)	FP = Fabric processed	
BL = Bending length	PT = Production time	

- "Foam-finishing with recipe-one" is 5.85 times preferable than the pad-finishing.

Same effect was noted for the remaining 10 finishes and chemical usage. Consumption of finishing chemicals in "foam-finishing with recipe-two" is 2.30 times more than the "foam-finishing with recipe-one". In addition, the chemical consumption in pad-finishing is nearly six times more the than "foam-finishing with recipe-one". Overall, foam-finishing has less discharge of finishing chemicals into the environment. In addition to the chemical saving, the energy and water savings are more in foam-finishing.

Concerning water cost, energy cost, water consumption, and usage of energy for a finish, statement Pf > Ff1 = Ff2 was noted. Both the foam-finishing with recipe-one and recipe-two are equivalent, and each is better than the pad-finishing. In addition, productivity of foam-finishing process looks much

Table 4 Finishing results

Level-one criteria	Level-two criteria	Level-three criteria	Pad-finishing (Pf)	Foam-finishing with recipe-one (Ff1)	Foam-finishing with recipe-two (Ff2)	Interpretation
Costs	Chemical cost (US$)	DHEU	193	33	110	Pf > Ff2 > Ff1
		DMDHEU	72	16	49	Pf > Ff2 > Ff1
		Citric acid	155	28	90	Pf > Ff2 > Ff1
		Maleic acid	306	49	166	Pf > Ff2 > Ff1
		Repellent alone	383	60	177	Pf > Ff2 > Ff1
		Repellent with citric acid	538	82	199	Pf > Ff2 > Ff1
		Repellent with maleic acid	389	61	97	Pf > Ff2 > Ff1
		Fire retardant (DAHP)	1019	151	360	Pf > Ff2 > Ff1
		Silicon softener	54	13	29	Pf > Ff2 > Ff1
		Polyethylene softener	26	7	15	Pf > Ff2 > Ff1
		Fatty acid softener	32	10	19	Pf > Ff2 > Ff1
	Cost of water (US$)		5.63	0.804	0.804	Pf > Ff1 = Ff2
	Energy cost for recipe application (US$)		250	107.14	107.14	Pf > Ff1 = Ff2
	Energy cost for foam making (US$)		0	0.117	0.117	Ff1 = Ff2 > Pf
Sustainability	Water used (liters)		2173.5	310.5	310.5	Pf > Ff1 = Ff2
	Energy used (kWh)		25	11	11	Pf > Ff1 = Ff2
	Chemical used (g)		1,682,100	283,500	652,050	Pf > Ff2 > Ff1
Productivity	Fabric output (g)		142.86	1000	1000	Ff1 = Ff2 > Pf
	Time period for production (hours)		8	4	4	Ff1 = Ff2 < Pf
Performance	DHEU	CRA (°)	116.2 ± 0.5	108 ± 1.5	117.5 ± 0.4	Ff2 > Pf > Ff1
		Tear strength (N)	25.3 ± 0.1	26.1 ± 0.05	25.7 ± 0.05	Ff1 > Ff2 > Pf
		Air permeability (mm/s)	45.5 ± 0.2	49.6 ± 0.5	47.8 ± 0.2	Ff1 > Ff2 > Pf
	DMDHEU	CRA (°)	118.5 ± 1.6	105.2 ± 1.0	126 ± 1.4	Ff2 > Pf > Ff1
		Tear strength (N)	20.6 ± 0.05	22.2 ± 0.01	21.9 ± 0.02	Ff1 > Ff2 > Pf
		Air permeability (mm/s)	44.1 ± 0.5	48.9 ± 0.5	46.3 ± 0.5	Ff1 > Ff2 > Pf
	Citric acid	CRA (°)	136.7 ± 1.8	121.5 ± 0.7	139 ± 1.1	Ff2 > Pf > Ff1
		Tear strength (N)	20.4 ± 0.1	23.1 ± 0.1	22.9 ± 0.1	Ff1 > Ff2 > Pf

Table 4 continued

Level-one criteria	Level-two criteria	Level-three criteria	Pad-finishing (Pf)	Foam-finishing with recipe-one (Ff1)	Foam-finishing with recipe-two (Ff2)	Interpretation
		Air permeability (mm/s)	41.4 ± 0.2	47.6 ± 0.5	44.8 ± 0.2	Ff1 > Ff2 > Pf
	Maleic acid	CRA (°)	123.2 ± 1.8	115 ± 1.9	125.5 ± 1.0	Ff2 > Pf > Ff1
		Tear strength (N)	24.1 ± 0.2	25.9 ± 0.2	24.7 ± 0.1	Ff1 > Ff2 > Pf
		Air permeability (mm/s)	42.9 ± 0.2	46.1 ± 0.2	44.3 ± 0.2	Ff1 > Ff2 > Pf
	Oil and water repellent alone	Shower test	5 ± 0.2	3 ± 0.15	4 ± 0.2	Pf > Ff2 > Ff1
		CRA (°)	122.5 ± 1.2	107 ± 1.1	121.5 ± 0.5	Pf > Ff2 > Ff1
		Tear strength (N)	27.1 ± 0.1	28.7 ± 0.05	27.9 ± 0.05	Ff1 > Ff2 > Pf
		Air permeability (mm/s)	49.3 ± 0.5	51.3 ± 0.2	49.9 ± 0.5	Ff1 > Ff2 > Pf
	Oil and water repellent + Citric acid	Shower test	4 ± 0.2	3 ± 0.2	4 ± 0.2	Pf = Ff2 > Ff1
		CRA (°)	141.2 ± 1.9	135.5 ± 1.7	139.2 ± 1.6	Pf > Ff2 > Ff1
		Tear strength (N)	20.6 ± 0.05	22.1 ± 0.05	21.2 ± 0.05	Ff1 > Ff2 > Pf
		Air permeability (mm/s)	39 ± 0.5	42 ± 0.2	41.5 ± 0.5	Ff1 > Ff2 > Pf
	Oil and water repellent + Maleic acid	Shower test	4 ± 0.15	2 ± 0.15	4 ± 0.15	Pf = Ff2 > Ff1
		CRA (°)	153.5 ± 1.5	139.5 ± 1.3	147.2 ± 1.1	Pf > Ff2 > Ff1
		Tear strength (N)	24.9 ± 0.1	26.1 ± 0.1	25.5 ± 0.1	Ff1 > Ff2 > Pf
		Air permeability (mm/s)	42 ± 0.2	43.5 ± 0.2	42.5 ± 0.5	Ff1 > Ff2 > Pf
	Fire retardant	Fire retardancy (width) mm	1.9 ± 0.03	3.0 ± 0.01	1.5 ± 0.02	Ff1 > Pf > Ff2
		Fire retardancy (length) mm	2.4 ± 0.02	2.4 ± 0.01	2.4 ± 0.01	Ff2 = Ff1 = Pf
		Tear strength (N)	20.5 ± 0.05	21.1 ± 0.1	20.9 ± 0.05	Ff1 > Ff2 > Pf
		Air permeability (mm/s)	36.1 ± 0.2	39.3 ± 0.5	38.1 ± 0.2	Ff1 > Ff2 > Pf
	Silicon softener	Bending length (cm)	5.1 ± 0.1	6.2 ± 0.1	5.3 ± 0.1	Ff1 > Ff2 > Pf
		Tear strength	31.3 ± 0.1	32.1 ± 0.1	32.0 ± 0.1	Ff1 > Ff2 > Pf
		Air permeability	49.1 ± 0.5	51.5 ± 0.5	50.0 ± 0.2	Ff1 > Ff2 > Pf
	Polyethylene softener	Bending length (cm)	5.2 ± 0.2	6.1 ± 0.1	5.4 ± 0.1	Ff1 > Ff2 > Pf

Table 4 continued

Level-one criteria	Level-two criteria	Level-three criteria	Pad-finishing (Pf)	Foam-finishing with recipe-one (Ff1)	Foam-finishing with recipe-two (Ff2)	Interpretation
		Tear strength	30.4 ± 0.05	31.9 ± 0.1	30.8 ± 0.05	Ff1 > Ff2 > Pf
		Air permeability	48.5 ± 0.2	51.1 ± 0.2	50.0 ± 0.2	Ff1 > Ff2 > Pf
	Fatty acid softener	Bending length (cm)	5 ± 0.2	6 ± 0.2	5.4 ± 0.2	Ff1 > Ff2 > Pf
		Tear strength	30.1 ± 0.1	31.4 ± 0.05	30.7 ± 0.05	Ff1 > Ff2 > Pf
		Air permeability	48.0 ± 0.5	50.0 ± 0.2	48.5 ± 0.2	Ff1 > Ff2 > Pf

higher with reference to the pad-finishing. Fabric processed in the foam finishing is seven times higher than the padding. Further, the production time is several times more in the conventional padding as more drying time is required to dry out the completely wet fabric by padding. In the following, the performance results are discussed based on standard tests methods mentioned in "Materials and methods" section (see also Table 4).

Air permeability and tear strength

For air permeability of each finish, the statement Ff1 > Ff2 > Pf can be observed, Fig. 3. The following is the explanation.

- "Foam-finishing with recipe-one" is better than both the "foam-finishing with recipe-two" as well as the pad-finishing.
- "Foam-finishing with recipe-two" is more than one time better than pad-finishing.

Air permeability is comparatively more in foam-finishing due to one sided application of the chemical onto the fabric surface, therefore, less chemical application in foam finishing will lead to less reduction in air permeability. Air permeability is more in "foam-finishing with recipe-one" than other two alternatives due to the less chemical consumption (Fig. 3). This factor may also affect the tear strength. It can be seen in Table 4 that the air permeability in foam recipes is comparable to the padding. However, foam recipes offer much more environmental protection than the conventional padding. For tear strength, the statement Ff1 > Ff2 > Pf can be observed for all the finishes and this statement can be explained as per following (Fig. 4).

- "Foam-finishing with recipe-one" is more preferable than both the pad-finishing as well as "foam-finishing with recipe-two".
- "Foam-finishing with recipe-two" is more than one time more preferable than pad-finishing.

Another reason for tear strength improvement in case of foam recipe is the faster fabric processing speed and consequently less time under drying and curing temperature which will lead to less decrease in the tear strength as compared to pad-finishing. The tear strength and the air permeability for "foam-

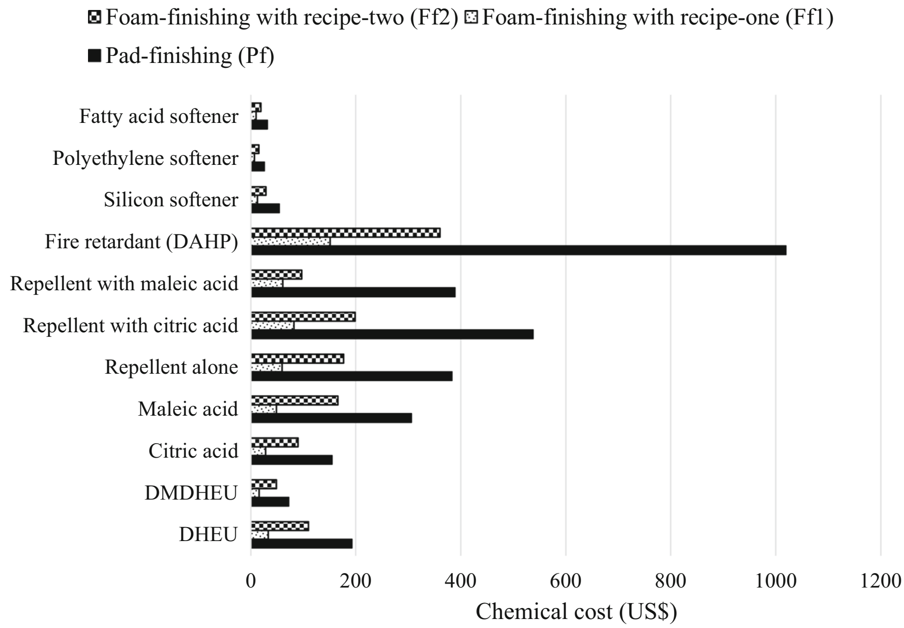


Fig. 2 Chemical cost (US$)

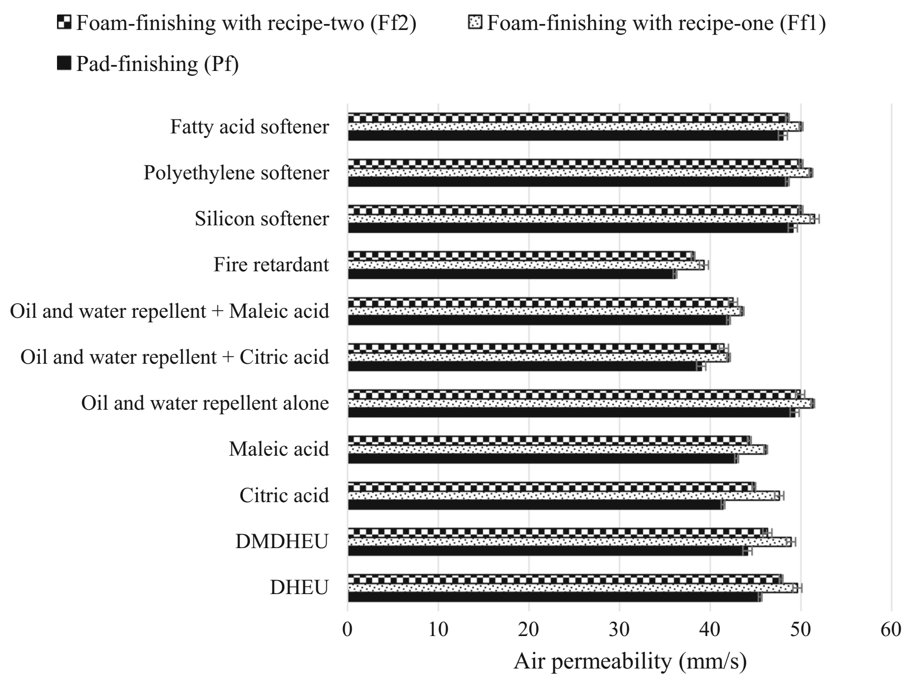


Fig. 3 Air permeability (mm/s)

finishing with recipe-two" are more close to pad-finishing.

Crease recovery angle

Untreated fabric indicated CRA value 75.5 ± 1.1 which was poor than the pad finished and foam finished fabrics. For CRA of the four cross-linkers, the statement Ff2 > Pf > Ff1 can be observed (Fig. 5). Hence, the

Fig. 4 Tear strength (N)

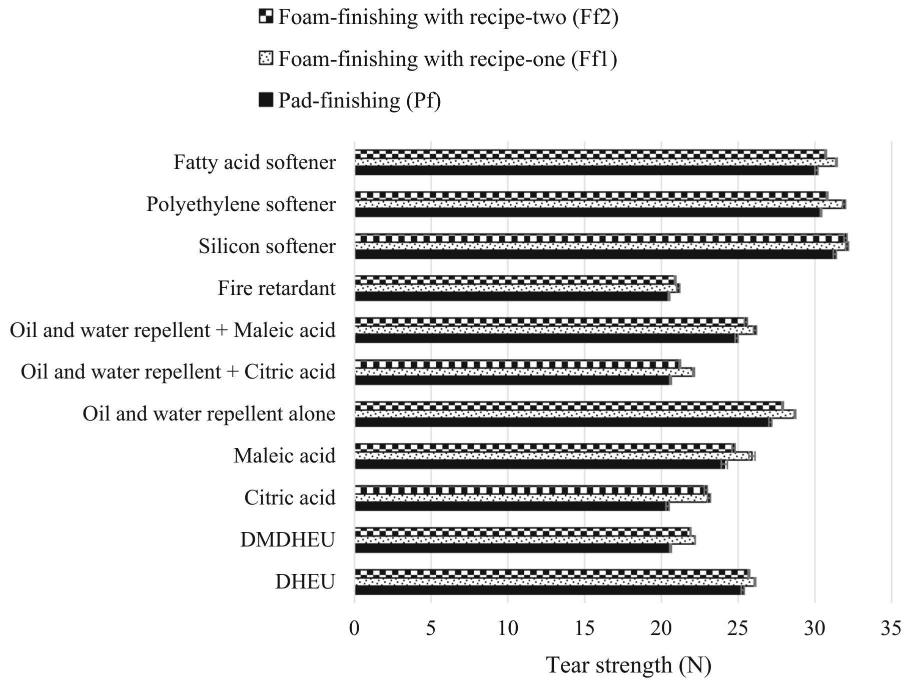
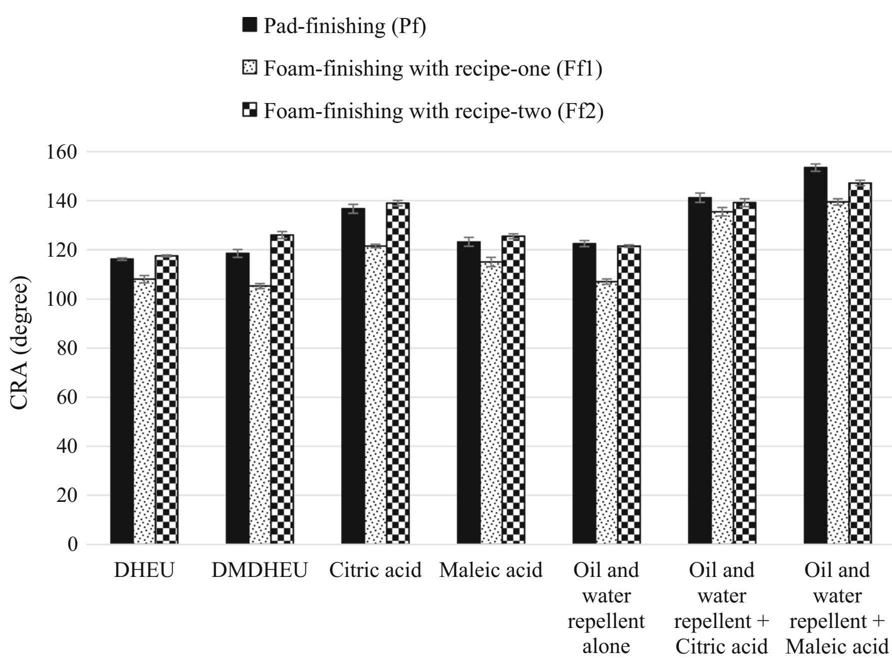
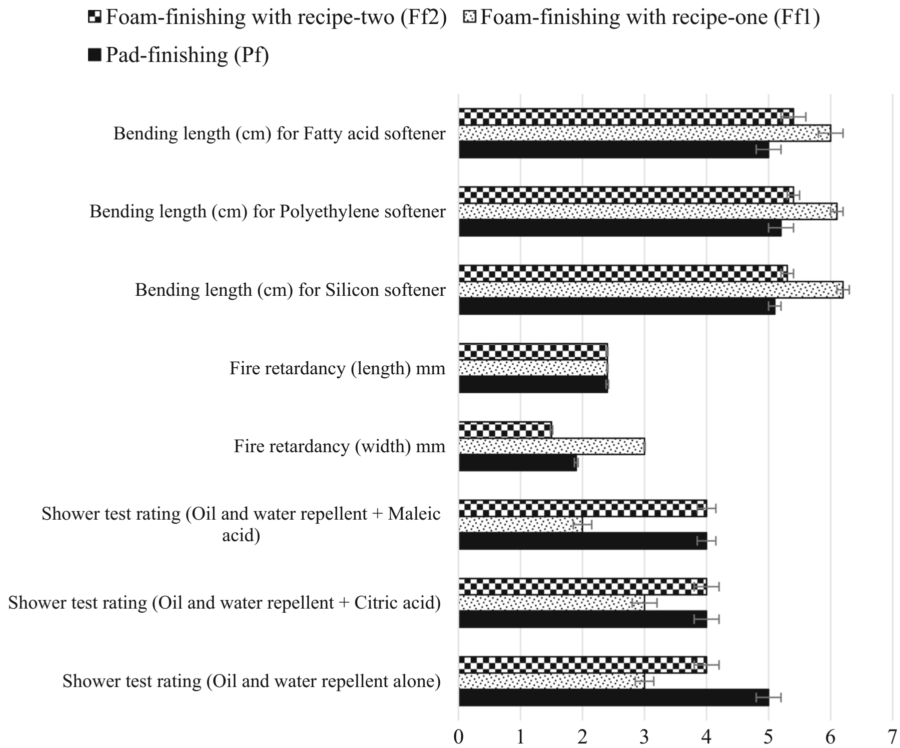


Fig. 5 Crease recovery angle (°)



increased concentration of the finishing chemicals in the "foam-finishing with recipe-two" has improved the CRA as compared to "foam-finishing with recipe-one" and similar to pad-finishing. Since during the foam finishing less cross-linker chemical is applied and that is also only on one side of the fabric then the CRA will be lower for foam-finishing with recipe-one as compared to padding. However, in case of foam-finishing with recipe-two, the cross-linker quantity is raised and consequently the CRA is also increased. The same

Fig. 6 Bending length (cm), fire retardancy (mm), and shower test rating (0–5 scale)



trend due to the same reason is observed for oil and water repellent finish recipes and for all three softener finish recipes as far as their performance of repellency and softness (bending length) respectively are concerned. For CRA of all the three oil and water repellent recipes, the statement Pf > Ff2 > Ff1 can be observed. This means that the pad-finishing is more preferable than foam-finishing. However, the CRA for pad-finishing and "foam-finishing with recipe-two" are very close to each other. Hence, the increase in concentration of finishing chemicals has improved the CRA in foam-finishing.

Shower test (oil and water repellency)

For shower test of all the three oil and water repellent recipes, the pad-finishing and "foam-finishing with recipe-two" are comparable (Fig. 6). This is due to increased concentration of finishing chemicals. However, it is important to note that oil and water repellent finishes are hydrophophic in nature, consequently, it is difficult to generate, stabilize and uniformly apply their foam onto the fabric. Nevertheless, the foam performance target was successfully achieved and comparable results as that of Padding was obtained.

Fire retardancy

For fire retardant, char width for "foam-finishing with recipe-one" is approximately 2 times inferior to both the pad-finishing and "foam-finishing with recipe-two" (Fig. 6). Hence, the pad-finishing and the foam-finishing with recipe-two are comparable. In case of char length, all the three alternatives show the comparable results. Cotton fabric is highly flammable and therefore, higher quantity of the fire retardant finish is required to achieve the fire retardancy. However, it is much difficult to generate the foam of the higher quantity (15%) of the fire retardant finish but it was successfully achieved in this research.

Bending length

For all the three softeners, the bending length for "foam-finishing with recipe-one" is inferior to both the pad-finishing and "foam-finishing with recipe-two" (Fig. 6). It is quite obvious as greater the amount

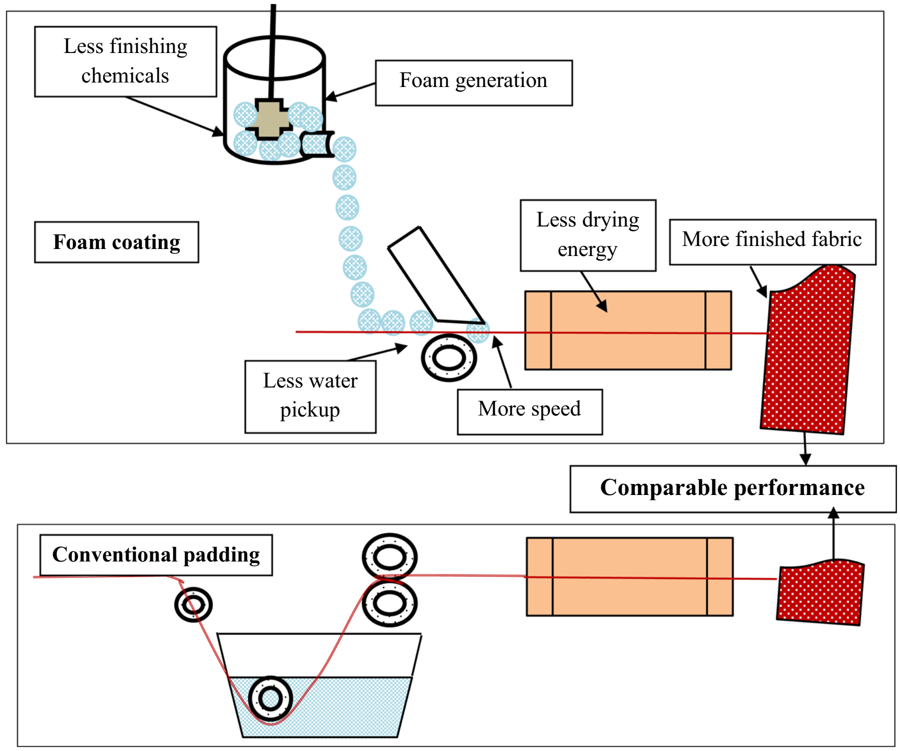


Fig. 7 Comparison between padding and foam-finishing

of softener, greater will be the finish fabric bending length. The pad-finishing and the foam-finishing with recipe-two are comparable.

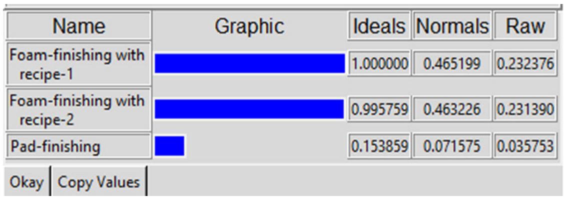
Analytic hierarchy process (AHP) model evaluation

Until now, the padding and foam finishing recipes have been compared with respect to four criteria. Figure 7 presents the conceptual model of the comparison between padding and foam-finishing. In many cases, the performance of the padding is much close to the optimized foam finishing recipe. However, decision making should not neglect environmental sustainability and other important criteria. If we include other three criteria (i.e. cost, productivity, and sustainability), the foam finishing looks much better than the padding. AHP methodology helps for decision making based on multiple criteria. In the following, three different cases evaluate the AHP model based on the above understandings.

Case-one: criteria in level one, two and three are same preferable

In this case, all the criteria in any level of hierarchy have same preference. In other words, we want to include all the four major criteria (i.e. sustainability, cost, productivity, and performance) and their sub-criteria into the decision making, and we give equal preferences to all criteria and sub-criteria. In this case, the analytic hierarchy process model developed in "Materials and methods" section was set as follows.

- In the level one criteria, all the four criteria are one-time superior with respect to goal. It interprets that we have given the same priority to four major criteria (i.e. sustainability, cost, productivity, and performance). Similarly, the criteria in the level two and level three have same preference as follows.
- In the level two criteria, the following preferences were used.
  - Chemical, water, and energy costs are same desirable regarding the Cost criterion.



Name	Graphic	Ideals	Normals	Raw
Foam-finishing with recipe-1		1.000000	0.465199	0.232376
Foam-finishing with recipe-2		0.995759	0.463226	0.231390
Pad-finishing		0.153859	0.071575	0.035753

Fig. 8 Case-one: criteria in level-one, level-two, and level-Three are similarly preferable

- Fabric output and processing time are equally preferable with respect to Productivity criterion.
- Water consumed, chemical usage, and energy consumed have same preference regarding the Sustainability criterion.
- All the 11 finishes have same preference regarding the Performance criterion.

- In the Level Three Criteria, the following preferences were used.
  - All the 11 finishes have same preference regarding the Chemical cost.
  - All the tests have same preference regarding their corresponding finish criteria.
- Preferences of the alternatives were derived from experimental data as discussed earlier. Figure 8 shows the AHP results based on the Case-one.

The column "Raw" in Fig. 8 is read directly from the Limit Supermatrix. The priorities of the alternatives are shown in the column "Normals" and are derived from column "Raw". The column "Ideals" is derived from the column "Normals" such that each value in the "Normals" is divided by largest value in the "Normals". The results based on column "Ideals" clearly show that the "foam-finishing with recipe-one" looks the best choice which has a priority of 1.00. In this way, it can be said that the foam-finishing with recipe-two is 99.57% as good as the "foam-finishing with recipe-one". Similarly, pad- finishing is 15.38% as preferable as "foam-finishing with recipe-one". "Foam-finishing with recipe-two" is 84.55% more preferable than pad-finishing. "Foam-finishing with recipe-one" is 0.42% superior than the "foam-finishing with recipe-two". If all the criteria are included in the decision making and have the same preference, the foam finishing with recipe-one is more preferable than padding as well as the foam finishing with recipe-two.

Case-2 evaluates the AHP model if some important tests are given more preference than other criteria.

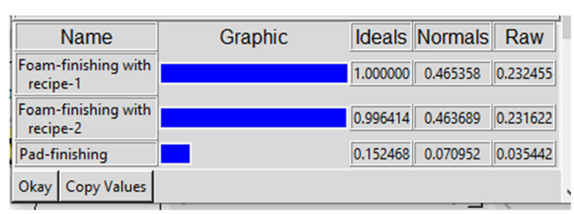
Case two: CRA, shower test, fire retardancy, and bending length are extremely more preferable

In this case, we are interested in decision making based on giving the highest preferences to some important finishing tests (i.e. CRA, shower test, fire retardancy, and bending length). Except these tests, all the other preferences have been considered same as in the Case One. For this purpose, the priorities for these tests have been derived in the Level Three as follows.

- The CRA, shower test, fire retardancy (char width), fire retardancy (char length), and bending length are exceptionally (nine times) superior than the air permeability and the tear strength with respect to the corresponding finish in the immediate upper level criteria.
- CRA and shower test were considered equally preferable regarding their corresponding finish.
- Air permeability and tear strength have same preferences regarding their corresponding finish.
- Fire retardancy (width) and fire retardancy (length) have same preferences regarding the corresponding finish.

Figure 9 shows the AHP results based on the Case-two.

The results of Case-two seem close to Case-one. However, the results of pad-finishing have slightly decreased and the results of "foam-finishing with recipe-two" have slightly improved. Still, the results favored "foam-finishing with recipe-one" due to its importance in many aspects such as less chemical cost, less chemical consumption, more tear strength, and more air permeability. However, some important properties such as CRA and shower test could not be achieved without chemical increase as in "foam-



Name	Graphic	Ideals	Normals	Raw
Foam-finishing with recipe-1		1.000000	0.465358	0.232455
Foam-finishing with recipe-2		0.996414	0.463689	0.231622
Pad-finishing		0.152468	0.070952	0.035442

Fig. 9 Case-two: CRA, shower test, fire retardancy, and bending length are extremely more preferable

finishing with recipe-two". In addition, the properties such as air permeability and tear strength in the "foam-finishing with recipe-two" are closer to pad-finishing. Nevertheless, "foam-finishing with recipe-two" is 85% superior than pad-finishing. "Foam-finishing with recipe-one" is 0.36% more preferable than the "foam-finishing with recipe-two". It can be said if all the four criteria have same preference and some important tests in sub-criteria have more preference, the foam finishing with recipe-one is more preferable than the foam finishing with recipe-two and padding. However, the foam-finishing with recipe-two (i.e. optimized recipe) shows some improvement compared with Case-one. Usually, the performance criteria should be given more preference compared with cost, sustainability, and productivity. In Case-three the performance and sustainability has been given more preference than cost and productivity.

Case three: sustainability and performance have exceptionally more preference than the productivity and cost

In this case, the production team is willing to give the more superiority to the sustainability and performance. Also, the production team is willing to give more superiority to the important finishing tests. For this purpose, the priorities for criteria and sub-criteria have been defined as follows.

Level One Criteria: Priorities have been derived as described below.

- Performance is nine times superior than the cost.
- Productivity and cost have same preference.
- Sustainability is nine times superior than the cost.
- Performance is nine times superior than the productivity.
- Sustainability and performance have same preference.
- Environmental sustainability is nine times more preferable than productivity with respect to goal.

The term nine times is used in the AHP methodology and indicates exceptional preference of one criterion over other criterion. The AHP methodology offers the preference flexibility based on the requirement of the decision maker.

Level Two Criteria: Priorities have been derived as described below.

Name	Graphic	Ideals	Normals	Raw
Foam-finishing with recipe-1		0.995966	0.455174	0.227385
Foam-finishing with recipe-2		1.000000	0.457018	0.228306
Pad-finishing		0.192133	0.087808	0.043865

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Fig. 10 Case three: performance and sustainability are extremely more preferable than cost and productivity

- Water and energy costs have same preference.
- Energy cost is nine times superior than the chemical cost.
- Water cost is nine times superior than the chemical cost.
- Water and energy consumptions have same preference.
- Energy consumption is nine times superior than the chemical consumption.
- Water consumption is nine times superior than the chemical consumption.

All the other preferences are same as in the Case two.

Figure 10 shows the AHP results based on the Case-three.

In this case, the optimized recipe (i.e. foam finishing with recipe two) indicated the first priority. However, the "foam-finishing with recipe-one" and recipe-two are comparable. In the individual results for some important tests, the foam finishing with recipe-two shows the performance closer to the conventional padding. In case of foam finishing with recipe-one, some additional cost and chemical quantity can be saved but the desired performance cannot be achieved. Hence, foam finishing with optimized recipe-two is more preferable than the foam finishing with recipe-one. In case of cost savings related to water, chemicals, and energy, the foam-finishing looks much better than pad-finishing. For cost and chemical saving, the best option looks the "foam-finishing with recipe-one". Key reasons behind the first priority of "foam-finishing with recipe-one" are less chemical consumption, more air permeability, and more tear strength. To justify the advantage of foam-finishing on pad-finishing, it is necessary to achieve similar performance for some most important properties such as CRA and shower test. These properties are comparable in the pad-finishing and foam-finishing with recipe-two.

Conclusion

This paper investigates the environmentally friendly foam-finishing of 11 nontoxic and sustainable finishes with reference to the traditional padding considering multiple criteria. The foam was successfully generated and applied on the cotton fabrics using four different cross-linkers, three different oil and water repellents, a fire retardant, and three different softeners. Foam finishing recipes provided much more cost savings compared with padding. Foam finishing provided 86% water saving and 56% energy saving compared with traditional padding. Regarding chemical savings, the foam-finishing with recipe-one offers 83% chemical saving with respect to padding. The foam-finishing with recipe-two (optimized recipe) offers 61% chemical savings. Foam coating offers six times more fabric output than the padding. In addition, the 50% production time can be saved in foam coating. Concerning crease recovery angle, the foam-finishing with recipe-two (optimized recipe) and padding were comparable while the foam-finishing with recipe-one exhibited poor results. Within four cross-linkers, the citric acid exhibited superior CRA (139° for foam finishing) than DHEU, DMDHEU, and maleic acid. The recipe with alone oil and water repellent exhibited inferior CRA (121.5° for foam finishing) than the recipes adding maleic acid (CRA 147.5° for foam finishing) and citric acid (139.25° for foam finishing). For all the finishes, foam coating offered comparable or better tear strength and air permeability than the conventional padding. The results of the AHP model indicated that the foam-finishing with recipe one, with least concentration of chemicals, has a first priority in terms of cost saving, sustainability, and some properties including the air permeability and the tear strength. However, the main purpose of cross-linkers and oil and water repellents is to improve some specific properties such as CRA and water repellency, respectively. This improvement was not possible without the increase in chemical concentration in the recipes. Even if the chemical concentration was increased in the foam-finishing with recipe two, the chemical consumption and sustainability of the foam-finishing was much favorable than the pad-finishing. In addition, the performance of the recipe with increased chemical concentration was comparable with pad-finishing. The foam finishing recipes involve less chemicals and more speed than the conventional pad-finishing, resulting in more fabric production. Therefore, it can be concluded that when the foam finishing technique is optimized, then it can give more sustainable, economical and good performance option as compared to conventional padding.

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