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Fast Fashion Brands: Sustainable Marketing Practices and Consumer Purchase Behaviour

Blagovne znamke hitre mode: trajnostne tržne prakse in nakupovalno vedenje potrošnikov

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Abstract

The fast fashion boom is faced with economic, environmental and social justice objections. Sustainable marketing initiatives have become a new style statement, and brands are shifting to environment-friendly manufacturing. This study explores how fashion apparel brands adopt sustainable marketing practices to promote sustainable purchase behaviour. A cross-sectional survey using a quantitative research design was followed to collect responses from fashion brand consumers. Variance-based partial least squares-structural equation modelling (PLS-SEM) was used to assess the hypothesized model. Two-step bootstrapping was conducted to explore the mediating role of brand perception in the relationship between sustainable marketing activity and brand loyalty. The study suggests that firms can support sustainable marketing practices by creating a brand image and building trust. This can influence consumers' perceptions of sustainability and promote brand loyalty. The study also emphasizes the significance of brand loyalty in developing sustainable purchase behaviour that endures over time. The study provides insights into sustainable marketing strategies and policies in indigenous markets.
Keywords: sustainable marketing, sustainable brand perception, sustainable brand loyalty, sustainable purchase behaviour

Izvleček

Razcvet hitre mode je soočen z gospodarskimi, okoljskimi in družbenimi ugovori. Trajnostne tržne pobude so postale novi slogani, blagovne znamke se preusmerjajo k okolju prijazni proizvodnji. Ta študija raziskuje, kako blagovne znamke modnih oblačil sprejmejo trajnostne trženjske prakse za spodbujanje trajnostnega nakupovalnega vedenja. S pomočjo presečne kvantitativne raziskave so bili zbrani odgovori potrošnikov modnih znamk. Hipotetični model je bil ocenjen s pomočjo metode najmanjših delnih kvadratov za modeliranje strukturnih enačb (PLS-SEM), ki temelji na varianci. Izveden je bil dvostopenjski zagon, da bi raziskali posredniško vlogo dojemanja blagovne znamke v razmerju med trajnostno tržno dejavnostjo in zvestobo blagovni znamki. Študija kaže, da z ustvarjanjem podobe blagovne znamke in graditvijo zaupanja podjetja lahko podpirajo trajnostne tržne prakse. To lahko vpliva

na dojemanje potrošnikov glede trajnosti in spodbuja zvestobo blagovni znamki. Študija poudarja tudi pomen zvestobe blagovni znamki pri razvoju trajnostnega nakupovalnega vedenja skozi čas ter ponuja vpogled v trajnostne trženjske strategije in politike na domačih trgih.
Ključne besede: trajnostno trženje, trajnostna percepcija blagovne znamke, trajnostna zvestoba blagovni znamki, trajnostno nakupovalno vedenje

1 Introduction

Public and private sector initiatives to promote sustainable consumption, global resource consumption and associated emissions continue to rise. The textile industry has a huge environmental impact. The industry faces many challenges, including fast fashion, complex global supply chains, consumer preferences and policy implications. However, it also presents opportunities for innovation and plays a significant economic role. Research in this area can drive positive change, influence industry practices, and contribute to a more sustainable and responsible textile sector. This study focuses on the fast fashion industry, which has seen high profits and sales due to design, production, logistics and retail advancements that incentivize customers to buy more apparel [1]. However, the fast fashion boom has been met with objections related to environmental and social justice. In response, the industry has implemented various sustainability initiatives that address the environment, society and economy, while focusing on the components of the marketing mix, such as product, price, place and promotion [2, 3].

Organizations prioritize sustainability in order to maintain their growth. Liu, Kim, Wang, and Kim [4] note that sustainability encompasses economic, social and environmental responsibilities. Companies can demonstrate their commitment to environmental sustainability by using demarketing strategies and integrating eco-friendly products. To ensure their expansion remains stable, businesses undertake various activities that focus on sustainability [5].

Over the years, there has been an increase in the adoption of sustainable marketing practices by firms, leading to significant changes in the way we live, produce, market and consume [6–8]. Today's consumers seem driven by more than just rational considerations when purchasing. They are increasingly prioritizing ideological and symbolic factors. According to a survey by the IBM Global Consumer Study [9], over half of the respondents (i.e. 51%) claimed that environmental sustainability has become more important to them than a year ago. The same study conducted in 2021, found that 50% of customers were willing to pay more for companies or goods that support sustainability. Additionally, the survey revealed that in 2022, almost half of the consumers (i.e. 49%) had already paid an average premium of 59% for goods with an environmentally friendly or socially conscious label in the previous year. Implementing sustainable marketing practices is thus essential for marketers who wish to establish brands that can be sustained over the long run, focusing on building brand trust and image, as suggested by Khandai et al. [10].

Studies on sustainable marketing initiatives lack research on the sustainable perceptions of fashion companies' performance about sustainable purchase behaviour. This highlights the significance of examining the role of brand image and trust in developing sustainable perception and loyalty as it relates to purchase behaviour. This study explores how fashion apparel brands pursue sustainable marketing activities and how consumers perceive them. It aims to investigate the relationship between sustainable marketing initiatives, brand image, brand trust, brand loyalty and sustainable purchase behaviour. By focusing on young fashion consumers' behaviour in Asian countries, we can understand how sustainable brand image and trust mediate customer loyalty to establish sustainable purchase behaviour.

The study aims to delineate a research model that explains the dynamics between sustainable marketing, perception, loyalty and purchase behaviour. Additionally, it offers suggestions for marketing practitioners by proposing different marketing strategies for young consumers' consumption trends in developing countries.

Global studies suggest that consumers are increasingly attracted to sustainable brands, focusing on environmental and societal impacts [11, 12], while sustainable marketing efforts are vital in encouraging consumers to adopt sustainable practices such as recycling, healthy eating, energy conservation, etc. While marketing and sustainability may not be at odds with each other, it is crucial to understand how these concepts can complement each other to encourage sustainable behavioural changes [13, 14].

1.1 Sustainable marketing and sustainable perception

Developing a sustainable marketing strategy requires careful consideration of the social environment, the local community's values and the ethical impact on the environment. This involves assessing corporate practices in areas such as marketing and sales. According to Elkington [15], all sustainable marketing initiatives should consider economic, social and environmental aspects. By distributing financial gains through localized financial assistance, economic marketing initiatives should benefit various parties, including customers, community stakeholders, staff and partners. Additionally, businesses should be incentivized to expand operations and increase profits, while [16, 17] found that companies' social activities, such as responses and attitudes towards their products, positively affect customers' attitudes towards a brand. Social interactions allow consumers to stay connected to their purchasing decisions and intentions, and emphasize the importance of eco-friendly consumption through initiatives such as creating environmentally friendly fashion items, the reuse of recycled banners, bag-sharing programmes and wildlife preservation for green development.

A brand's image is shaped by a person's beliefs, ideas and impressions about a product. This image comprises customers' perceptions of a brand [18, 19]. Maignan and Ferrel [20] suggest that marketing strategies focused on sustainability can benefit a brand in various ways. These benefits include enhancing brand image, driving business profitability and ensuring long-term success. Research shows that customers tend to have a more positive perception of companies that actively practice social responsibility than those that do not [21, 22].

Establishing and nurturing trust in a brand is of importance for businesses as it can offer an edge over competitors, leading to improved performance over the long run [23]. According to Johnson and Graysons [24], trust is a bond that can evolve and surpass what can be justified based on available knowledge. When a business invests in building relationships, it demonstrates a level of confidence in the value of the partnership, as the emotional connection between the one trusting and the one being trusted strengthens over time. According to Hiscock [25], the ultimate aim of marketing is to create an emotional bond between the consumer and the brand, which is sparked and strengthened through trust. Companies devote significant resources to building brand trust, which gives brands a long-term competitive advantage and ultimately improves organizational performance [23]. According to Morgan and Hunt [26], trust is created when one entity has confidence in the dependability and integrity of another entity. They discovered that loyalty and commitment follow trust.

H_1: *Sustainable marketing activity (SMA) influences brand image (BIG).*

H_2: *Sustainable marketing activity (SMA) positively impact brand trust. (BTR).*

H_3: *Sustainable marketing activity (SMA) positively impact sustainable brand loyalty (SBL).*

1.2 Sustainable perception and sustainable brand loyalty

The effectiveness of pro-environmental messages is still questionable, according to Chan and Hsu [27], even though organizations may use them to enhance their brand image and attract customers [28]. Yadav et al. [29] suggest that consumers who value the environment are more likely to be interested in a brand's pro-environmental actions. In a scenario study by Namkung and Jang [30], consumers with higher environmental awareness were likelier to value the green brand image and engage in eco-friendly behaviours than those with lower environmental consciousness. Brand image significantly impacts brand loyalty, as Brunner et al. [31] and Jung et al. [32] highlight.

Expanding a brand through sustainable marketing techniques positively impacts brand trust. According to a study by Carter [33], 53% of customers surveyed believe that brands should be genuinely interested in social issues instead of just engaging in social responsibility for marketing purposes. Sustainable marketing strategies also provide organizations with competitive advantages by fostering brand loyalty, according to Hesse et al. [34] and Jung et al. [35]. Furthermore, brand trust is crucial in mediating the relationship between social responsibility and brand loyalty, as Khan and Fatma [36] stated.

H_4: Brand image (BIG) influences sustainable brand loyalty (SBL).

H_5: Brand trust (BTR) influences sustainable brand loyalty (SBL).

1.3 Sustainable brand loyalty (SBL) and sustainable purchase behaviour (SPB)

Brand loyalty refers to a consumer's attachment to a specific brand. This concept is widely discussed in current literature [37, 38]. In Akturan's [39] study, it was found that there is a strong correlation between consumer purchase intent and the value consumers place on environmentally friendly brands. Researchers have explored attitude-based and behavioural loyalty, as determined by how frequently consumers purchase [40, 41]. Customers' loyalty to a brand largely depends on their dedication and attitude. This factor is influenced by the level and type of customer purchasing intentions [42]. Consumers who show positive purchasing intentions are more likely to exhibit brand loyalty. The way consumers engage with a product category greatly influences their attitude toward a particular brand [43]. With this in mind, it is reasonable to assume that there is a positive connection between brand loyalty and purchase intent regarding eco-friendly products. We therefore hypothesize:

H_6: Sustainable brand loyalty (SBL) positively influences sustainable purchase behaviour (SPB).

A mediating variable is a variable that connects two other variables in a causal chain. Baron and Kenny [44] describe it as something in the middle. The researchers in Kartono & Warmika's [45] study used a brand's image as a mediating variable. They found that sustainable marketing strategies impacted consumer loyalty, mediated by the brand image. In other words, the more sustainable marketing strategies customers perceive and achieve, the stronger the sense of brand image and brand loyalty will be. Astini [46] also found that a sustainable marketing strategy can foster a favourable brand image and increase client loyalty. Sustainable marketing tactics can create an exceptional sustainable brand image in the eyes of consumers, especially in the face of escalating environmental problems. Kotler and Keller [47] define brand image as a customer's association with a product. A green marketing approach can increase consumer loyalty by improving a customers' perception of a brand's image [48]. They posit that a strong sustainable marketing strategy will boost a brand's reputation and increase customer loyalty. Trust refers to the expectation that two or more parties will collaborate and fulfil their respective duties and responsibilities. It is the belief that the other person's words or promises will be followed through in a stable and mutually beneficial relationship. This definition, proposed by Morgan and Hunt [49], highlights the importance of trust in any exchange-based relationship, and the following hypothesis were put forth in this study:

H_7: Brand image (BIG) mediates the relationship between sustainable marketing activity (SMA) and sustainable brand loyalty (SBL).

H_8: Brand trust (BTR) mediates the relationship between sustainable marketing activity (SMA,) and sustainable brand loyalty (SBL).

The relationship between constructs and the proposed hypothesis is presented in Figure 1.

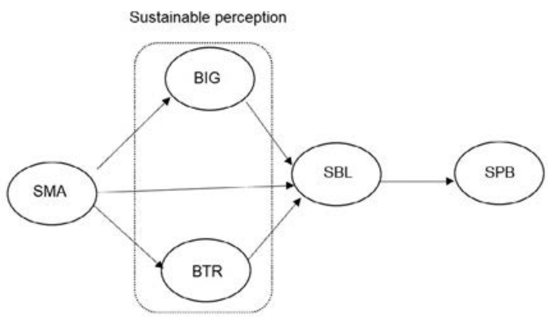

Figure 1: Conceptual framework
(SBL – sustainable brand loyalty; SPB – sustainable purchase behaviour; BIG – brand image; SMA – sustainable marketing; BTR – brand trust)

2 Materials and methodology

A detailed approach to address the established proposition is presented in the following sub-sections.

2.1 Research and instrument design

A quantitative cross-sectional survey design was used in this study. Delhi-North Capital Region respondents were surveyed using a self-administered online questionnaire. The respondents were ensured that the data would be kept confidential and would be used for academic research only. Participation in the survey was voluntary. Moreover, the survey was divided into two sections. The first section started with a briefing on sustainable apparel and demographic profile statements. The second section entailed an indicator description for all constructs to measure millennials' sustainable apparel purchase intention. The survey was circulated through various social media platforms. The description of the measures used in the study and validated by literature is provided in Table 1. The responses were measured using scale items anchored to a 5-point Likert scale (1-strongly disagree to agree 5-strongly).

Table1: Latent construct description

Construct	Items	Scale	Reference
Sustainable brand loyalty (SBL)	SBL1	I am excited to buy the brand again because of its environmental performance.	[50]
	SBL2	As a result of the brand's environmental functionality, I choose to purchase it above other brands.	
	SBL3	Due to the brand's environmental attributes, I hardly ever contemplate using other brands.	
	SBL4	Since the brand is environmentally friendly, I want to keep buying it.	
Sustainable purchase behaviour (SPB)	SPB1	I buy the brand because it cares about the environment.	[51]
	SPB2	I will buy the brand again because it treats the earth well.	
	SPB3	Overall, I am content to buy the product because it is environmentally beneficial.	
Brand image (BIG)	BIG1	The brand is regarded as the leading example of sustainable development	[52]
	BIG2	The company specializes in building a green reputation.	
	BIG3	When it comes to environmental aspects, the brand excels.	
	BIG4	The brand is credible in environmental performance.	
Sustainable marketing (SMA)	SMA1	The brand uses materials that are good for the environment and society.	[53, 54]
	SMA2	Brands with technological innovation and production prevent environmental pollution.	
	SMA3	Throughout the design process, the brand takes the surroundings into account and supports efficient management.	
Brand trust (BTR)	BTR1	The brand is truthful and committed to the environment.	[55–57]
	BTR2	The brand offers top-notch products and environmental services.	
	BTR3	The brand keeps its promise and protects the environment.	

2.2 Non-response error

Non-response error refers to a type of bias that can occur in survey research when individuals invited to participate either decline or cannot be reached. This issue introduces the possibility of systematic differences between respondents and non-respondents, which can lead to a distortion of a study's findings. To ensure the reliability and validity of survey-based research and maintain the credibility of study findings in various fields, it is crucial to recognize and address the non-response error. To assess the non-response error, the sample was divided into three categories as proposed by de Winter et al. [58]: (i) early responders (those who responded without a reminder), (ii) late responders (those who responded after receiving a reminder), and (iii) non-responders (those who did not submit the questionnaire at all). Using the 2 test, the statistical analysis indicated no statistically significant difference between the three groups in terms of social, demographic and study-related factors. In other words, the characteristics of the respondents with regard to these aspects did not significantly differ based on when or whether they responded to the survey. However, the statistical analysis did not find any significant differences between the groups based on social, demographic and study-related factors, ruling out non-response errors in the study.

2.3 Sample design

For this study, the sample group comprised consumers who are residents of the Delhi-North Capital Region and at least 18 years old. Respondents were selected through a non-probabilistic convenience sampling technique in various malls and retail establishments in Noida, Delhi, and Gurgaon, which were chosen due to the concentration and popularity of the brands there. Out of 630 individuals who were approached, 487 provided responses. After filtering out empty responses and nearly identical responses to scaled items, 371 responses were used for the final analysis, resulting in a response rate of 59%. To ensure the study's external validity, a non-response error test was recommended for response rates below 85% [59].

Table 2: Respondent profile

Respondent		**Number**	**Percentage (%)**
Gender	Male	122	32.88
	Female	249	67.11
Age	18–24	177	47.70
	25–34	194	52.29
Education qualification	Graduate	140	37.73
	Postgraduate	194	52.29
	Doctorate	13	3.50
	Others	24	6.46
Occupation	Student	114	30.72
	Public sector	20	5.39
	Private sector	163	43.93
	Business	36	9.70
	Others	38	10.24
	0–3 lakh[a)]	65	17.52
Monthly family income	3–6 lakh[a)]	202	54.44
	More than 6 lakh[a)]	104	28.03
	Total	371	100

[a)] 1 lakh = 100.000

According to the demographic breakdown of respondents shown in Table 2, 32.88% were men, and 67.11% were women. The 25 to 34 age group exceeded the other age group by 5%. Most respondents held postgraduate degrees, were employed by private companies and had monthly family incomes ranging from 3 to 6 lakh Indian rupees. In some nations, a postgraduate degree is equivalent to a graduate degree.

3 Results and findings

In our research paper, we chose SMART PLS instead of CB-SEM due to its suitability for our exploratory study with a relatively small sample size. SMART PLS's main focus is on predicting dependent variables, which aligned well with our research goals. Additionally, its robustness in handling non-normal data enhanced the reliability of our results. The flexibility of SMART PLS accommodates the specific characteristics of our dataset, allowing for a more effective and meaningful analysis. The study utilized partial least square-structure equation modelling (PLS-SEM) due to its predictive and exploratory nature. PLS-SEM is widely accepted because it is less sensitive to sample size considerations, has no limiting measurement features, and can accurately forecast the target variable. Data analysis was performed using software such as Smart-PLS 2.0 and SPSS 18.0. The analysis employed structural equation modelling based on the two-step method [60]. First, it was determined whether the measurement model met the requirement of a linear relationship between an explicit variable and the latent construct. Second, the structural model of the construct was evaluated for building path linkages.

3.1 Measurement model

In this investigation, concept reliability and validity were measured according to the criteria defined by Hair et al. [61]. The loading of the rest of the indicators, as shown in Table 3, suggests the dependency of the indicators [61]. Indicators with a factor loading of less than 0.7 were removed from the analysis. Internal consistency was calculated using Chronbach's Alpha (α) and composite reliability (ρc). According to the table, the composite reliability score ranged from 0.847 to 0.912, while Cronbach's alpha ranged from 0.741 to 0.838. The reliability indicators, such as Cronbach's alpha and composite reliability, were significantly higher than the specified cutoff point of 0.7 [62]. In order to evaluate concept validity, convergent and discriminant validity were utilized, as suggested by Hair et al. [61]. All AVE values (ranging from 0.679 to 0.831) were above 0.5, indicating that the latent concept accounted for more than 50% of the indicators' variance and established convergent validity [63].

Table 3: Result measurement model

Construct	Items	Loading	AVE	ρc	α
Sustainable brand loyalty (SBL)	SBL1	0.863	0.715	0.902	0.841
	SBL2	0.775			
	SBL3	0.852			
	SBL4	0.837			
Sustainable purchase behaviour (SPB)	SPB1	0.878	0.679	0.859	0.742
	SPB2	0.843			
	SPB3	0.735			
Brand image (BIG)	BIG1	0.746	0.717	0.847	0.731
	BIG2	0.813			
	BIG3	0.950			
	BIG4	0.915			
Sustainable marketing activity (SMA)	SMA1	0.789	0.831	0.922	0.851
	SMA2	0.883			
	SMA3	0.915			
Brand trust (BTR)	BTR1	0.746	0.805	0.912	0.848
	BTR2	0.774			
	BTR3	0.964			

The latent variable correlation matrix (Table 4) diagonally displays the square roots of AVE values. Convergent validity for all constructs was confirmed by the fact that all off-diagonal correlation values were well below the square roots of AVE values [64]. Additionally, the findings indicate that respondents had a very favourable opinion of eco-friendly clothing regarding SPB, SMA and BTR. The measurement model's findings imply enough empirical data to support the constructs' reliability and validity. Kock [65] showed that demonstrating convergent and discriminant validity does not address typical method bias and suggests a comprehensive collinearity test. All of the latent constructs' VIF values were determined to be lower than 3.3, which completely rules out model contamination by common method bias [65].

Table 4: Descriptive and discriminant validity

	Mean	SD	SBL	SPB	BI	SMA	BTR
SBL	3.840	0.867	***0.845***				
SPB	3.450	0.794	0.343	***0.824***			
BI	4.428	0.946	0.367	0.461	***0.846***		
SMA	3.450	0.794	0.343	0.435	0.452	***0.911***	
BTR	3.681	0.889	0.425	0.062	0.693	0.353	0.897

3.2 Structural model

Figure 2 illustrates the assessment of the structural model and the results of the path analysis. R^2 values versus indicated ranges of 0.19, 0.33 and 0.67, indicating weak, moderate and considerable effects, respectively, were used to test the model's predictive power [66]. The reported R^2 values were 0.51 and 0.42, justifying the moderate effect of the predictor on the outcome variable. It was decided that Stone-Geisser Q^2 would be used assess the model's prediction through bootstrapping and cross-validated redundancy. With a default threshold of $Q^2 > 0$, the Q^2 data highlighted the importance of extrinsic constructs in predicting endogenous constructs [67]. The choice to include secondary parameters in the model was supported by the finding that the Q^2 value was determined to be 0.271 using the non-parametric bootstrapping method, and the results are shown in Table 5. The predictor constructs SMA, BIG, BTR and SBL predict the outcome variable with significant path coefficients (β) ranging between 0.445 to 0.224. The variance inflation factor (VIF) ranges from 1.336 to 2.832 [68], indicating no multicollinearity issue.

Table 5: Path model assessment

Hypothesis	Relationship	*β*	t value	Decision	VIF
H1	SMA-->BIG	0.422	8.124	Accepted	1.647
H2	SMA-->BTR	0.445	8.344	Accepted	1.336
H3	SMA-->SBL	0.365	6.624	Accepted	1.684
H4	BIG-->SBL	0.224	4.221	Accepted	2.832
H5	BTR-->SBL	0.294	3.271	Accepted	1.455
H6	SBL-->SPB	0.355	5.769	Accepted	1.671

3.3 Brand image and brand trust mediation analysis

The potential mediating effect of brand image and trust on environmental marketing activity and sustainable brand loyalty was examined following the Preacher and Hayes [69] procedure. The two-step bootstrapping procedure first explores indirect and then direct effects. The two-step bootstrapping procedure was applied, as shown in Figure 2. The direct effect and variance inflation factor (VIF) can be used to examine the mediator effect. Mediation analysis results are represented in Table 6. The VIF value for both hypotheses is more than 20% of the threshold value. BIG is thus argued to have a mediation effect on the SMA-SBL relationship. Furthermore, BTR is argued to mediate the SMA-SBL relationship, and its magnitude is considered partial. These findings presented in the table support the hypothesis and confirm the mediating role of BIG and BTR in the SMA-SBL relationship.

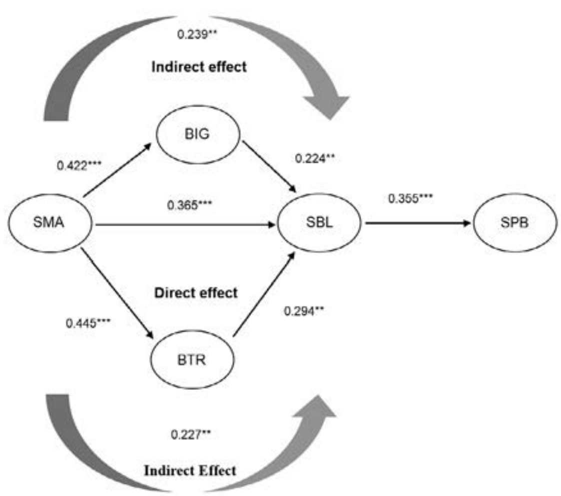

Figure 2: Structural model result

Table 6: Mediation analysis

Hypo-thesis	Effect	Path	Path coef.	Indirect effect	SD	Total effect	VAF	t value	P-value	Result
H_7	Direct effect	SMA--->SBL	0.454					12.391	0.000	Accepted
	Indirect effect	SMA--->SBL	0.365			0.554	0.239	2.029	0.020	Accepted
		SMA--->BIG	0.422	0.239	0.024	0.554	0.239	2.029	0.020	Accepted
		BIG--->SBL	0.224	0.239	0.024	0.554	0.239	2.029	0.020	Accepted
H_8	Indirect effect	SMA--->SBL	0.365			0.469	0.213	2.645	0.010	Accepted
		SMA--->BTR	0.445	0.227	0.038	0.469	0.213	2.645	0.010	Accepted
		BTR--->SBL	0.224	0.227	0.038	0.469	0.213	2.645	0.010	Accepted

4 Conclusion and implications

Sustainable marketing is essential for fast fashion brands to adopt responsible business practices throughout the product lifecycle. Fast fashion, which is characterized by quick trend turnover and rapid production cycles, has faced criticism for its negative impact on the environment and labour conditions. Sustainable marketing in this industry aims to address these issues by promoting ethical sourcing, using eco-friendly materials, reducing waste through recycling initiatives and transparent communication about sustainable efforts. Brands that embrace sustainable marketing in fast fashion demonstrate a commitment to responsible practices and meet growing consumer demand for ethically produced and eco-friendly fashion alternatives.

This study investigated how fashion apparel brands carry out sustainable marketing activities and how consumers perceive them. Its aim was to explore the relationship between sustainable marketing initiatives, brand image, brand trust, brand loyalty and sustainable purchase behaviour. This paper emphasizes the behaviour of young fashion consumers and the importance of sustainable marketing activity on sustainable brand image and brand loyalty, which in turn significantly impact sustainable purchase behaviour. By combining the concepts of brand image and brand loyalty, this study aimed to expand research on sustainable marketing and develop sustainable purchase behaviour through an increase in sustainable brand image and green brand loyalty.

The significant positive impact of sustainable marketing activity on brand image can help improve established fashion brands' reputations. Sustainable marketing plays a crucial role in creating a positive brand image by aligning a brand with consumers' values, building trust and loyalty, gaining a competitive edge, and positioning the brand as an authentic and socially responsible entity on the market. As consumer awareness of environmental and social issues increases, the significance of sustainable marketing in shaping brand image is likely to become even more prominent. This supports the idea that economic activities, such as upgrading facilities and investing in technology to create a productive retail environment, can positively impact customers' perception of brands. In other words, when the financial interests of customers and staff are aligned, it can lead to a better brand image. When a fashion brand adopts sustainable management practices, it can also demonstrate global awareness of environmental issues to customers, further improving their brand perception [70]. It can also show how brand trust, sustainable marketing activity and brand image influence consumer loyalty. Trust, sustainable marketing, and brand image positively impact brand loyalty. A fashion brand's eco-friendly marketing strategies can help create lasting connections with customers, increase market share and establish a competitive advantage over other fashion markets. By focusing on building a strong relationship based on conventional fashion markets and consumer loyalty, a brand's image, consumer satisfaction and trust will become the driving forces, producing significant synergies from sustainable marketing operations [71]. Establishing strong brand trust plays a crucial role in creating a long-lasting relationship between a brand and its customers. Customers' trust in a brand is not just based on logic but also elicits an emotional response. This emotional bond creates customer loyalty and the desire to buy the brand's products. Research indicates that brand loyalty is a market-based resource that can provide sustainable competitive advantages. Furthermore, these findings also support the correlation between sustainable marketing practices and brand loyalty. Through integrated marketing communication, marketers can engage with customers through various touchpoints, creating a chain reaction that strengthens brand trust and loyalty [72]. The study also identified three ways to strengthen sustainable brand loyalty. First, it can be done through the direct impact of sustainable marketing activity on brand loyalty. Second, it can be done through strengthening the brand image and lastly through brand trust. Brand loyalty was found to be a strong precursor for sustainable purchase behaviour. Firms can enhance their sustainable brand image and attract customers with sustainable brand loyalty by seizing every opportunity to engage in sustainable activities. Given that resources are limited, firms must allocate their resources effectively to support and invest in sustainability. By doing so, they can develop the two positive determinants of sustainable brand image and brand loyalty, encouraging customers to engage in sustainable purchase behaviour [73].

This study highlights the impact of sustainable marketing activities, including economic, social, environmental and cultural factors, on a company's brand image on the traditional fashion market. These findings can serve as the basis for further research in related theories. The study also confirms the relationship between sustainable marketing, sustainable perception, and sustainable purchase behaviour. It extends previous research by examining existing fast fashion brands. Finally, applying the research model to fast fashion brands is significant due to its relative rarity. The study contributes to existing academic literature and will aid future research regarding the traditional fashion market.

The research revealed some important practical implications. First, it shows that sustainable marketing (economic, social and environmental) can enhance a brand's image, increase customer loyalty and boost their sustainable purchase behaviour. Therefore, if a company wants to improve its customers' sustainable purchase behaviour, it should reduce scepticism regarding sustainable products, and improve its sustainable brand image and loyalty. To enhance customer satisfaction, trust and loyalty, fashion market organizations must improve their brand image. One effective way to achieve this is by engaging in sustainable marketing activities encompassing economic, social, environmental and cultural aspects. Such activities are essential for the survival of fashion market organizations in turbulent market environments. Second, companies must increase their sustainable brand image since it partially mediates the research framework. By doing so, firms can enhance their sustainable brand loyalty, which, in turn, can improve consumers' green purchase behaviour. Marketers can research traditional fashion market strategies by considering the multidimensional needs of consumers. For example, a traditional fashion market may organize a festival for local people and provide support for social, environmental and cultural events, just like any other general firm. These activities are likely to create a positive image. Third, companies must raise their consumers' green brand loyalty to encourage sustainable purchase behaviour.

This study has limitations because it only focused on one product category (fast fashion apparel) and one country (India) for its respondents. Therefore, applying the results to other product categories and countries is difficult. In the future, researchers can conduct a cross-cultural study to validate the findings and compare different product categories. As a quantitative study, the conclusions are drawn from the information gathered through a closed-ended questionnaire. However, future research could include qualitative elements to capture latent or deep human concerns that cannot be accurately measured through a questionnaire, especially when examining consumers' emotional reactions to sustainable brands and products. The research findings are valuable to academics, professionals, managers and decision-makers, and can be used as a reference for further studies.

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Research on Sustainable Textile Production: Waterless Dyeing of PET and Recycled PET Fabrics

Raziskave o trajnostni proizvodnji tekstila: brezvodno barvanje poliestrskih in recikliranih poliestrskih tkanin

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Abstract

Due to water limitations and the growing global demand for raw materials, manufacturers and consumers are seeking more environmentally friendly alternatives. Polyester, a non-biodegradable fibre derived from petroleum, can be replaced with recycled polyester (r-PET), a sustainable alternative that reduces environmental impacts through the reuse of materials. The textile finishing industry, known for its high water and energy consumption, is calling for the development of low-water-consumption technologies. One innovative approach involves waterless dyeing procedures using a supercritical carbon dioxide ($scCO_2$) medium that is particularly suitable for dyeing synthetic fibres. To assess its effectiveness, a study compared traditional water dyeing with $scCO_2$ medium dyeing on woven fabrics made from both polyester (PET) and recycled polyester (r-PET) fibres with varying weights. After conducting tests on the dyed fabrics, the data revealed that r-PET fabrics dyed using a supercritical carbon dioxide ($scCO_2$) medium appeared darker than fabrics dyed using traditional water dyeing techniques. Moreover, r-PET fabrics demonstrated better colour fastness. Notably, the K/S_{sum} values (measurement of colour intensity) of r-PET fabrics were at least as good as those of PET-based fabrics in all cases of dyeing, while the fastness values were similar for both PET and r-PET fabrics.
Keywords: supercritical carbon dioxide medium, polyester fabric, recycled polyester fabric, dyeing, sustainable

Izvleček

Zaradi omejitev pri porabi vode in naraščajočega svetovnega povpraševanja po surovinah proizvajalci in potrošniki iščejo okolju prijaznejše alternative. Biološko nerazgradljivi poliester na osnovi nafte je mogoče nadomestiti z recikliranim poliestrom (r-PET), trajnostno alternativo, ki s ponovno uporabo materialov zmanjšuje vplive na okolje. Industrija dodelave tekstila, znana po veliki porabi vode in energije, kliče po razvoju tehnologij z majhno porabo vode. Eden inovativnih pristopov vključuje postopke barvanja brez vode z uporabo superkritičnega ogljikovega dioksida ($scCO_2$), ki je posebej primeren za barvanje sintetičnih vlaken. Da bi ocenili njegovo učinkovitost, so bile tkanine iz poliestrskih (PET) in recikliranih poliestrskih (r-PET) vlaken z različno ploščinsko maso primerjalno barvane po tradicionalni metodi v vodni kopeli in s $scCO_2$. Tkanine iz r-PET, barvane v superkritičnem ogljikovem dioksidu, so

bile videti temnejše od tkanin, barvanih s tradicionalno metodo z vodo. Poleg tega so tkanine iz r-PET imele boljšo barvno obstojnost. Vrednosti K/S_{sum} (merjenje intenzivnosti barve) tkanin iz r-PET so bile vsaj tako dobre kot tiste pri tkaninah iz PET v vseh primerih barvanja, medtem ko je bila obstojnost barv pri tkaninah iz PET in r-PET podobna.
Ključne besede: superkritični medij ogljikovega dioksida, poliestrska tkanina, reciklirana poliestrska tkanina, barvanje, trajnost

1 Introduction

Two of the most important problems for the textile industry are industrial waste and water consumption [1]. Given the chemicals they contain, the water they consume and the associated drying processes, traditional water dyeing processes cause a significant amount of energy and resource consumption. The byproducts of dyeing do not degrade and cannot be recycled [2]. Dyeing processes in a supercritical medium involve a solution that can be applied to reduce this energy and resource consumption. No water is used for dyeing in supercritical environments. Preferred instead, is CO_2, which readily adapts to the supercritical medium. CO_2 is not a flammable substance, is non-toxic and is reasonably priced. It can easily reach the critical pressure (P_c = 7.38 MPa) and critical temperature (T_c = 31.1 °C) [3]. Supercritical carbon dioxide dyeing (scCO_2) has come to the fore in recent years among dyeing processes with its short dyeing time, easy recovery, high dye uptake and zero waste emission. Similar to the dyeing processes used for synthetic fibres, studies have been carried out in the dyeing of natural fibres in recent years [4, 5].

Polyester (PET) fibres have long been widely used in the textile industry due to their good mechanical properties and excellent dyeability. According to statistics, PET constitutes approximately 50% of the fibre market and growth is expected to increase in the coming periods [6]. Polyester also currently accounts for around 49% of the world's apparel, while estimates indicate that this proportion will nearly quadruple by 2030. It is thought that this increase in dependence on polyester textiles will bring environmental problems [7]. The use of recycled polyester (r-PET), as a textile raw material produced using various methods (physical or chemical), has alternative applications to virgin polyester [8, 9]. The use of recycled polyester instead of virgin polyester reduces dependence on petrochemicals, and creates advantages such as reduced energy consumption and fewer carbon dioxide emissions. It has been found that the production of r-PET yarns requires 50% less energy than virgin polyester yarns, while carbon emissions are reduced by more than 55% and water consumption is reduced by 20% [10]

Wile investigating research in literature, it was found that polyester fibre is successfully dyed in scCO_2 medium without using any water, whereas the traditional polyester dyeing process uses high amounts of water, energy and chemicals [11–15]. Supercritical carbon dioxide dyeing was reported to offer an environmentally friendly alternative with results comparable to synthetic fibre dyeing, while eliminating water consumption and reducing air pollution [16]. Polyester fabrics are dyed using disperse dyes and, in traditional dyeing processes, dispersants are used to achieve uniform dispersion and stability [17]. However, the fact that disperse dyestuffs have plasticizing and swelling properties against hydrophobic polymers, and dissolve in a scCO_2 medium without a co-solvent, make this technology important [18].

Although there are many studies on the dyeing of PET fabrics in literature, no experimental study was found in terms of comparing the traditional water dyeing method of PET and r-PET fabrics and the dyeing processes in a scCO_2 medium. In this study, traditional water dyeing and scCO_2 medium dyeing were performed to compare the dyeing performances of woven fabrics produced from PET and r-PET fibres in different weights. The colour performance, fastness values and strength values of the fabrics were compared.

2 Experimental

2.1 Materials

In the study, 100% polyester and 100% recycled polyester plain woven fabric, manufactured by Berteks A.Ş., were utilized. The warp and weft densities of the fabrics were 20 warp/cm and 20 weft/cm, respectively. Fabrics were produced from two spun yarns of Ne 30/1 (20 tex) and Ne 30/2 (20 tex). Ne 30/1 fabric weights were 63 g/m^2 and 60 g/m^2 for PET and r-PET fabrics, respectively. Ne 30/2 fabric weights were 96 g/m^2 and 99 g/m^2 for PET and r-PET fabrics, respectively. Two colours, Dianix Rubin S-2G (C.I. Disperse Red 167) and Dianix Yellow S-6G (C.I. Disperse Yellow 114) were chosen to be used in dyeing. In traditional dyeing, acetic acid ($C_2H_4O_2$), sodium hydrosulfite ($Na_2S_2O_4$), sodium hydroxide (NaOH) produced by Merck and dispersant produced by Onan Kimya were used.

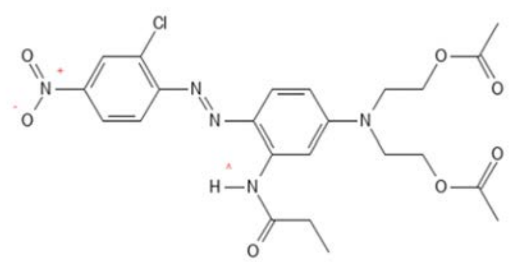

Figure 1: Molecular structure of Disperse Yellow 114

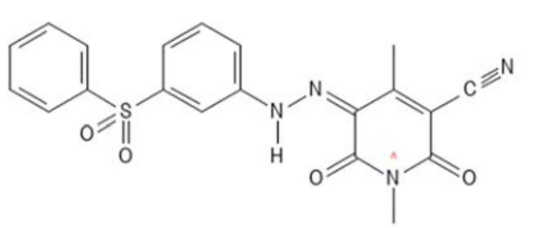

Figure 2: Molecular structure of Disperse Red 167

2.2 Traditional dyeing

Traditional dyeing was carried out at dyestuff concentrations of 0.1% and 1% in a solution ratio of 1:30, 1 ml/L dispersant and 1 ml/L acetic acid bath at 120 °C for 60 minutes [14]. After the samples were dyed, they were post-washed with 2 g/L NaOH and 2 g/L $Na_2S_2O_4$ at 80 °C (Figure 3).

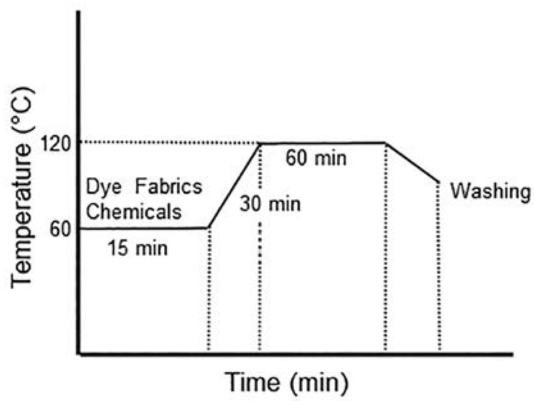

Figure 3: Dyeing diagram

2.3 Supercritical CO_2 chemical reaction and dyeing apparatus

The waterless dyeing processes of polyester fabrics were carried out in a device manufactured by DyeCoo, in a container with a volume of 290 mL. The prepared containers were kept in a Vestel SD 200 model deep freezer for cooling, and carbon dioxide was added to the container. The fabrics were wrapped in mesh and placed inside the container, and steel balls were placed inside. The prepared containers were placed in an oil bath containing polyethylene glycol in a Rapid Xiamen Model H-12 device manufactured by DyeCoo for $scCO_2$ treatment. Dye ratios of 0.1% and 1% were chosen. The experiments were carried out at 120 °C under 25 MPa pressure for 60 minutes [15, 19, 20]. The amount of CO_2 needed was calculated from http://webbook.nist.gov/chemistry/ according to the pressure and temperature values. After the process, the samples were post-washed with acetone.

2.4 Characterization of the dyed textiles

Colour strength

After dyeing, the *K/S* values of the samples were calculated from the reflectance values of the maximum absorbance (λ_{max}) at the appropriate wavelength using a Konica Minolta CM3600D spectrophotometer under illuminant D65 using a 10° standard observer. The K/S_{sum} values of the specimens (obtained by summing all *K/S* values measured at 10-nanometer intervals within the measurement wavelength range) were assessed.

Colour fastness to washing and rubbing

Washing fastness tests were carried out using TEST Laboratory Equipment 412 NB HT according to the ISO105:C06-B2S test method. Rubbing fastnesses were determined according to TS EN ISO 105-X12 standards. The results were measured in a reflectance spectrophotometer and the values were recorded.

Colour fastness to light

Light fastness tests were carried out in accordance with the ISO 105-B02:2014 standard. Light fastness refers to the ability of a dye to resist fading when exposed to light. Textile dyes are classified for light fastness on a scale from one to eight. The measurement of light fastness often involves the use of a Xenotest150S Arc device. At the end of the light fastness test, which lasted for three days (72 hours), the colour fading of the fabrics was observed and the colour values of the fabrics measured in the reflectance spectrophotometer were recorded.

FTIR (Fourier-transform infrared spectroscopy) analysis

The structure of PET and r-PET fabrics was analysed using FTIR spectroscopy (Shimadzu, IRSprit) at room temperature. Samples were scanned in the range of 400 cm^{-1} and 4000 cm^{-1}.

Tensile strength

Tensile strength tests were performed using a SHIMADZU Model AG-Xplus (Kyoto, Japan) test device in accordance with the ISO 13934-1 standard, and the results were recorded.

Scanning electron microscope (SEM) analysis

The surface characteristics of the raw fabric, and $scCO_2$-dyed, and traditionally dyed samples were studied through SEM analysis. Employing an in-house method, the images were captured at a magnification of 30× and 1000x to magnify the morphological features.

3 Results and discussion

This experimental investigation encompassed two distinct dyes, namely red and yellow, utilized at dye concentrations of 0.1% and 1%.

3.1 Dyeing with C.I. Disperse Red 167

The K/S_{sum} values related to Disperse Red 167 dyeing are presented in Figures 4 and 5. When reviewing these figures, it is clear that elevating the dyeing concentration leads to an augmentation in K/S_{sum} values for both PET and r-PET fabric types in both traditional and waterless dyeing processes. This outcome could be attributed to intensified dye molecule absorption onto the fibre surface with increasing concentration, resulting in surface layer formation. A comparison between dyeing methodologies conducted in aqueous solutions and in a $scCO_2$ medium, as depicted in Figures 4 and 5, reveals that $scCO_2$ dyeing yields more intense colours than traditional dyeing. The same dye concentration produces deeper shades when employed in $scCO_2$ dyeing. Mechanical recycling stands as the predominant approach for repurposing polyester fabrics. Remarkably, this technique does not alter the molecular structure of polyester fibres, thus rendering the dyeability of both PET and r-PET fabrics quite similar [21, 22]. When evaluating fabric components, it is clear that the colour strength of r-PET fabrics surpasses that of PET fabrics. Figure 6 illustrates visual representations of PET and r-PET fabrics subjected to Disperse Red

167 dyeing, employing both traditional and $scCO_2$ methods. The images underscore the darker hues attained for both PET and r-PET-based fabrics in the $scCO_2$ medium.

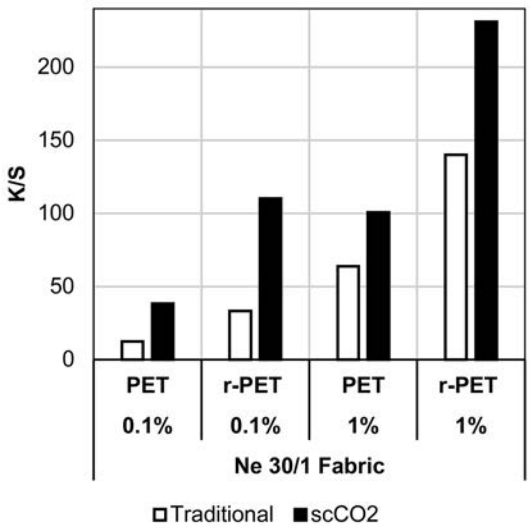

Figure 4: K/S_{sum} values of dyeing with Disperse Red 167 (Ne 30/1 Fabric)

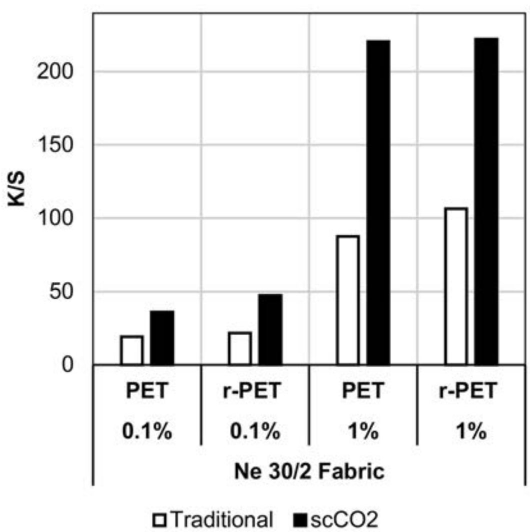

Figure 5: K/S values of dyeing with Disperse Red 167 (Ne 30/2 Fabric)

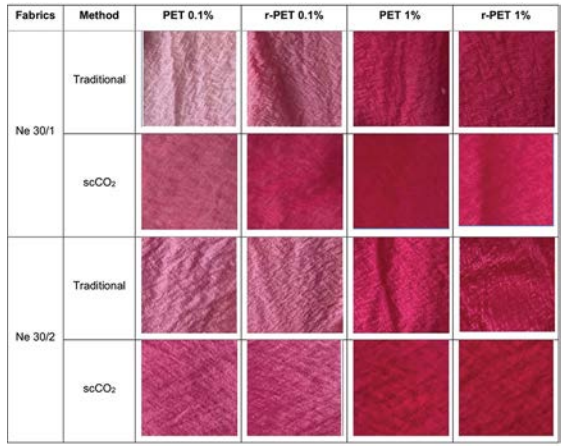

Figure 6: Images of Ne 30/1 fabrics and Ne 30/2 fabrics dyed with Disperse Red 167

Analysis of dyeing effectiveness should take into account both colour fastness and colour strength. According to Table 1 for the red dyestuff; commercially acceptable, high washing fastness values (4/5 grey scale values). In addition, there was no significant difference in washing fastness values between PET and r-PET fabrics. The observed rubbing fastness were in the range of 4–5.

The lightfastness of dyed textiles is inherently linked to both the chemical structure and physical attributes of the fibres themselves. When assessing the lightfastness data, it is evident that for the red dyestuff applied to fabrics through a $scCO_2$ medium, the fabrics dyed using traditional techniques display superior fastness characteristics. Enhanced dispersion of the dye within the fibre matrix corresponds to reduced fading effects. In this context, it can be inferred that dye molecules achieve better entrapment within the fibre structure when used in fabrics dyed through a $scCO_2$ medium [23]. Lightfastness values typically increase when the dyestuff concentration is increased [24], a trend corroborated by the findings presented below. When reviewing Table 2, no notable distinction in lightfastness values emerges between PET and r-PET fabrics.

Table 1: C.I. Washing and rubbing fastness values of fabrics dyed with Disperse Red 167

Sample		Dye concentration (%)	Method	Washing fastness						Rubbing fastness	
				WO [a]	PAC [b]	PES [c]	PA [d]	CO [e]	CA [f]	Wet	Dry
Ne 30/1 Fabrics	PET	0.1	Traditional	4–5	4–5	5	4–5	4–5	4–5	4	4–5
			$scCO_2$	4–5	4–5	5	4–5	4–5	4–5	4–5	5
	r-PET	0.1	Traditional	4–5	4	5	4–5	4–5	4–5	4–5	5
			$scCO_2$	4–5	4–5	4–5	4–5	4–5	4–5	4	4–5
	PET	1	Traditional	4	4–5	4–5	4	4–5	4	4–5	5
			$scCO_2$	4–5	4–5	4–5	4–5	4–5	4–5	4	5
	r-PET	1	Traditional	4	4–5	4–5	4	4–5	4	4–5	5
			$scCO_2$	4–5	4–5	4–5	4–5	4–5	4–5	4	5
Ne 30/2 Fabrics	PET	0.1	Traditional	4	4–5	4–5	4	4–5	4	5	4–5
			$scCO_2$	4–5	4–5	4–5	4–5	4–5	4–5	4–5	5
	r-PET	0.1	Traditional	4	4–5	5	4–5	4–5	4–5	5	4–5
			$scCO_2$	4–5	4–5	4–5	4–5	4–5	4–5	4–5	4–5
	PET	1	Traditional	3–4	4–5	4–5	4	4–5	4–5	4	5
			$scCO_2$	4–5	4–5	4–5	4–5	4–5	4	4	4–5
	r-PET	1	Traditional	4	4–5	4–5	3–4	4–5	4–5	4	5
			$scCO_2$	4	4–5	4–5	4	4–5	4	4–5	4–5

[a] wool; [b] acrylic; [c] polyester; [d] polyamide; [e] cotton ; [f] acetate

Table 2: C.I. Light fastness values of fabrics dyed with Disperse Red 167

Sample		Dye concentration (%)	Fastness	
			Traditional method	$scCO_2$ method
Ne 30/1 Fabrics	PET	0.1	1	3–4
	r-PET	0.1	1	3–4
	PET	1	3	4
	r-PET	1	3	3
Ne 30/2 Fabrics	PET	0.1	3	4
	r-PET	0.1	2–3	3–4
	PET	1	2–3	4
	r-PET	1	3	4–5

3.2 Dyeing with C.I. Disperse Yellow 114

Figures 7 and 8 illustrate the K/S_{sum} values associated with Yellow 114 dyeing. A detailed analysis of these figures reveals an increase in K/S_{sum} values for both PET and r-PET fabrics, whether subjected to traditional water dyeing or waterless dyeing, when dyeing concentrations were increased. This observation aligns with the notion that higher dye concentrations lead to increased absorption of dye molecules onto the fibre surface, culminating in the formation of a surface layer, as discussed earlier. Taking into account the dye concentration, it is evident that the colour potency of Disperse Yellow 114 dyestuff is more pronounced in $scCO_2$ dyeing processes than in traditional methods, which is in line with the trend noted for Disperse Red 167 dyestuff. It is evident from Figures 7 and 8 (although the K/S_{sum} values of r-PET fabrics conventionally dyed with Disperse Yellow 114 are generally lower than PET fabrics) that the colour strength of r-PET fabrics in dyeing in a $scCO_2$ medium was much higher than PET fabrics. This observation underscores the notable advantages of employing a $scCO_2$ medium for dyeing r-PET fabrics.

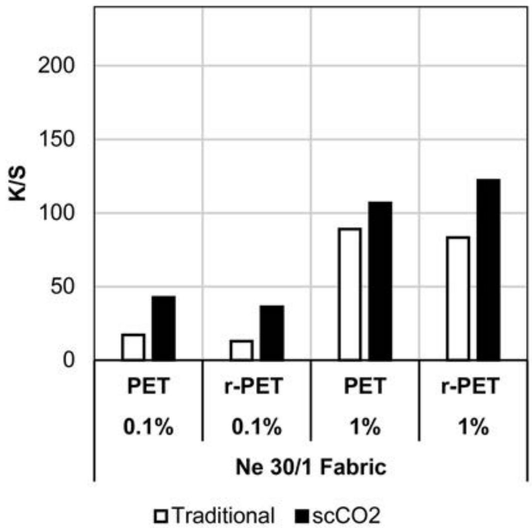

Figure 7: K/S values of dyeing with Disperse Yellow 114 (Ne 30/1 Fabric)

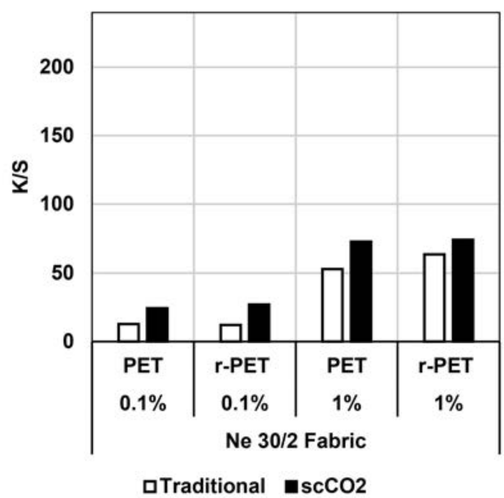

Figure 8: K/S values of dyeing with Disperse Yellow 114 (Ne 30/2 Fabric)

Shown in Figure 9 are images depicting fabrics of Ne 30/1 and Ne 30/2 varieties, both dyed with Disperse Yellow 114 dyestuff. These dyeing results align with the patterns depicted in the K/S_{sum} graphs, as apparent from the visual examination of the images.

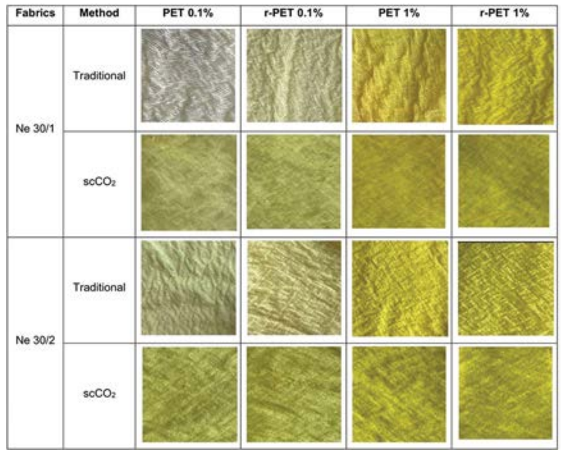

Figure 9: Images of Ne 30/1 fabric and Ne 30/2 fabric dyed with Disperse Yellow 114

The washing fastness values pertaining to dyeing carried out using Disperse Yellow 114 dyestuff are presented in Table 3 below. Notably, the obtained results exhibit washing fastness values that are commercially acceptable and of a high standard (rated as 4/5). The observed rubbing fastnesses were in the range of 4–5. Furthermore, when comparing the $scCO_2$ dyeing approach with the traditional method, it is evident that the $scCO_2$ process yields values that are either on par with or exceed the performance of the traditional method, with instances where the $scCO_2$ process even outperforms the traditional method. When the data is thoroughly analysed, it can be concluded that the fabric type, whether PET or r-PET, does not exert any discernible influence on the washing fastness values

Table 3: C.I. Washing fastness values of fabrics dyed with Disperse Yellow 114

Sample		Dye concentration (%)	Method	Washing fastness						Rubbing fastness	
				WO [a]	PAC [b]	PES [c]	PA [d]	CO [e]	CA [f]	Wet	Dry
Ne 30/1 Fabrics	PET	0.1	Traditional	4–5	4–5	5	4–5	4–5	4–5	4–5	4–5
			$scCO_2$	4–5	4–5	4–5	5	4–5	4–5	4	5
	r-PET	0.1	Traditional	4–5	4–5	5	4–5	4–5	4–5	4	4–5
			$scCO_2$	4–5	4–5	5	4–5	4–5	4–5	5	5
	PET	1	Traditional	4–5	4–5	5	4–5	4–5	4–5	4–5	4–5
			$scCO_2$	4–5	4–5	5	4–5	4–5	4–5	4–5	5
	r-PET	1	Traditional	4–5	4–5	4–5	4–5	4–5	4–5	5	5
			$scCO_2$	4–5	4–5	5	4–5	4–5	4–5	4	4–5
Ne 30/2 Fabrics	PET	0.1	Traditional	4–5	4–5	5	4–5	4–5	4	4	5
			$scCO_2$	4–5	5	4–5	4–5	4–5	4–5	4–5	4–5
	r-PET	0.1	Traditional	4–5	4–5	5	4–5	4–5	4–5	4	4
			$scCO_2$	4–5	5	5	5	4–5	4–5	4	4–5
	PET	1	Traditional	4–5	4–5	5	5	4–5	4–5	4–5	5
			$scCO_2$	4–5	5	4–5	4	5	3–4	4–5	5
	r-PET	1	Traditional	4–5	4–5	5	4–5	4–5	4–5	4–5	4–5
			$scCO_2$	4–5	5	4–5	4	5	3–4	4–5	5

[a] wool; [b] acrylic; [c] polyester; [d] polyamide; [e] cotton ; [f] acetate

The light fastness test results are given in Table 4. As previously stated, the distribution of the dyestuff into the fibre and the amount of fading are inversely proportional. When the findings were compared to the traditional method, dyeing performed using a $scCO_2$ medium showed higher light fastness values. Additionally, when the results from Table 4 light fastness values between PET and r-PET materials are compared, there is no apparent difference.

Table 4: C.I. Light fastness values of fabrics dyed with Disperse Yellow 114

Sample		Dye concentration (%)	Method	Fastness
Ne 30/1 Fabrics	PET	0.1	Traditional	1
			$scCO_2$	3–4
	r-PET	0.1	Traditional	1
			$scCO_2$	3
	PET	1	Traditional	3
			$scCO_2$	4–5
	r-PET	1	Traditional	2–3
			$scCO_2$	4–5
Ne 30/2 Fabrics	PET	0.1	Traditional	2
			$scCO_2$	3–4
	r-PET	0.1	Traditional	2
			$scCO_2$	3–4
	PET	1	Traditional	2–3
			$scCO_2$	3–4
	r-PET	1	Traditional	3
			$scCO_2$	4–5

3.3 Analysing FTIR results

The FTIR results showed that PET and r-PET fibres produced peaks that were consistent with available literature [25–27]. The 2920 cm^{-1} and 2850 cm^{-1} peaks are compatible with the asymmetric and symmetric stretching of the CH_2 groups from the ethyl chains in the fibre. The peak at 1712.7 cm^{-1} is associated with the C=O bond. While the 1408 cm^{-1} stretching vibration is attributed to the aromatic ring, it is associated with the peak CH_2 groups found at 1338.5 cm^{-1} [26]. Peaks of 1242.1 cm^{-1} and 1095.5 cm^{-1} are attributed to the stretching vibrations of the C–O groups. Finally, the peak at 721.3 cm^{-1} is usually associated with the deformation peak originating from the benzene rings in the fibre chains of the C–H groups [27].

When analysing the FTIR results (Figure 10), it is evident that both the dyeing process and the chosen dyeing medium have no discernible impact on PET and r-PET fabrics. The fact that dyeing processes in a $scCO_2$ medium do not damage the molecular structure and that the fibre structure is preserved can be understood from the results.

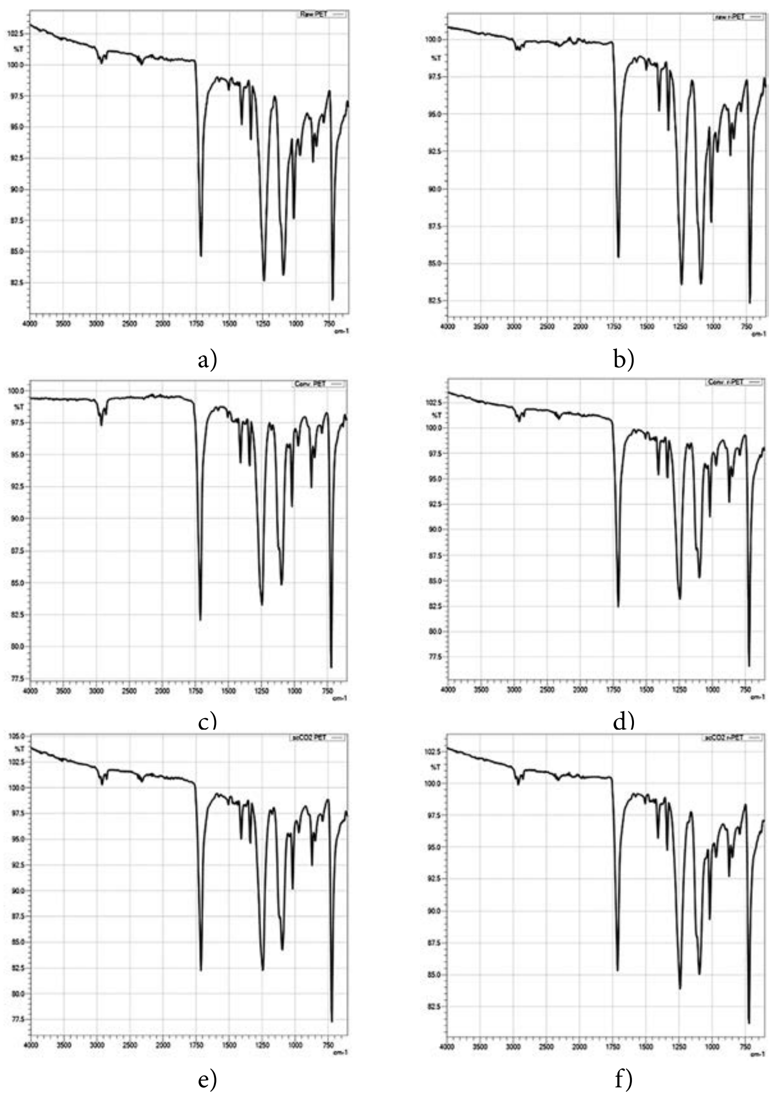

Figure 10: a) Untreated PET fabric, b) Untreated r-PET fabric, c) Traditional dyed PET fabric, d) Traditional dyed r-PET fabric, e) $ScCO_2$ dyed PET fabric, f) $scCO_2$ dyed r-PET fabric

3.4 Tensile strength analysis

The effects of dyeing and traditional dyeing processes in a supercritical medium on the tensile strength of PET and r-PET fabrics were investigated. Maximum force (N) values were measured as shown in Figures 11, 12 and 13. When the results were evaluated, it was observed that the maximum strength values of PET and r-PET fabrics are close to each other, however the strength values of PET fabrics are generally higher. This situation was comparable with studies in literature [28]. It was observed that the maximum strength values of the samples dyed in a $scCO_2$ medium, in both colours, are generally higher than the traditional water dyeing process. The thickness of the fabrics strengthens the structure of the fabric, as stated in literature, and causes the fabric to be more durable [29]. For this reason, it was observed that the maximum strength values of thick fabrics were higher for both colours. It was observed that the strength values of dyed fabrics are generally higher than the raw fabric strength values for both colours. Compared to the other samples, the samples dyed with a $scCO_2$ medium have the highest strength values.

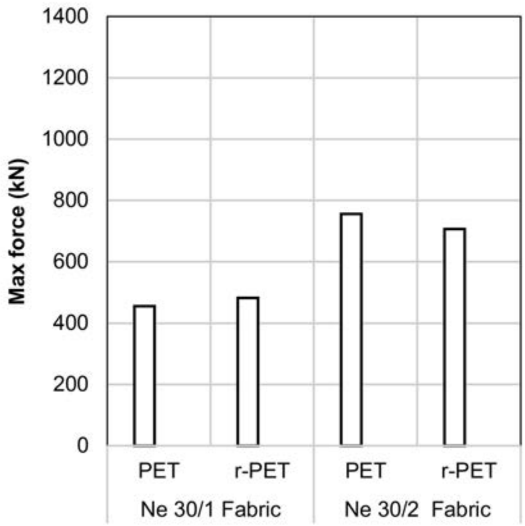

Figure 11: Strength values of raw fabrics

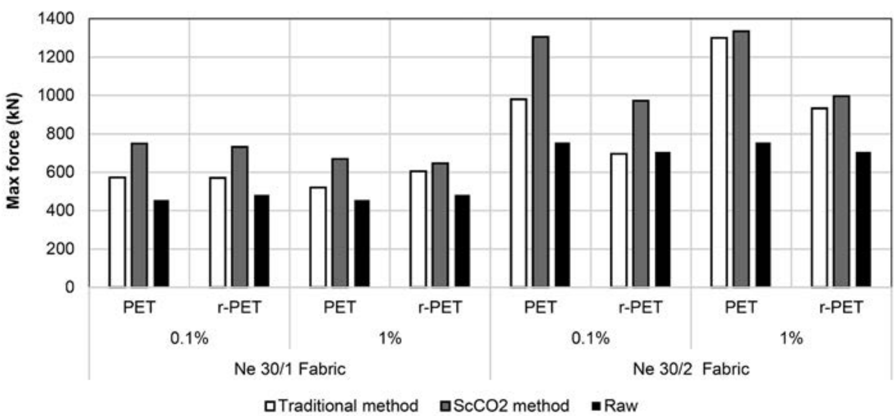

Figure 12: Maximum force values of dyeing with Disperse Red 167

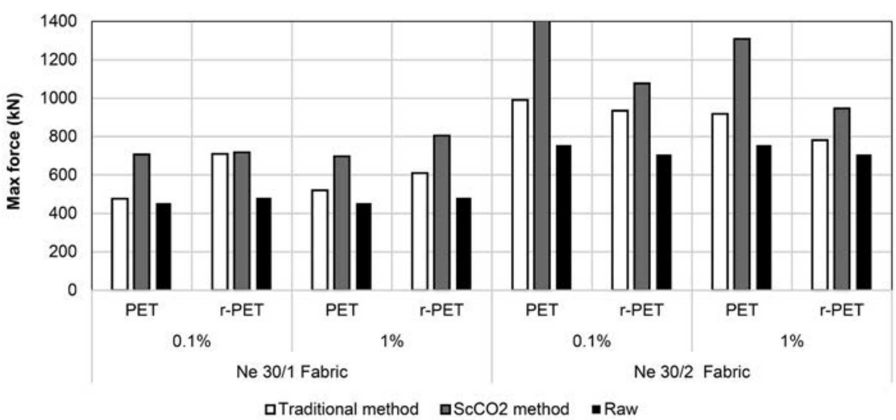

Figure 13: Maximum force values of dyeing with Disperse Yellow 114

3.5 SEM analysis

SEM images of the most intensely coloured sample are presented in Figure 14. Based on this, it can be observed that samples dyed in a $scCO_2$ medium and the raw sample exhibit similar SEM images. In contrast, the sample dyed using the traditional method displays a slightly more intricate structure, with fibres appearing more prominently on the surface. This is believed to be a result of the mechanical effects induced by the movement of the dye bath in the traditional dyeing method. It was thus presumed that samples dyed using the $scCO_2$ method cause less damage to the fibre structure.

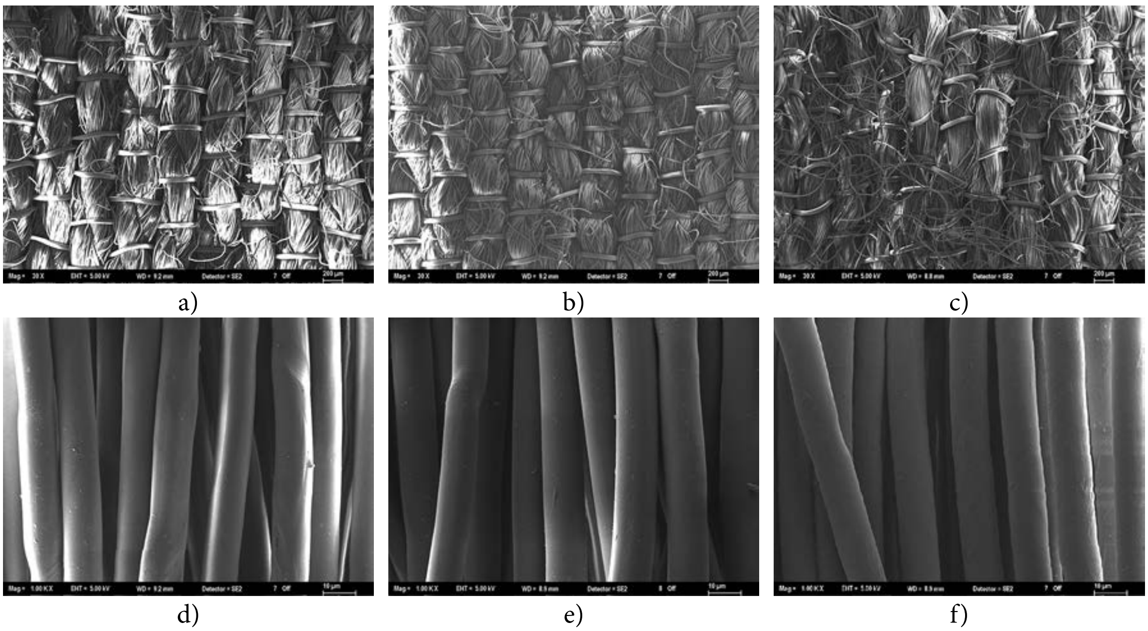

Figure 14: SEM images of samples: a & d) raw fabric; b & e) $scCO_2$ dyeing; c & f) traditional dyeing

4 Conclusion

As conventionally understood, polyester fabric is typically dyed using traditional aqueous dyeing methods at temperatures of around 130 °C, often necessitating the inclusion of auxiliary chemicals [30, 31]. Interestingly, a notable observation emerges, wherein higher K/S_{sum} values are achieved in a $scCO_2$ medium, characterized by lower dyeing temperatures and an absence of additional chemicals beyond dyestuffs. This holds true when comparing the dyeing outcomes of a $scCO_2$ medium to those of the traditional water-based dyeing method. Furthermore, the achievement of effective dyeing for r-PET fabrics in a waterless medium bears significant importance in today's context, where resource depletion underscores the significance of recycling efforts. Notably, the K/S_{sum} values attributed to r-PET fabrics generally surpass those of PET fabrics when subjected to dyeing in $scCO_2$ mediums. This is in line with existing literature where studies also provide support for this trend [21]. It was understood that the highest K/S values occurred in a $scCO_2$ medium at 120 °C and a 1% dyestuff concentration. This phenomenon can be attributed to the higher proportion of amorphous regions in r-PET fabrics compared to PET fabric, resulting in dye molecules becoming entrapped within these amorphous regions [32]. The used of less dyestuff during the $scCO_2$ dyeing process for r-PET fabrics, as opposed to PET fabrics, highlights a noteworthy advantage in terms of both conserving raw materials and energy resources. This presents a beneficial prospect for sustainability. Despite the absence of a significant divergence in terms of washing and light fastness properties between PET and r-PET fabrics, the fastness values of materials dyed in $scCO_2$ mediums are generally better than those obtained through water-based methods. FTIR analysis corroborates that $scCO_2$ dyeing processes do not compromise the molecular structure of PET and r-PET fabrics, preserving their chemical composition without alteration. Although the mechanical attributes of r-PET fabrics may slightly lag behind those of PET fabrics, the disparity is not substantial enough to impede their use. Additionally, dyeing carried out in $scCO_2$ mediums typically yields enhanced tensile strength values. In light of these findings, it is reasonable to conclude that $scCO_2$ mediums establish a more protective environment for fabrics. Based on the experimental findings, r-PET fabrics hold the potential to serve as a viable alternative to PET fabrics in waterless dyeing processes. Given the imperative to curb waste and judiciously exploit limited resources, dyeing r-PET-based fabrics in $scCO_2$ mediums is emerging as a promising and forward-looking solution.

Conflict of Interests

The authors declare that they have no conflict of interest.

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Design of a Novel Creel Conditioning System for Circular Knitting Machines

Zasnova novega sistema kondicioniranja cevčnice za krožne pletilnike

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Abstract

Maintaining a certain humidity level in yarn packages and removing fiber fly from the environment is very important for production efficiency and product quality in textile mills. Humidity has a significant impact on the quality and efficiency of fabrics, especially those made from hydrophilic fibers. The high temperature and low humidity level in the factory environment lead to lower yarn strength and higher yarn breakage. The solution is to use a centralised air conditioning system to ensure optimum temperature and humidity levels. However, air conditioning the entire factory environment is a costly approach and does not provide satisfactory production efficiency. In this study, a new creel system for circular knitting machines was designed that provides excellent conditioning of the yarn packages. With this new creel system, more efficient production and economical conditioning were achieved.
Keywords: conditioning, creel conditioning system, circular knitting machine, efficiency, fabric quality

Izvleček

Vzdrževanje določene ravni vlažnosti v navitkih preje in odstranjevanje prosto lebdečih vlaken iz okolja sta pomembna za učinkovitost proizvodnje in kakovost izdelkov v tekstilnih proizvodnih obratih. Vlažnost pomembno vpliva na kakovost in uporabne lastnosti pletiva, še zlasti če je izdelano iz prej iz hidrofilnih vlaken, pri katerih se zaradi visoke temperature in nizke vlažnosti zraka v tovarniškem okolju lahko zniža trdnost, kar vodi v večje število pretrgov. Za zagotovitev optimalne temperature in vlažnosti zraka je bil uveden sistem centralnega klimatiziranja celotnega tovarniškega okolja, kar po drugi strani pomeni velike stroške in nezadovoljivo učinkovitost proizvodnje. V tej študiji je bil zasnovan nov sistem cevčnice za krožne pletilnike, ki zagotovi odlično kondicioniranje navitkov preje ter poleg bolj ekonomičnega klimatiziranja tudi učinkovitejšo proizvodnjo pletiva.
Ključne besede: kondicioniranje, sistem za kondicioniranje cevčnice, krožni pletilnik, učinkovitost, kakovost blaga

1 Introduction

The properties of textile fibres are in many cases strongly influenced by atmospheric moisture content. Many fibres, particularly natural fibres, are hygroscopic, meaning that they can absorb water vapor from a humid atmosphere and release the water in a dry atmosphere. If sufficient time is allowed for moisture transfer, an equilibrium can be reached. Therefore, the moisture content of yarn packages is of great importance for production efficiency and product quality in textile mills. In particular, natural fibre yarns are weaker, thinner, more brittle and less elastic due to low moisture content, resulting in increased friction and susceptibility to static electricity [1, 2]. In addition, low humidity results in a hairier yarn structure and the accumulation of flies in the yarn packages and knitting machines. The problem of fly and micro-dust accumulation leads to yarn and needle breakage and a less comfortable working environment. On the other hand, if the relative humidity is higher than specified, the friction coefficient of fibres increases, and the yarns tend to stick to the surfaces as they pass through, eventually disrupting the production process. Ultimately, as the production of inferior quality fabrics increases, so does the cost of production and the waste rate, resulting in reduced efficiency [3–5]. For this reason, the development of automation systems and technologies has been identified as a key factor for manufacturers to ensure their survival on the market [4].

A review of literature shows that the impact of environmental conditioning on the production performance in textile plants is significant. Although the standard relative humidity for textile mills has been set at around 65%, relative humidity conditions should be maintained at 80–85% for the production of cotton fabrics [2]. Another study found that the ideal relative humidity for yarn production from cotton fibre is 35–65% and for fabric production from cotton yarn is 70–85%. If the relative humidity of the air is less than ideal, the moisture evaporation from the textile surface will increase. In addition, static electricity, which can occur in a textile plant with a low humidity level, can cause problems in terms of worker health, production performance and machine breakdown. By maintaining a relative humidity of around 50%, static electricity can be naturally dissipated and such problems can thus be alleviated [6]. Özdemir and Şardağ (2005) stated that with the correct steaming process, the tenacity properties of yarns are improved and curling problems are reduced, while the amount of dust and waste generated during the processes is reduced, which ultimately increases productivity in weaving and knitting processes [7]. Akarslan (2008) investigated the effect of conditioning factors such as temperature, pressure and duration on yarn strength using artificial intelligence and found that the moisture content and mechanical properties of the yarn increased with an increase in temperature and pressure [8]. In another study, Akarslan et al (2008) found that the amount of moisture in the yarn decreased to 5% due to the effect of high machine speeds and environmental conditions, and that this was unacceptable in terms of commercial and operational efficiency. Therefore, they suggested the use of post-spinning yarn conditioning to provide the required amount of moisture in the yarns and to achieve the commercial moisture level. The conditioning of yarns eliminates the internal stresses that occur during yarn production and improves the physical properties of the yarns. In addition, the mass transfer coefficient of the conditioning system has been calculated by conditioning with saturated steam in a vacuum environment and at low temperatures [9].

On the other hand, during the processing of staple yarns, short fibres are released from the yarn surface and are referred to as fibre-fly (fluff, lint). This fly generation causes several serious problems, including yarn breakage due to clogged yarn guides and feeders, fabric defects, such as holes and thick spots, and occasionally mechanical defects, such as broken needles resulting in production losses. This problem can reduce machine efficiency by 15–20%.

The fly problem has led to new techniques, such as enclosing creels, lint blower systems, covering part of the knitting machine with polyethylene sheets, etc [10]. The amount of fly from cotton yarns during weft knitting is about 45–50% at the yarn package creel, about 30% at the yarn guides, tensioning and stop motion devices, and 25% at the knitting point [11]. A closed chamber around the creel is the most reliable way of ensuring clean yarn feed, improved machine output and fewer knitting faults. The air jets in the enclosed chamber clean the bobbin tops, surfaces and the yarn reserve. These dusts are then sucked into a floor-mounted filter [12–14]. In the return-air system developed by Gupta (2011), knitting machines and creels are installed in an enclosed climatic chamber [15]. The normal or humidified air is supplied to these cabins through ducts installed in the ceiling, and the return air is exhausted through ducts installed under the floor. In this way, the air in the plant is constantly replaced with fresh air during the production process, which also helps to remove airborne fibre flies. The transferred air can be cooled or humidified to create the desired conditions. However, the system needs to be redesigned to reduce power consumption and increase efficiency.

In modern knitting factories, central air conditioning is used and the floors are covered with epoxy to create a vacuum aspiration system to collect dust from the environment and to maintain the optimum temperature and humidity in the hall. However, conditioning the entire environment of a factory is an expensive approach, both in terms of investment and management costs, and does not facilitate satisfactory production efficiency. In addition, this system is not sufficient to solve the problem of fibre fly generation and to ensure the desired humidity level in the yarn packages.

In addition, the waxing of cotton yarn, which is widely used in circular knitting machines in the textile industry, has a negative effect on the moisture absorption capacity of the yarn. Therefore, when the ambient temperature is above 30°C, the yarns gain a higher moisture absorption capability. Such a high temperature makes working conditions difficult. On the other hand, high humidity production conditions required for fabric production shorten the lifespan of the machines. Although the yarn conditioning process is used when the yarns are in the form of bobbins to eliminate these problems, this effect disappears in a short time if the environment of the knitting factory is not air-conditioned.

This study has developed an innovative creel air conditioning system for circular knitting machines to overcome the cost and application problems associated with central air conditioning systems. With this system, instead of providing the desired air conditioning throughout the entire facility, the required environmental conditions are provided in a climatic chamber that surrounds the creel where the packages are placed. This reduces the installation and running costs of a large scale conditioning system. This creel air conditioning system has been developed as an alternative to the central air conditioning systems available on the market, while reducing yarn breakage and needle breakage that occur during the production process, thus avoiding problems associated with fibre flies and fibre neps. As a result, waste and defects, which are defined as major problems for the knitting industry [16], are reduced and knitting efficiency is increased. Other important benefits of the system include reduced energy requirements and the ability to adapt to different air temperatures and humidity levels in the cabinet according to the type of yarn used in each machine.

1.1 Design of a new creel conditioning system

As part of this study, a new creel conditioning system (TPE 2015/03319: Turkish Patent Institute) capable of providing the desired moisture and temperature values was designed and installed in the creel of a Pilotelli 102 system single-jersey circular knitting machine. A technical drawing of the developed system is shown in Figure 1.

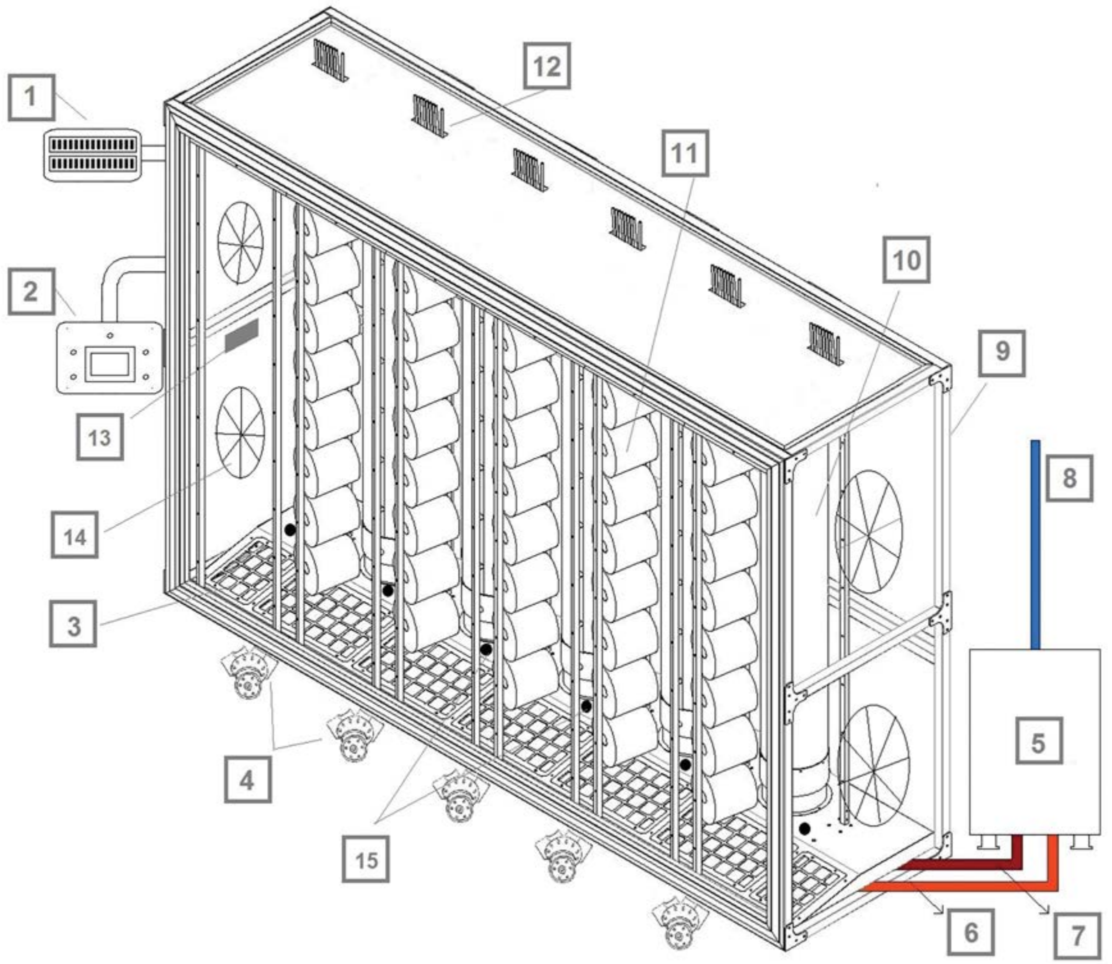

Figure 1: Technical drawing of the creel conditioning cabinet that was developed
1 – circuit breaker panel; 2 – control panel; 3 – suction device; 4 – fan motors; 5 – compact steam generator; 6 – water return; 7 – hot water pipe; 8 – cold water inlet; 9 – chamber; 10 – air ducts; 11 – creel (yarn packages); 12 – delivery pipes; 13 – temperature and humidity sensor; 14 – heaters; 15 – steam outlets

The circuit breaker panel (1) houses the main switch that ensures the operation of the system and the fuses that protect all the electrical equipment in the system. The control panel (2) regulates the operation of the fan motors (4) and the compact steam generator (5) by adjusting the temperature and humidity values in the chamber (9). Air movement in the cabinet is provided by air ducts (10) with outlets and fan motors (4) mounted under the cabinet. The air ducts oscillate left and right to ensure the homogeneous distribution of airflow in the chamber. In addition, the blown air lifts the fibre flies and dust particles that have accumulated on the yarn packages (11) in the cabin and removes them from the packages. The suction device (3) installed on the floor of the cabinet ensures that these flies and dust particles are absorbed and retained on the perforated plates of the device. The hot and humid air drawn in by the suction device is passed through the dust filter and pumped back into the air ducts. Significant energy savings are achieved by recycling the hot and humid air.

The compact steam generator shown in Figure 2 starts producing steam 15–20 minutes after the system is started. The steam produced in accordance with the temperature and humidity values entered on the control panel is transferred through the hot steam pipe (7) and released into the chamber through the steam outlets (15). When the desired temperature and humidity are reached in the chamber, the temperature and humidity sensor (13) stop producing steam. The temperature and humidity in the chamber are initially maintained by hot steam only. The heaters (14) are activated when the temperature is not sufficient. The steam condensed in the hot steam pipe, which carries the steam produced in the compact steam generator to the cabin, is returned to the steam generator through the water return (6), thus reducing the water and energy consumption of the system. If the water level in the compact steam generator drops, water is sent to the boiler through the cold water inlet (8).

Figure 2: Steam generator providing moisture to the cabinet

Each yarn in the creel is fed to the knitting zone via seprate feed pipes (12). This ensures that the yarns are transferred to the knitting machine in a closed system without coming into contact with each other and without losing the moisture content they have gained in the cabin.

Figure 3: General view of the creel conditioning cabinet that was developed (TPE 2015/03319)

2 Experimental

Cotton yarns, which are widely used on the market and are commonly associated with problems such as fibre flies, neps, and breakage, were used in the trial studies of the designed conditioning system. The properties of 100% cotton yarn and the measurement methods are given in Table 1.

Table 1: Yarn properties used in the trials

Yarn properties	Measurement method	Value
Yarn count (Ne)	EN ISO 2060	30/1
Yarn twist (T/m)	EN ISO 2061	803
Yarn hairiness (H)	ASTM D 5647	4.69
Yarn-to-metal friction coefficient (μm)	ASTM D 3108	13.70
Yarn breakage resistance (N)	EN ISO 2062	2.71
Yarn breaking elongation (%)	EN ISO 2062	19.39

Single jersey fabric structure, one of the most widely produced structures in the textile industry, was chosen for the trials. The test samples were produced on a Pilotelli single-bed circular knitting machine with a 34” diameter, 28 gauge and 102 feeders. Preliminary trials determined the optimum machine speed to be 28 rpm and the optimum loop length to be 0.3 cm/loop during the production process. In order to demonstrate the advantages of the developed system, production was primarily carried out in the existing operating environment (unconditioned). For the unconditioned ambient conditions, the mean ambient temperature (T_{mean}) was 35 °C and the mean ambient humidity (H_{mean}) was 35%.

To determine the performance of the climatic chamber, production was carried out at three different cabin temperatures (30 °C, 35 °C and 40 °C) and three different humidity levels (50%, 60% and 70%). A minimum of 25 kg of fabric was knitted under each environmental condition to enable industrial-scale sample production and efficient fabric quality control.

To determine the impact of the cabin on production performance, fabric quality and yarn waste were identified, as well as the number and causes of machine stoppages during production using the creel conditioning cabin. The fabrics produced were visually inspected on a lighted inspection table, and the type and number of fabric defects were determined. In addition, the total amount of yarn used to produce each kg of fabric was determined to calculate the yarn waste rate for each fabric.

3 Results and discussion

The effects of the developed creel conditioning system on production performance, fabric quality and yarn waste will be evaluated in separate sections.

3.1 Effects on production performance

The effect of the designed creel system on production performance was determined by identifying the reasons for and the number of stoppages during the production of single jersey fabrics at different temperature and humidity levels, both in the operating environment and in the conditioning cabin. The reason for this is that machine stoppages during fabric production can lead to fabric defects [2]. At this stage, the number of machine stoppages due to thread and needle breakages was taken into consideration. As there may be a difference between rolls of fabric, the number of stoppages was divided by the weight of each roll of fabric to give the number of stoppages per 1 kg of fabric. Equation 1 was used to determine the reduction in machine downtime using the creel conditioning system. All the values obtained are given in Table 2 and the graph of these values is shown in Figure 4.

$$MSR = \frac{(MS_{current} - MS_{cabin})}{MS_{current}} \times 100\ (\%) \tag{1}$$

Table 2: Machine stoppage and yarn waste values for fabric production in the current condition and in the new conditioning cabin

Production	Temperature (°C)	Relative humidity (%)	Yarn breakages (number/kg)	Broken needles (number/kg)	Total machine stoppages (stops/kg)	MSR (%)
Operating environment	35	35	1.0078	0.0000	1.0078	--
New conditioning cabin	30	50	0.1307	0.0000	0.1307	87
	30	60	0.2190	0.0000	0.2190	78
	30	70	0.2113	0.0000	0.2113	79
	35	50	0.1015	0.0000	0.1015	90
	35	60	0.0000	0.0000	0.0000	100
	35	70	0.0526	0.0000	0.0526	95
	40	50	0.0000	0.0000	0.0000	100
	40	60	0.0433	0.0433	0.0866	91
	40	70	0.0866	0.0433	0.1299	87

Here, MSR shows the machine stoppage rate (%); $MS_{current}$ shows the total number of machine stoppages during knitting under current conditions; and MS_{cabin} indicates the total number of machine stoppages during knitting with the new conditioning system.

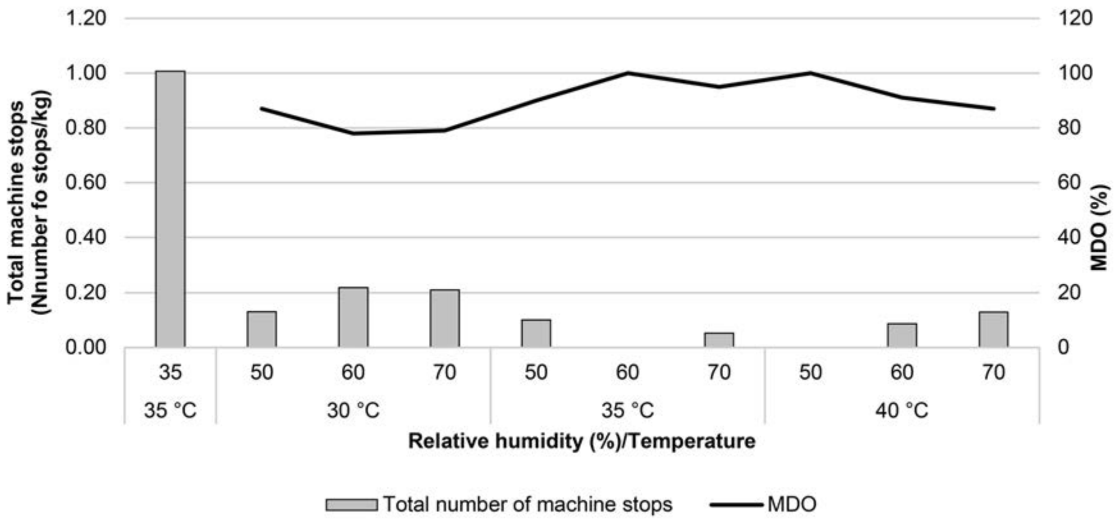

Figure 4: Machine stoppage analysis for the production of unit kg fabric under current conditions and in the new conditioning cabin

The results revealed that the use of the new creel conditioning system dramatically reduced the number of machine stoppages. It was observed that the number of machine stoppages during production with the conditioning cabin decreased by 80–100% at different temperature and humidity levels, resulting in a significant increase in production efficiency. It should be noted that there were no machine stoppages at 35 °C and 60% humidity and 40 °C and 50% humidity. As stated in the literature, as the moisture content of cotton yarns decreases, the yarns become brittle and the machine stoppages due to yarn breaks increase unless appropriate environmental conditions are ensured [6].

3.2 Effects on fabric quality

In order to determine the effect of the creel conditioning system on the fabric quality, single jersey fabrics produced at different temperature and humidity levels both in the operating environment and in the conditioning cabin were examined on a lighted inspection table and number of defects in the fabric was determined. At this stage, holes, flies, and neps, which are the most common problems encountered in the production of knitted fabrics from cotton yarn, were taken as the basis. Bearing in mind that there may be differences among the rolls of fabric, the number of defects obtained was calculated per 1 square meter of fabric. Equation 2 was used to calculate the defect change rate, which defines the fabric quality using of the new conditioning system.

$$DCR = \frac{TDcurrent - TDcontione}{TDcurrent} x100 \tag{2}$$

Table 3: Number of defects in fabrics produced under current conditions and in the new conditioning cabin

Production	Temperature (°C)	Relative humidity (%)	Holes (fault/m²)	Flies (fault/m²)	Neps (fault/m²)	Total number of fabric faults (number/m²)	Defect change rate (%)
Operating environment	35	35	0.0095	0.0953	0.1144	0.219	-
New conditioning cabin	30	50	0.0080	0.1356	0.1595	0.303	-38
		60	0.0180	0.1347	0.2334	0.386	-76
		70	0.0000	0.1246	0.2410	0.366	-67
	35	50	0.0125	0.0377	0.1991	0.258	-18
		60	0.0000	0.0227	0.0512	0.074	66
		70	0.0112	0.0279	0.0725	0.112	48
	40	50	0.0000	0.0477	0.0358	0.084	61
		60	0.0055	0.0709	0.0600	0.136	38
		70	0.0000	0.0550	0.0495	0.105	52

Where DCR is the defect change rate, $TD_{current}$ is the total number of defects in the knitted fabric under current conditions and $TD_{conditioned}$ is the total number of defects in the knitted fabric with the new conditioning cabin. The obtained values are presented in Table 3 and the graph of these values is shown in Figure 5.

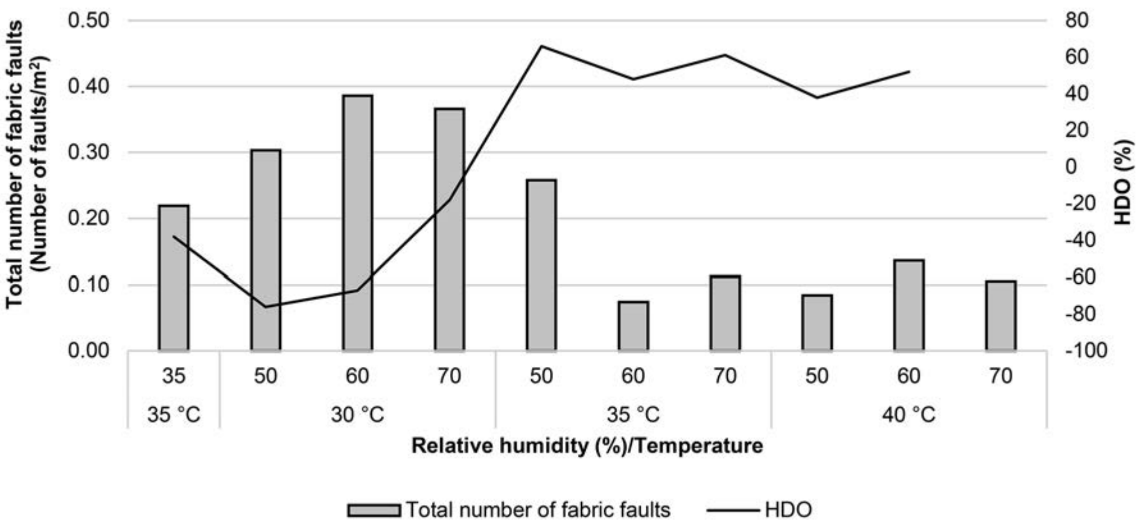

Figure 5: Analysis of defects in 1 square metre of fabric produced under current conditions and in the new conditioning cabin

The results presented in Table 2 and Figure 3 show that the number of defects detected in the fabric is higher than that detected in the knitted fabric when the temperature is 30 °C during production with the conditioning cabin, regardless of the humidity values. It was observed that the number of fabric defects decreases as the temperature and humidity in the conditioning cabin increase. In view of these results, it was determined that the optimum working conditions for cotton yarns in terms of fabric quality are 35 °C temperature and 60% humidity.

3.3 Effects on yarn waste

The yarn waste rate for each fabric roll was calculated to determine the effect of the creel conditioning system on the amount of yarn waste using equation 3 for fabrics produced at different temperature and humidity levels, both in the operating environment and in the new conditioning cabin.

$$YWR = \frac{TYcurrent}{TYconditioned} x100 \quad (3)$$

where YWR is the yarn waste ratio (%), $TY_{current}$ represents the total amount of yarn used (kg) and $TY_{conditioned}$ is the total fabric weight (kg). The values obtained are presented in Table 4.

Table 4: Number of defects in fabrics produced under current conditions and in the conditioned environment

Production	Temperature (°C)	Relative humidity (%)	Yarn waste rate (%)
Operating environment	35	35	1.34
New conditioning cabin	30	50	0.34
		60	0.34
		70	0.34
	35	50	0.00
		60	0.00
		70	0.00
	40	50	0.75
		60	0.75
		70	0.75

The results obtained indicate that the amount of yarn waste that occurred during production with the new conditioning cabin is considerably lower than the amount of waste observed in the knitted fabric under the current environmental conditions. Based on these results, it was established that the optimum working conditions in terms of fabric quality at a temperature of 35 °C, regardless of humidity.

4 Conclusion

In order to demonstrate the benefits of the developed creel system, single jersey samples were knitted using cotton yarns, which are widely used in the circular knitting industry and which, due to their hydrophilic nature, are most affected by the climatic conditions of the environment. By reducing the number of yarn breaks during fabric production as a result of creel conditioning, yarn waste and machine stoppages were significantly reduced, resulting in an increase in efficiency and production capacity. It was determined that when the temperature of the conditioning cabinet is 35–40 °C, there is a significant reduction in fabric defects caused by yarn breaks and flies during fabric production. As the fly problem is reduced by working in an optimal climate-controlled environment, the negative factors that threaten both fabric quality and employees' health are prevented. It was established that the quality of the climatic chamber, where optimum efficiency and quality are achieved for the yarn and machine parameters studied, is a temperature of 35 °C and a humidity rate of 60%.

The creel air conditioning system developed in this study can provide air conditioning in the machines where production takes place, under conditions suitable for the raw materials used in production, instead of air conditioning the entire factory during the production of knitted fabrics. By conditioning only the creel cabin and not the entire operating environment, it offers significant advantages in terms of lower investment costs, less energy requirements, and the ability to ensure air temperature and humidity values suitable for all yarn types, thus ensuring more efficient knitted fabric production. It is possible to use the system on different knitting machines and for different yarn materials and knitting structures. Another advantage of this system is that it reduces energy consumption by recycling the hot air and humidity within the system.

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Study on Motives Underlying the Buying of Fast Fashion in India Despite Associated Sustainability Issues

Raziskava motivov za nakupovanje hitre mode v Indiji kljub problemom s trajnostjo

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Abstract

The purpose of this study was to identify motivational factors for consumers in making a purchase decision for a fast fashion product. The term fast fashion is used to refer to cheaper replicas of luxury fashion trends. Apart from impacting the environment adversely, fast fashion has several other issues as well. Fast fashion has many sustainability issues but its demand is growing at a tremendous pace. The motives for the preference for fast fashion were explored in this study. Both primary and secondary data were used to conduct this research. The primary data was collected for this study via questionnaire. All the factors are rated on the 7-point Likert scale. Furthermore, the laddering technique of interviewing was employed to investigate the underlying values. The study revealed that "creating self-identity" is the most influencing motive for consumers in making a purchase decision for a fast fashion product, while "showing dominance" is the least influencing motive for consumers in making a purchase decision for a fast fashion product. This study offers insight into the factors influencing buying decisions for a fast fashion product. This research can help address the issue of sustainability in the fashion industry. These findings can also be used to promote sustainable fashion.
Keywords: sustainable fashion, fast fashion, fashion buying motives, consumer buying decision, sustainability issues, slow fashion

Izvleček

Namen te raziskave je ugotoviti motive potrošnikov pri odločanju o nakupu izdelkov hitre mode. Izraz hitra moda se uporablja za cenejše replike luksuznih modnih trendov. Hitra moda prinaša poleg škodljivega vpliva na okolje tudi številne druge težave. Čeprav je povezana z različnimi trajnostnimi problemi, povpraševanje po njej izjemno hitro raste. Za izvedbo raziskave so bili uporabljeni primarni in sekundarni podatki, pri čemer so bili primarni podatki zbrani z vprašalnikom. Vsi dejavniki so bili ocenjeni s pomočjo sedemstopenjske Likertove lestvice. Za raziskavo osnovnih vrednot je bila uporabljena tehnika anketiranja s hierarhičnim razvrščanjem. Študija razkriva, da je »ustvarjanje lastne identitete« odločilen motiv za potrošnike pri nakupu izdelka hitre mode, medtem ko je

»izkazovanje prevlade« najmanj vpliven motiv. Študija razkriva pomembne dejavnike za nakupno odločitev za izdelek hitre mode in lahko koristi pri reševanju vprašanj trajnosti v modni industriji. Te ugotovitve lahko uporabimo tudi za promocijo trajnostne mode.
Ključne besede: trajnostna moda, hitra moda, motivi modnih nakupov, potrošniška nakupna odločitev, vprašanja trajnosti, počasna moda

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1 Introduction

The term "fast fashion" is used to refer to cheaper replicas of luxury fashion trends. Fast fashion is characterized by frequent consumption, short product lifecycles and cheap production practices. Fast fashion helps in satisfying the deep desire for high-end fashion among its consumers. Generally, these consumers are from a young age group. They opt for fast fashion to satisfy these needs, even if it has unsustainable impacts on society and the environment [1]. Sustainability can be defined in many ways. One definition is "sustainability is about much more than our relationship with the environment; it's about our relationship with ourselves, our communities, and our institutions" [2]. Along with the traditional belief of economic, environmental and social sustainability, the linking of sustainable manufacturing and consumption with the capacity to change positive design practices is offered by transformative and co-operative design actions [3]. Ethical behaviour and sustainability have become important in the fashion industry in last two decades [1]. Fast fashion brands have also realised that highly profitable, less expensive and trendy fast fashion is accompanied by ethical issues [4]. There are many sustainability issues associated with the manufacturing of fast fashion, such as the farming of cotton, which requires a huge quantity of water, the release of untreated dyes and chemicals into domestic water resources, a poor working environment and low wages for the workers [5]. Fast fashion is growing at a tremendous pace, despite the amount of emphasis placed on green and sustainable practices everywhere. Consumers seldom buy according to their ethical or environmental attitudes. This deviation of consumer behaviour from their attitudes is still not explained and understood completely [6]. Consumers seldom make rational buying decisions and their decisions rarely reflect their moral values. Consumers generally give more weight to the price of the product than to sustainability [6]. Consumers throw away large quantities of clothing every year as waste that contributes to landfills. Garments that cannot be sold on the market create solid waste blocking the flow of rivers, while clogging parks and greenways [7]. Fast fashion has led consumers to see garments as disposable. This creates more environmental and health hazards in underdeveloped and developing countries than the lack proper waste disposal systems [8].

Consumers buy clothes for several reasons. People use their clothes to convey the self-image desired by society [9]. The fashion used by consumers reflects their beliefs and attitudes. It also reflects their knowledge about fashion and clothing. Clothes also depict the interest of the wearer in fashion and garments [10]. This research explored how consumers perceive fast fashion. Moreover, the factors behind their preference for fast fashion at the cost of sustainability were also studied. The findings of this research can help address the issue of sustainability in the fashion industry. These findings can also be used to promote the sustainable fashion.

1.1 Factors in the growth of fast fashion

Fast fashion is growing at a tremendous pace. Mass production was the key to success in the fashion industry until four decades back. Styles were remained standardized, as factories were restricted to fewer design options [11]. Consumers were barely conscious of fashion and style at that time, and thus preferred very basic apparel [12]. Fashion products have a shorter lifecycle. Fashion products go through four phases during their life: launch, growth and public acceptance, mass conformity, and decline/obsolescence. In the early era of the clothing industry, fashion calendars were made on the basis of fashion shows, trade fairs and fabric exhibitions. The calendars consisted of a general pattern of seasonal development for spring/summer or autumn/winter collections. The changing business environment has transformed the global fashion industry. Competition in the fashion apparel industry had increased since the end of 1980s. This occurred as many large retailers started to dominate the industry [13]. These fashion brands developed an infrastructure with the aim of providing merchandise at low prices in less time. This helped retailers and manufacturers to maintain low costs. Hereafter, a trend emerged to source manufacturing processes to offshore countries and places with cheaper labour [14]. Although outsourcing helped to reduce costs, it increased lead times. Various additional costs also came into existence, such as the costs of forced markdowns, maintaining inventories and obsolescence. These costs outweighed the saving in the labour costs of outsourcing [15]. An improving atmosphere for fashion-oriented clothing raised the markdowns required to clear stock at the end of seasons. This has been confirmed by further studies that profits cannot be earned in fashion business through mass production [16].

A sudden rise in fashionable apparel products was observed in the early 1990s. This occurred as consumers became more concerned about fashion, and the demand for simple and classical apparel declined [17]. However, retailers began to focus upon the expansion of their collections with new and innovative products in the early 1990s [13]. Retailers also began to focus on a quick response to the demands of consumers for the latest fashion trends [18]. To sustain and grow their business, fashion and apparels retailers changed their business models to buyer-driven rather than product-driven, and allied with suppliers on various markets and established their own unique brands. This resulted in an increase in profits. Fashion products have very short lifecycles, while consumer demand is also volatile. Fashion retailers must thus make fashion merchandise available to their consumers before their competitors do. The more rapid inclusion of customer preferences in design and product development raises profit margins for retailers [15]. Fashion shows and fashion runways, which were initially accessible by buyers, designers and fashion managers, represent the inspiration for the fashion and apparel industry. Since the beginning of 21st century, catwalks and fashion shows have been available to the public through fashion magazines or the web. This demystified the fashion development process [19]. Aware consumers are exposed to the latest designs and fashion in real time. Retailers such as Zara, Mango and H&M started to offer new collections in two to five weeks in order to attract these consumers [13]. Forecasting is a very cumbersome process. It can be very difficult to predict future fashion and bring it to the market in this reduced amount of time. To overcome this issue, the fashion industry began to utilize real-time data to understand consumers' needs [20]. Fast fashion retailers were forced to adapt and evolve their internal processes to cope with the dynamic atmosphere created by fast fashion products [21]. To bring a product to points of sale in timely manner, all key players in the fashion supply chain had to work in sequence. There was additional time loss due to ineffective communications and reworks. A fashion product could not be sold in the required season due to all these factors. These challenges have led the fashion industry to restructure in order to improve its performance [22]. Quick responses and just-in-time techniques were employed to respond quickly to consumer demands at low costs [12].

1.2 Fast fashion and sustainability issues

The United States Environmental Protection Agency has defined environmental justice as "fair treatment and meaningful involvement of all people regardless of race, colour national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations and policies" [23]. There are many sustainability issues associated with the manufacturing of fast fashion. The global fast fashion industry's supply chain begins with textile manufacturing where both man-made and natural fibres are produced. The majority of clothing comprises polyester or cotton. Polyester is made from oil and the production of cotton requires a large amount of water. Many pesticides are also used for growing cotton. Textile processes, such as dyeing, finishing and printing, adds to hazards because wastewaters are generally discharged into domestic water resources without proper treatment. This results in the addition of heavy metals and many other toxic materials to water resources, with a negative impact on the health of local residents and animals [24]. Post-textile manufacturing, the next phase in the fast fashion supply chain, is garment manufacturing. Garment production employs more than 40 million workers across the globe [25]. Apart from impacting the environment adversely, fast fashion has several other issues as well. Some 90% of global clothing is made in low and medium income countries. Occupational hazards and safety norms are generally not enforced in these countries because of weak organizational management and the political infrastructure [26]. This has resulted in various occupational hazards, such as respiratory problems from poor synthetic air particles and cotton dust due to bad ventilation and musculoskeletal issues due to repetitive movements. Reported health issues include lung cancer, damaged endocrine function, overuse injuries, accidental injuries and death [27]. There have been many disasters due to poor working conditions, such as the factory collapse in 2013 that killed more than 1,100 Bangladeshi workers [28]. Despite such tragedies, working conditions have not improved for workers in poor countries. The apparel industries have shifted the occupational and environmental loads related to fast fashion from developed and resourceful countries to under-developed/ developing countries [5]. Fast fashion has led consumers to see garments as disposable. Consumers throw away large quantities of clothing every year as waste that contributes to landfills [7]. Garments that cannot be sold on the market create solid waste that blocks the flow of rivers, and clogs parks and greenways. This creates more environmental and health hazards in underdeveloped and developing countries that lack proper waste disposal systems. Moreover, consumers have very limited or no knowledge of the environmental impact of the fast fashion clothing. To promote sustainability in the industry, consumers must be educated about the issues [8].

1.3 Challenges for sustainable fashion brands

Sustainable fashion is an approach to satisfying consumer needs for fashion without harming the environment and society. Combining sustainability and fashion was previously considered a paradox. In recent times, however, the cooperation of these two is much anticipated, but it is difficult to define sustainable development, as the meaning of sustainability is constantly evolving. This makes it even more difficult to define sustainable fashion. Fashion is supposed to be an innovative field, but it is way behind in terms of sustainability. Fashion also lags far behind in the field of research. The research publications about fashion and sustainability that are most relevant are from the 21st century. Because fashion is continuously changing, it is very important to think wisely so that these changes can be directed towards sustainable fashion. Though the participation of global fashion brands is not very encouraging, there are many small-scale and domestic brands that are striving to make sustainability a prominent feature of the fashion industry [29].

Consumers want sustainable fashion now. This may be due to awareness about the deteriorating environment. Consumers prefer to spend on environmentally friendly fashion products. Fashion in its present form, especially fast fashion, is unsustainable. Despite the willingness of all stakeholders to pursue sustainable fashion, actual progress in this direction is not convincing. The Following constraints can be attributed to blocking the path to sustainable fashion.

1.3.1 Lack of understanding of sustainable products

One of the prime reasons for the slow growth of sustainable fashion is ambiguity and confusion in the understanding of sustainable products amongst all the stakeholders. For instance, natural fibres are considered more environmentally friendly than synthetic fibres, as natural fibres are biodegradable. However, there are other sustainability issues associated with the production of natural fibres, such as water consumption and chemical discharge. Consumers are thus supposed to pick the product with less sustainability issues. This makes the choice harder, as products that do not harm the environment and society do not exist. There is no universal scale to define a sustainable product. Industry would certainly prefer sustainable changes that are economical to implement. In some cases, where all the choices are non-sustainable, a cost effective alternative will always be preferred by all the stakeholders [30].

1.3.2 No scalable standard for supply chains of sustainable fashion

Supply chains are not different for sustainable fashion brands and non-sustainable fashion brands. Profitability is always given more weight when running a business. Every brand must select from existing alternatives of supply chain partners to distribute its products. This challenge becomes even more difficult with the increased scale of business. If a brand wants to opt for a completely sustainable supply chain, it would require tremendous efforts. It must assess all internal processes and would also require sustained cooperation from all supply chain partners. Thus, the non-availability of an existing supply chain model to scale up the business for sustainable fashion products is a great hindrance in the growth of sustainable fashion brands [30].

1.3.3 Investment constraints

It requires investment to replace an existing infrastructure and machines. For instance, to incorporate a new dyeing machine which consume less water than the existing will require scrapping the old machine and buying of new machine. If the quality of product is same in both cases, this will add unnecessary cost to the business but price for the product cannot be increased due to competitive market. Many business brands may not have investment required for sustainable processes available with them. Also, majority of fashion brands are not able to control their suppliers for changing their processes to sustainable ones. Performing all the operations of the supply chain is also not a feasible alternative due to huge capital investment involved and underutilization of resources by a brand itself [30].

1.3.4 Technological constraints

Fashion brands must rely on existing manufacturing technology available with their suppliers. They cannot force suppliers to use a particular machine or technology. They bargain for the price, time and quality only. As manufactures cater to many buyers and have very calculated profit margins, it becomes very difficult for fashion brands to persuade them to change the existing machines and technology [30].

1.3.5 Cultural constraints

The pace of change an existing culture is always slow. This can be attributed to many factors. The major reason is the reluctance of people to accept changes, as they become part of the existing culture. The competition in the fashion apparel industry increased when many major retailers began to dominate the industry. These fashion brands developed an infrastructure with the aim of providing merchandise at low prices in less time. This helped retailers and manufacturers to maintain low costs. Hereafter, a culture of outsourcing manufacturing processes developed. In the present scenario, fashion brands function based on the outsourcing model for production activities to achieve a balance of cost, time and quality [30].

1.3.6 Short product lifecycle

The product lifecycles of fashion products has decreased dramatically. All activities, such as product development, transportation, manufacturing and the consumption of fashion goods, are happening at a faster pace. This can be attributed to fast fashion. As catwalks and fashion shows became available to the public through fashion magazines or the web, consumers have become exposed to the latest designs and fashion in real time. Retailers such as Zara, Mango and H&M offer new collections in two to five weeks in order to attract consumers. It can be very difficult to predict future fashion and bring it to the market in this reduced amount of time less time. Fast fashion retailers were forced to adapt and evolve their internal processes to cope with the dynamic atmosphere created by fast fashion products. To bring a product to points of sale in a timely manner, all the key players in the fashion supply chain had to work in sequence. These challenges led the fashion industry to restructure to improve its performance. Quick responses and just-in-time techniques are employed to respond quickly to consumer demands at low costs. However, this has resulted in an increase in transportation costs. There is increasing demand for road and air transportation. These modes of transportation create a greater carbon footprint than sea or rail transportation. Fashion brands are forced to choose less environment friendly modes of transportation, or they will lose customers who prefer faster deliveries [30].

1.3.7 Greenwashing

Greenwashing is a process adopted by companies to project themselves as more eco-friendly than they actually are. This is a very unfortunate but prevalent practice. It discourages fashion brands and other supply chain players from putting real efforts into improving the sustainability of their products and operations [30].

1.4 Motives for buying fast fashion

As economic goods, fast fashion goods are bound by the basic laws of economics. Demand for fast fashion goods depends on the price and income. A higher price for a product leads to lower demand, while higher income creates higher demand. However, economic perspective does not recognize the emotional aspect of consumer buying behaviour. Humans are unable to make decisions in a rational way like machines do. There will always be a difference between the buying decision predicted by economics and buying decision actually made. Social, emotional and cognitive needs must thus be taken into considerations to understand fast fashion buying behaviour. According to Maslow, different product consumptions are related to different types of needs. For instance, clothing is related to physiological needs, while fashion is related to love, belongingness and esteem needs. From an anthropological perspective, consumer behaviour is a cultural phenomenon. It is considered to be an unnatural culture that pushes consumers to consume in a particular way. Thus, a consumer buying decision is a complex process. Factors affecting consumer buying decisions are price, self-image, perceived risks, additional cost of buying, hedonism and social factors [31].

Consumers buy clothes for several reasons. People use their clothes to convey the self-image desired by society [9]. The fashion used by consumers reflects their beliefs and attitudes. It also reflects their knowledge about fashion and clothing. Clothes also depict the interest of the wearer in fashion and garments. A study on kids' wear brands showed that over 85% of consumers considered the fit of the garments a very important aspect for satisfaction [10]. The buying decisions of fashion consumers are found to be affected by uniqueness, self-concept, brand image, word of mouth and perceived quality [32]. Consumers seldom buy according to their ethical or environmental attitudes. This deviation of consumer behaviour from their attitudes is still not explained and understood completely. Consumers seldom make their buying decision in a rational way and, for the most part, their decisions hardly reflect their moral values. Consumers generally give more importance to the price of the product than to sustainability. It has been cited by many researchers that sustainability alone cannot be sufficient motivation for consumers to change their purchase behaviour. Three different reasons could be attributed to this. One is the complex nature of fashion sustainability. The second is the diversity of consumers' ethical spheres. The third is that fashion buying does not come under an altruistic act. Sustainability is found to be of low significance for consumers when making a buying decision [6].

It can thus be concluded that apart from the economic factors that influence the fast fashion buying, there are also emotional and social factors. The emotional and social factors affecting fast fashion buying decision can be summed up as being trendy, earning respect, appreciation and praise, showing dominance, blending in with social groups and creating self-identity. Research has been conducted to identify the impact of these factors on fast fashion buying. The extent of the impact was studied to understand the dominating factors for buying fast fashion.

3 Methodology

Exponential non-discriminative snowball sampling was employed to collect data from students aged 17–22 years from various universities in India. This sampling method is primarily used in research for unknown and rare population. It is used for situations where it is hard to select respondents for a sample. It is a very fast, cost effective and convenient method of sampling for such studies. A total 396 responses were received. Questionnaires were distributed using e-mail and completed questionnaires were received in the same way. The required sample size, at a confidence level of 95% and margin of error 5% for a population size exceeding 2,500, is 384 (research advisors, 2006). Fifty respondents selected randomly were called for a telephone interview to further investigate the underlying values for fast fashion buying. Both primary as well as secondary data were used to conduct this research. The primary data was collected for this study via questionnaire. After studying literature relevant to emotional factors influencing fast fashion buying, the identified prominent factors were being trendy, earning respect, appreciation and praise, showing dominance, blending in with social group and creating a self-identity. All the factors were rated on the 7-point Likert scale. The respondents were asked to rate the importance of various factors in making a purchase decision for a fast fashion product. A score of 1 for least important and a score of 7 for most important were assigned. A pilot test was conducted before the actual data collection to discover the face validity of the measurement scale. The pretest of the questionnaire proved that all the measurement factors were relevant and sufficient in terms of coverage. The value of Cronbach's alpha (Table 1) was found to be 0.74. A multiple-question Likert scale with a Cronbach's alpha value greater than 0.7 is considered acceptable. The face validity of the measurement scale used for the study was thus established. A total 396 responses were received from various participants from different universities in India. Responses received were sufficient for this study, as the required sample was 386. Furthermore, the laddering technique of interviewing was employed to investigate the underlying values. Telephone interviews were conducted to assess the underlying reason for the preference of a particular factor over others.

Table 1: Reliability test for multiple-question Likert scale

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum S^2 y}{S^2 x}\right)$$

Variables	Description	Values	Internal consistency
K	number of items	50	Acceptable
S^2y	sum of item variance	17.24	
S^2x	variance of total score	63.21	
α	Cronbach's alpha	0.74	

Questionnaire for buying fast fashion (closed-ended)
Fast fashion describes low-priced but stylish clothing that moves quickly from design to retail stores to meet trends, with new collections being introduced continuously. Brands like Zara, H&M, UNIQLO, GAP and Topshop are from the fast fashion field.

* *Required*
1) Name *
2) E-mail
3) Mobile number
4) Age *
5) Gender *
6) City
7) How important is "being trendy" for you when buying fast fashion products? *
8) How important is "gaining respect from others" for you when buying fast fashion products? *
9) How important are "appreciation and praise" for you when buying fast fashion products? *
10) How important is "dominating in a peer group" for you when buying fast fashion products? *
11) How important is "blending with a social group" for you when buying fast fashion products? *
12) How important is "creating a self-identity" for you when buying fast fashion products? *

The questions 7–12 could be answered on a scale as follows:
Not important at all ○1 ○2 ○3 ○4 ○5 ○6 ○7 extremely important

Questionnaire for buying fast fashion products (telephone interview)
1) Why do you buy fast fashion products?
2) Why is that important to you?
3) Why is that relevant to you?
4) Are you aware of sustainability issues, i.e. social and environmental hazards caused by fast fashion products?
5) If yes, why don't you switch to sustainable fashion products/brands?

Questions in the questionnaire regarding motive to buy fast fashion products
1) How important is "being trendy" for you when buying fast fashion products?
2) How important is "gaining respect from others" for you when buying fast fashion products?
3) How important is "appreciation and praise" for you when buying fast fashion products?
4) How important is "dominating in a peer group" for you when buying fast fashion products?
5) How important is "blending with a social group" for you when buying fast fashion products?
6) How important is "creating a self-identity" for you when buying fast fashion products?

3 Results and discussion

The respondents rated the importance of various factors in making a purchase decision for a fast fashion product (Table 2). They gave 7 for the most important factor and 1 for the least important factor. Many of the respondents gave the same ratings to more than one factor. There was thus an overlap in the data. A total of 92 (23%) respondents rated "being trendy" as the most important factor in making a purchase decision for a fast fashion product, 127 (32%) respondents rated "earning respect" as the most important factor in making a purchase decision for a fast fashion product, 108 (27%) respondents rated "appreciation and praise" as the most important factor in making a purchase decision for a fast fashion product, 67 (17%) respondents rated "showing dominance" as the most important factor in making a purchase decision for a fast fashion product, 70 (18%) respondents rated "blending with a social group" as the most important factor in making a purchase decision for a fast fashion product and 166 (42%) respondents rated "creating a self-identity" as the most important factor in making a purchase decision for a fast fashion product. As evident from Table 2, the highest number of respondents rated "creating a self-identity" as the most important factor in making a purchase decision for a fast fashion product. Thus, "creating a self-identity" is the most influential factor for consumers in making a purchase decision for a fast fashion product.

Moreover, 8 (2%) respondents rated "being trendy" as the least important factor in making a purchase decision for a fast fashion product, 19 (5%) respondents rated "earning respect" as the least important factor in making a purchase decision for a fast fashion product, 13 (3%) respondents rated "appreciation and praise" as the least important factor in making a purchase decision for a fast fashion product, 33 (8%) respondents rated "showing dominance" as the least important factor in making a purchase decision for a fast fashion product, 14 (4%) respondents rated "blending with a social group" as the least important factor in making a purchase decision for a fast fashion product and 12 (3%) respondents rated "creating a self-identity" as the least important factor in making a purchase decision for a fast fashion product. As summarized in Table 3, the highest number of respondents rated "showing dominance" as the least important factor in making a purchase decision for a fast fashion product. Thus, "showing dominance" is the least influential factor for consumers in making a purchase decision for a fast fashion product. The findings of telephone interviews reveal that consumers prefer fast fashion to stay updated with ever-changing fashion trends. Moreover, the majority of consumers found using fast fashion as a way to convey their personality. Thus, the underlying motives found are "creating a self-identity" and "being trendy", which is also supported by the questionnaire responses. Furthermore, telephone interactions showed that the majority of respondents were not aware of the social and environmental hazards caused by fast fashion products. Some respondents who understood the adverse impact of fast fashion do not find themselves capable of changing their behaviour due to peer pressure and the unavailability of alternatives.

Table 2: Responses to all factors

Question	Likert Score 1 (%)	Likert Score 2 (%)	Likert Score 3 (%)	Likert Score 4 (%)	Likert Score 5 (%)	Likert Score 6 (%)	Likert Score 7 (%)
How important is "being trendy" for you when buying fast fashion products?	2	4	6	14	26	24	23
How important is "gaining respect from others" for you when buying fast fashion products?	5	6	5	14	18	20	32
How important is "appreciation and praise" for you when buying fast fashion products?	3	3	5	14	22	24	27
How important is "dominating in peer group" for you when buying fast fashion products?	8	8	12	19	23	13	17
How important is "blending with a social group" for you when buying fast fashion products?	4	8	7	17	17	29	18
How important is "creating a self-identity" for you when buying fast fashion products?	3	3	3	11	14	24	42

The most influential factors (Table 3) and least influential factors (Table 4) should be taken into consideration while devising any marketing strategy to gain the desired results.

Table 3: Most influential factor

Factor	Being trendy (%)	Earning respect (%)	Appreciation and praise (%)	Showing dominance (%)	Blending with a social group (%)	Creating a self-identity (%)
Percentage of respondents	23	32	27	17	18	42

Table 4: Least influential factor

Factor	Being trendy (%)	Earning respect (%)	Appreciation and praise (%)	Showing dominance (%)	Blending with a social group (%)	Creating a self-identity (%)
Percentage of respondents	2	5	3	8	4	3

4 Conclusion

Fashion is all about change. It is continuously changing and evolving. With the advent of fast fashion, the pace of this change has increased tremendously. Apart from impacting the environment adversely, fast fashion has several other issues as well. There are various occupational hazards, such as respiratory problems from synthetic particles and cotton dust due to bad ventilation and musculoskeletal issues due to repetitive movements. Waste in the form of landfills is increasing continuously as garments are thrown away every season. The impact of fast fashion is more severe in underdeveloped and developing countries, as there is a lack of proper waste disposal systems. Fast fashion buying is influenced by various economical, emotional and social factors, such as price, income, self-image, perceived risks, hedonism, beliefs/attitudes, peer group and awareness about fashion. This study sheds light on the factors that influence consumer decisions to purchase fast fashion products. The factors whose impact on fast fashion buying has been studied are, being trendy, earning respect, appreciation and praise, showing dominance, blending with a social group and creating a self-identity. This study offers insight into the factors that influence buying decisions for a fast fashion product. It can be concluded from this study that "creating a self-identity" the is most influential factor while making a purchase decision for a fast fashion product, while "showing dominance" is least important factor. The factors identified in this study can be used create a consumer base for sustainable fashion brands. This research can help address the issue of sustainability in the fashion industry. These findings can also be used to promote sustainable fashion. Sustainable fashion brands should focus on the predominant factor, i.e. "creating a self-identity" to make consumers buy sustainable/slow fashion. The findings of telephone interviews reveal that the majority of respondents were not aware of the social and environmental hazards caused by fast fashion products. Thus, educating consumers about the sustainability issues of fast fashion will help mitigate the adverse effects of fast fashion. The promotion of sustainable fashion and slow fashion may result in a reduction in fast fashion consumption. This may reduce the negative social and environmental impacts due to fast fashion.

A more comprehensive study can be conducted to prove the extent of the impact of these factors on the buying behaviour of fast fashion consumers. This study was limited to university students from National Capital Region of India, aged 17–22 only.

Further research can be conducted to include participants from different countries and age groups. The findings may differ in other states in India and other countries of the world.

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Comparative Performance of Textured Yarn Drawn through Apron and Godet in Draw Texturing Machine

Primerjava kakovosti prej, izdelanih na razteznoteksturirnih strojih z jermeni in strojih z galetami

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Abstract

Over the past 20 years, in filament draw texturing, very few developments and innovations have been introduced into production machineries. The growing demand for energy efficiency, faster production rates and greater production flexibility have prompted our investigation into non-traditional approaches to improve yarn control during the texturing. Instead of aprons, small individually driven godets are a solution for high-speed manufacturing, yarn control and energy saving. The drawing godets, where the yarn can be considered an elastic coupling element between two consecutive godets, pose a new challenge for consistency in velocity control. Though some machinery manufacturers have introduced the godet system, the yarn quality produced by the godet system is not systematically evaluated and compared vis-à-vis the apron system. The current study prepared textured yarns in both apron and godet systems while maintaining the same texturing parameters. Differences in the yarn's bulk, modulus, breaking elongation, tenacity and boiling water shrinkage were assessed and compared. Woven and knitted fabrics were prepared from textured yarns, and a comparative analysis of fabric properties was performed with respect to their tearing strength, air permeability, drape and dyeability. Better quality of yarn and fabrics can be prepared in the godet system, which is energy saving, of higher speed and requires low maintenance technology in comparison to the apron system.
Keywords: draw texturing, godet, apron, texturing, bulk, false twist texturing, yarn control

Izvleček

V zadnjih dvajsetih letih je bila strojna oprema za raztezno teksturiranje filamentnih prej zelo malo posodobljena ali inovirana. Naraščajoče zahteve po energetski učinkovitosti, višji produktivnosti in proizvodni prilagodljivosti so spodbudile našo raziskavo o netradicionalnih pristopih k izboljšanju kontrole preje med teksturiranjem. Majhne, individualno gnane galete namesto jermenov so rešitev za visokohitrostno proizvodnjo, kontrolo preje in varčevanje z energijo. Raztezne galete, kjer je prejo mogoče obravnavati kot elastični spojni element med dvema zaporednima

galetama, so nov izziv doslednega nadzora hitrosti. Čeprav so nekateri izdelovalci strojev že uvedli sistem galet, kakovost te preje ni bila sistematično ovrednotena in primerjana s kakovostjo preje, izdelane z jermenskim sistemom. V tej raziskavi je bila izvedena primerjava teksturiranih prej, izdelanih s pomočjo obeh sistemov pri enakih parametrih teksturiranja, in sicer razlike v voluminoznosti, modulu elastičnosti, pretržnem raztezku, trdnosti in krčenju prej v vreli vodi. Lastnosti tkanin in pletiv, izdelanih iz primerjanih teksturiranih prej, so bile ocenjene glede trdnosti, zračne prepustnosti, možnosti drapiranja (pada) in obarvljivosti. Ugotovljena je bila boljša kakovost preje, tkanin in pletiv iz preje, izdelane na stroju z galetami, ki je energijsko varčnejši, omogoča višje proizvodne hitrosti in manj vzdrževanja kot stroj z jermeni.
Ključne besede: raztezno teksturiranje, galeta, jermen, teksturiranje, voluminoznost, teksturiranje z lažnim vitjem, kakovost preje

1 Introduction

In the field of texturing, false-twist technology is the most popular and dominant technology for providing bulk and/or stretch to synthetic yarns. False twist texturing is a process in which a bundle of continuous filament yarn is subjected to drawing and twisting while being heated simultaneously and then twisting in the reverse direction as the strand of filaments is gradually cooled. The process is also called simultaneous draw texturing. The resulting yarn develops stretch and bulk, known as textured yarn. Partially oriented yarn (POY) is the standard feed material for texturing machines [1].

Over the past 20 years, very few developments and innovations have been introduced into production machines in filament draw texturing. The increasing need for energy saving, higher production speed and low maintenance has brought us to think about unconventional solutions for yarn control during the whole texturing process sequence. Though there are several studies available in the literature on the effects of various process parameters of texturing on yarn properties, limited information is available on the effect of the drawing system itself on yarn properties [2–7]. There are four T's, i.e. Twist, Time, Temperature and Tension, which are found to be important parameters affecting textured yarn properties and are widely studied by various researchers [3, 8–10]. Each of these parameters is important to get a perfect textured yarn with the desired physical properties.

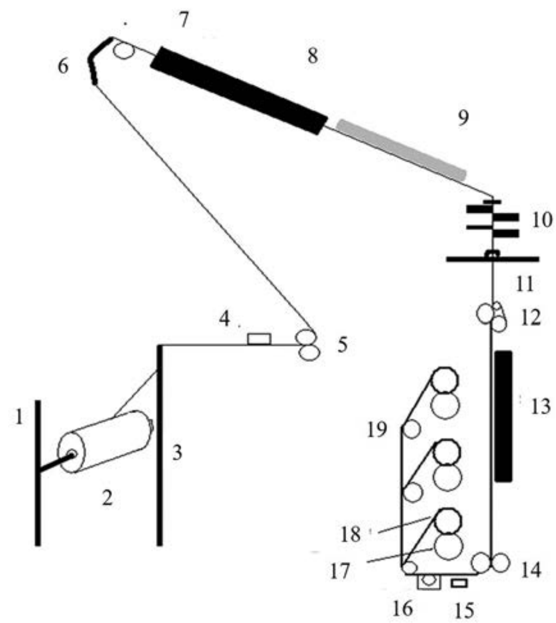


Figure 1: Line diagram of conventional draw texturing machine with nip roller attachment

Legend: 1 – creel, 2 – POY package, 3 – guide rod, 4 – cutter, 5 – input roller, 6 – telephone guide, 7 – twist stopper, 8 – primary heater, 9 – cooling plate, 10 – positorque unit, 11 – thread guide, 12 – intermediate roller, 13 – secondary heater, 14 – output roller, 15 – sensor, 16 – anti-static roll, 17 – drum, 18 – package, 19 – thread guide

The draw ratio is one of the essential parameters that decide the desired textured yarn denier from the supply of POY. The draw ratio is altered by adjusting the speed of the input and intermediate roller [9]. The intermediate roller speed is generally kept constant and the input roller speed is altered to attain the desired draw ratio. Figure 1 presents the line diagram of a conventional texturing machine.

All the feed, intermediate and output roller systems (also called shafts) have two rollers, a steel roller and a rubber-coated nip roller. The rubber-coated nip roller is used to grip the yarn better during the texturing and control the yarn tension. The POY from the spool enters the input roller. It is drawn between the input and intermediate roller, where drawing, heating, cooling and simultaneous false twisting are done to get the desired yarn with bulk and texture. After the intermediate roller, the yarn is passed through the secondary heater to set the yarn, then passed through the output roller, and finally onto the winding drum to form the package via oil roll [10].

The input, intermediate and output rollers control the yarn tension during the texturing process. The yarn tension must be uniform at every location at all positions. Any tension variation can create yarn defects like tight spots, bulk variation and low strength characteristics. Such tension variation can happen due to the poor grip of the outgoing yarn from one pair of rollers to the next. The improper grip can be due to the less spring load of the roller holder, bad condition of the nip roller, groove formed in the nip roller, improper roller hardness, the created gap between the steel and nip roller, roller vibrations etc. Cases become severe at higher texturing speeds and for finer denier yarns [10, 11].

There have been further developments in the roller systems (shafts). In the intermediate roller section, two wrappings are applied on the nip rollers for a better grip, as shown in Figure 2 [12]. However, many accessories are involved in maintaining the wrappings and attracting many other drawbacks. Roller gaps, vibrations and groove formations disturb the yarn path and the tensions causing defective yarn formation. Frequent buffing is another drawback that causes additional cost hikes. Cases become severe at higher texturing speeds and for finer denier yarns [12, 13].

To get rid of all of these, industries initially opted for the apron system in the intermediate zone; however, later, the aprons were put in the input and output zones. Figure 3 shows the apron assembly in the texturing machine. Each assembly consists of a

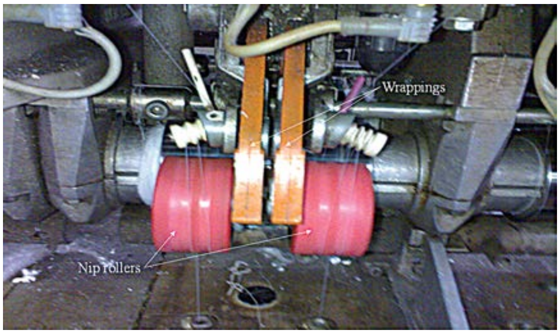


Figure 2: Double wrappings in intermediate rollers

rubber belt mounted on the main steel roller with the help of two crowned rollers at both sides of the belt. A spring-loaded apron holder pressures the belt. The apron rollers are crowned for uniform pressure distribution by accurate alignments and prevent any deflection. The crowned rollers are small tom-tom-shaped rollers designed especially for better grip not to allow the belt to come out from the steel roller.

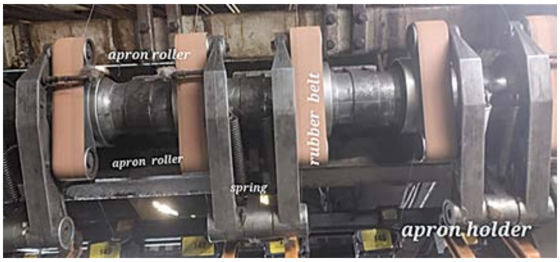


Figure 3: Apron assembly in draw texturing machine

With further development, the concept of godet in draw texturing machine was first brought in the year 2003 for better drawing among the input and intermediate zones where the slippage is just eliminated with stress-free yarn feeding with uniform and consistent yarn evenness of the textured yarn [14]. The godets are individually motor-driven and steel-made chrome-plated rollers and are a one-time investment only. Here, the godet replaces conventional rollers to transport the yarn upstream and downstream to the texturing zone. Figure 4 shows the godet system in the texturing machine. It is claimed that the godet system provides better yarn quality and process stability, and guarantees reduced energy and spare part consumption.

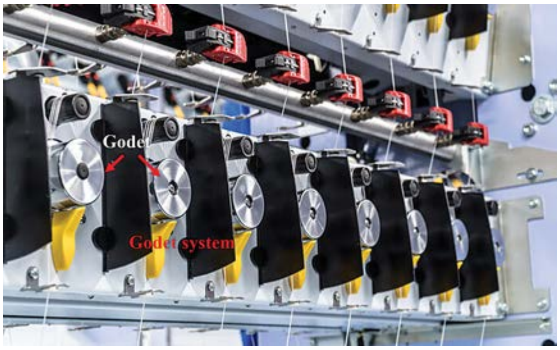


Figure 4: Godet system in draw texturing machine [14]

Figure 5 shows a line diagram of the entire draw texturing machine with a godet attachment. At the output zone, the apron is used, which is considered a secondary zone to the drawing zone. Here, the apron can serve the purpose of setting the yarn well by stabilising overfeed.

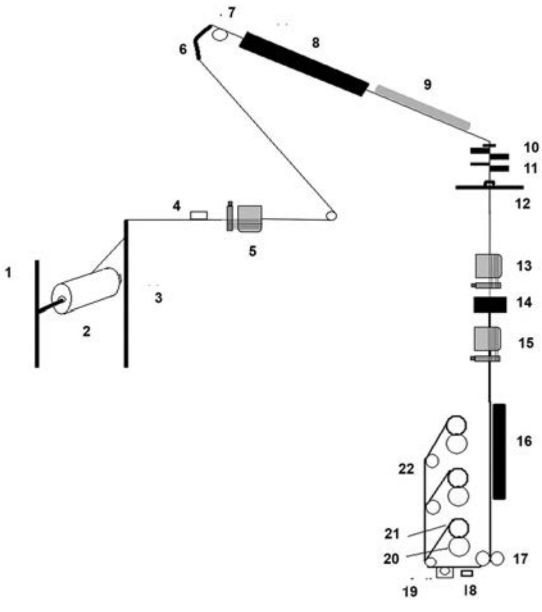


Figure 5: Line diagram of draw texturing machine with motorised godet attachments

Legend: 1 – creel, 2 – POY package, 3 – guide rod, 3 – cutter, 3 – godet, 4 – yarn guide, 5 – twist stopper, 6 – primary heater, 7 – cooling plate, 8 – friction texturing unit, 9 – thread guide, 10 – godet intermediate zone, 11 – intermingling zone, 12 – additional godet for better intermingling, 13 – secondary heater, 14 – output roller, 15 – sensor, 16 – antistatic roll, 17 – drum, 18 – package, 19 – thread guide

From the descriptions above, it is understood that the machinery manufacturers have made efforts to improve the textured yarn quality, increase the life of spares and minimise costs. The conception of godet technology has arrived in the industry for the betterment of product quality, performance of the machinery and cost reduction. However, the yarn quality produced by the godet system is not systematically evaluated and compared to the vis-à-vis apron system. In this study, textured yarns were prepared both in an apron and godet system, keeping the same texturing parameters, and yarn qualities like bulk, liner density, tenacity, breaking elongation, modulus and boiling water shrinkage were evaluated and compared. Woven and knitted fabrics were prepared from textured yarns and properties like tearing strength, air permeability, drape and dyeability were evaluated and compared.

2 Materials and methods

Polyester POY (dtex 161.1/34 semi-dull) was used as feed yarn. Trial 1 was made on a texturing pilot machine with an apron system. Trial 2 and Trial 3 were made on a texturing machine equipped with a godet system but with different draw ratio levels. Detailed machine parameters are shown in Table 1.

The yarn samples prepared from Trial 1 (apron system), Trial 2 (godet system) and Trial 3 (godet system) were used as weft in a waterjet loom to prepare plain woven fabrics. The speed of manufacturing (550 rpm), reed (72/3), picks/meter (3150), ends/meter (4252) and warp yarn linear density (88.89 dtex, 72 intermingling filaments) was kept similar for the preparation of woven fabric samples.

The yarn samples prepared in Trial 1 (apron system), Trial 2 (godet system) and Trial 3 (godet system) were used in a circular knitting machine to prepare single jersey fabrics using the same machine parameters.

Table 1: Machine and process parameters of texturing machine for sample preparation

Parameters	Trial 1	Trial 2	Trial 3
Process parameter	apron system	godet System I	godet System II
Speed (m/min)	700	700	700
Draw ratio	1.85	1.85	1.78
Ratio of disk surface speed to yarn speed (D/Y)	1.55	1.55	1.55
Primary heater temperature (°C)	205	205	205
Secondary heater temperature (°C)	170	170	170
Stabilising overfeeds (%)	5.5	5.5	5.5
Take up (%)	4.5	4.5	4.5
Primary heater length (m)/Tube diameter (mm)	1.75/7	2/7	2/7
Secondary heater length (m)/Tube diameter (mm)	1.40/4	1.40/4	1.40/4
Cooling plate length (m)	1.65	1.75	1.75
PU disc configuration	1-4-1	1-4-1	1-4-1
Disc diameter (mm)/Thickness (mm)	54.5/9	54.5/9	54.5/9
Input tension (T_1) (cN)	27	40	30
Output tension (T_2) (cN)	15	38	22
Ratio of output tension to input tension (T_2/T_1)	0.55	0.95	0.73

2.1 Measurement of birefringence and molecular orientation

In line with Ehringhaus, the compensation method was used for filament birefringence determination using an advanced polarising microscope (Radical RXLr-5 POL). The diameter of the filament was measured microscopically using an eye-piece micrometre. The measurements were performed at a wavelength of 546.1 nm (white light), and the birefringence ($n = \Delta/d$) was calculated using the measured retardation (Δ) and fibre thickness (d)

2.2 Measurement of yarn bulk

The yarn bulk after the texturing was characterised by bulking factor (θ), which is defined as the ratio of the specific volume of the textured yarn to the specific volume of the parent filament yarn before the texturing, as shown in Equation 1:

$$\theta = \frac{Specific\ volume\ of\ textured\ yarn}{Specific\ volume\ of\ parent\ filament\ yarn} \tag{1}$$

The specific volume of yarn (v) is given by Equation 2:

$$v = \frac{\pi d^2 l}{4m} = \frac{\pi d^2}{4T_t \times 10^{-3}} \tag{2}$$

where d is the mean yarn diameter in meter, l is the length of the sample in meter, m is the mass in gram, and T_t is the linear density of the yarn in tex. The mean diameter of yarn samples was measured by using a Leica optical microscope (DM 2500P) with 40× magnification. The yarn diameter was measured by using annotation in the image processing software.

2.3 Measurement of linear density

To measure linear density, 100 m length of yarns was wound on a wrap reel with 1 m circumference and weighed on an electronic analytical balance with a sensitivity of 0.1 mg. Linear density in dtex was calculated. The average linear density was taken from five samples.

2.4 Measurement of tensile properties

The tensile properties of textured yarns were measured with an Instron 3356 Tensile Tester. The instrument operates at a constant rate of extension principle. Following ASTM D 2256_with a gauge length of 50 cm, the cross-head moving speed was adjusted to give a yarn failure time of 20 s ± 3 s [15]. Thirty tests were conducted for each yarn package, and the average tenacity, elongation and modulus results were obtained.

2.5 Measurement of boiling water shrinkage

The boiling water shrinkage test was performed according to the DIN 53866 standard [16]. Six specimens were tested. Tensioning weight of 0.125 cN/tex was applied to the yarn, which was 1 m in length, and a hank was formed. The first length in this condition was recorded as l_1 and then the load was removed. The yarn was wetted in a soap solution (1 g of soap/1 L water) and left in the solution at 100 °C for 15 min and then dried for one hour at 60 °C, after which the yarn was hung for 1 h on the device. Afterwards, the same weight was applied to the yarn, and the length was recorded as l_2. Boiling water shrinkage was calculated with Equation 3:

$$Boiling\ water\ shrinkage\ (\%) = \frac{l_1 - l_2}{l_1} \times 100 \quad (3)$$

2.6 Measurement of woven fabric properties

A universal tensile tester was used to measure the fabrics' tearing strength using the tongue (single rip) tearing strength approach in accordance with the ASTM D2261 standard [17]. Samples measuring 20.3 cm (8 inches) long by 7.6 cm (3 inches) wide were cut from both warp and weft directions, with an additional 7.6 cm (3 inches) cut made for tear propagation. The jaws were 7.6 cm (three inches) apart from one another. A 5.1 cm/min (2-inch per minute) test speed was used. The average tearing strength was computed after five samples were examined in both warp and weft directions. The ASTM D737 test standard, which measures the airflow rate under constant air pressure drop, was used to measure the air permeability of all fabrics using an air permeability tester FX3300 [18]. For each fabric, five samples were measured in order to get an average value. The Cusick drape tester measured the three-dimensional fabric drape due to gravity. The experimental method involved hanging a 15 cm radius fabric specimen over, a 9 cm radius supporting disc. A parallel light source inside the drape tester formed a shadow from the draping specimen onto a piece of paper; the shadow pattern on the paper was traced out and drape coefficient was then calculated [14].

2.7 Dyeing and colour measurements

Dyeing was performed in a sample jet dyeing machine (ATAC, Turkey) with the following dyeing parameters. Dye (CI Disperse Blue 56) concentration: 2% on the weight of fabric, dispersing agent (Disperol PE, Unichem): 2 g/L, acetic acid: 1 g/L to maintain pH between 5 and 5.5, M : L 1 : 10, temperature: 120 °C, pressure: 2 N/m^2, fabric speed: 30 m/min, time 1 h. After the dying, samples were thoroughly rinsed and treated with a solution containing 2 g/L NaOH and 2 g/L Na_2S to remove loose dye molecules from the fabric surface. Finally, the fabrics were rinsed again and dried for further testing.

The colour strength of dyed fabrics was measured with a Datacolour SPECTRUM 650 TM spectrometer. The *K*/*S* values of the dyed fabrics were measured over the visible wavelength range 400–700 nm. This *K/S* ratio is related to the reflectance *R* of an opaque colourant layer and is expressed with Equation 4:

$$\frac{K}{S} = \frac{Coefficient\ of\ absorption}{Coefficient\ of\ scattering} = \frac{(1-R)^2}{2R} \quad (4),$$

where *K* is the absorption coefficient, *S* is the scattering coefficient and *R* is the reflectance value at maximum absorbance wavelength. The surface colour strength, i.e. *K/S* value, is directly proportional to the concentration of dye molecules on dyed textile samples as well as attributed to higher light absorption.

3 Results and discussion

In all three trials conducted, no package fault was found. The resultant yarn linear density, tenacity, breaking elongation, modulus and boiling water shrinkage of control yarn and three textured yarns are shown in Table 2.

Table 2: Yarn properties before and after texturing trials

Sl. no.	Yarn samples	Properties						Birefringence
		Linear density (den)	Tenacity (g/den)	Breaking elongation (%)	Initial modulus (g/den)	Boiling water shrinkage (%)	Bulk factor (θ)	
1	Control yarn (POY)	149.21 (4.32)	1.79 (0.09)	327.00 (9.12)	8.07 (0.10)	33.33 (1.12)	0	0.09
2	Trial 1 (apron system)	91.78 (2.01)	3.78 (0.12)	64.51 (1.88)	13.17 (0.19)	23.33 (0.98)	16.4 (1.01)	0.12
3	Trial 2 (godet system I)	85.46 (1.22)	3.88 (0.11)	46.02 (1.11)	12.10 (0.14)	20.00 (0.98)	14.4 (0.95)	0.13
4	Trial 3 (godet system II)	88.33 (1.23)	3.78 (0.12)	52.99 (1.21)	11.00 (0.11)	16.67 (0.88)	18.7 (1.12)	0.12

(Standard deviation is shown in brackets.)

3.1 Linear density of yarns prepared from apron and godet system

It can be seen from Table 2 that the linear density of the control POY decreased significantly (p-value < 0.05) after the texturing. Among the three trials of texturing, the linear density of Trial 1 was found to be the highest. This indicates that the linear density of the yarns in the apron system is higher than that of the godet system. This is due to the godet system's higher yarn tension (T_1) compared to the apron system despite the draw ratio being maintained constant.

3.2 Linear density of yarns prepared from godet system with different draw ratio

It was observed that the linear density of yarn from Trial 3 was significantly higher (p-value < 0.05) than from Trial 2. This is due to the decrease in yarn tension (T_1) from 40 to 30 cN as a result of the decrease in draw ratio from 1.85 to 1.78. The linear density of the yarn increases with decreasing yarn tension.

3.3 Tenacity of yarns prepared from apron and godet system

Table 2 shows that after the texturing, the tenacity of the control POY increased by more than twice. The godet system (Trial 2) produced yarn that is stronger than that of the apron system (Trial 1). The godet has a wrapping system which provides a better yarn tension control with no slippage, resulting in higher and uniform tension and thus in better molecular orientation and good mechanical strength. However, in the apron system, there is no such yarn tension control system. As a result, there is the development of low yarn tension with inconsistency causing poor molecular orientation and inferior mechanical strength. Moreover, the life of apron is shorter in comparison to godet.

The improvement in the tenacity of yarns after the texturing is due to a higher level of yarn tension resulting in the improvement in molecular orientation along with filament axis, which is evident from the data of birefringence, as shown in Table 2. The higher the value of birefringence the better will be molecular orientation. The birefringence of control POY was 0.09 and rose to 0.12 after Trial 1 (apron system) and to 0.13 after Trial 2 (godet system). Therefore, at higher levels of yarn tension, the molecular orientation of textured yarns improved, resulting in better tenacity, which happened with the textured yarn prepared from the godet system. In the case of the godet system itself, if the draw ratio decreased, yarn tenacity decreased. This can be verified with the tenacity results of Trial 3 and Trial 2, where the tenacity of yarn from Trial 3 was lower than that of Trial 2.

3.4 Breaking elongation of yarns prepared from apron and godet system

It can be observed that the yarn breaking elongation decreased significantly after the texturing. The reduction of the breaking strain was due to the formation of a more crystalline structure of the filament yarns caused by better heat treatment in the secondary heater zone [3]. At a higher level of crystallinity, the scope for molecular movement is smaller, which gives a stiffer mechanism in the filament structure, attributing to low tensile strain.

In comparison to the apron system, there was a more significant reduction of breaking elongation in the case of the godet system. On the other hand, in the godet system, yarn breaking elongation increased if the draw ratio decreased and D/Y increased. The decrease in breaking elongation is attributed to the higher crystallinity of the yarn structure.

3.5 Initial modulus of yarns prepared from apron and godet system

The initial modulus of the yarn increased significantly after the texturing, which is due to a remarkable reduction of breaking elongation and increment of tenacity. The modulus of the yarn textured in the apron system was found to be higher than that of the godet system. Therefore, it is evident that the yarns textured from the godet system are more flexible than that of the apron system. In the godet system, if the draw ratio decreased or D/Y increased, the yarn modulus decreased.

3.6 Boiling water shrinkage of yarns prepared from apron and godet system

The boiling water shrinkage significantly reduced after the texturing. Compared to the apron system, shrinkage was found greater in the godet system. Even in the godet system, if the draw ratio decreased and D/Y increased, yarn shrinkage was found to be more prominent.

The chain folding of macromolecules in the amorphous phase to form a crystalline structure as a result of increasing chain mobility caused boiling water shrinkage. The entropic relaxation of excited stretched chains resulting from macromolecule rearrangements caused by internal stress during orientation is the mechanism responsible for the shrinkage of the oriented polymer structure above the glass transition temperature. In contrast to amorphous polymers, semi-crystalline polymers exhibit crystallisation during these rearrangements [3, 15].

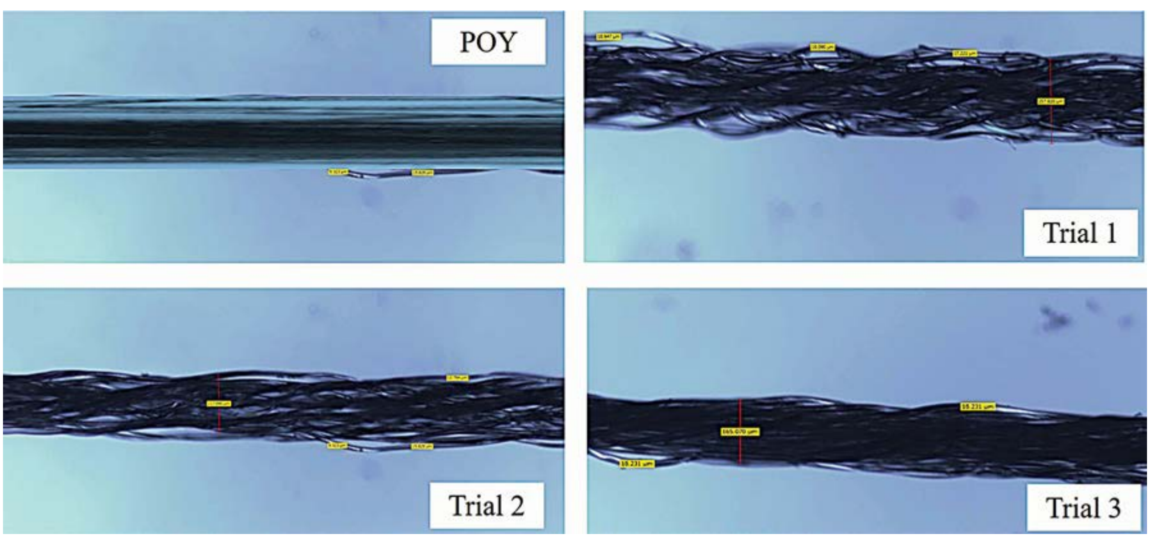


Figure 6: Optical microscopy images of textured samples (40× magnification)

3.7 Optical microscopic images of textured yarn samples

The mean yarn diameters of all yarn samples were measured in the microscopic images by using image processing software. The microscopic images of all yarn samples are shown in Figure 6. It can be seen that the control yarn has straight monofilaments without any crimp in the yarn body. After the texturing, the straight configuration of the filament changes to a curly configuration, generating crimps in the yarn structure. The yarns are thus becoming bulkier in structure. The bulk factor (θ) of all yarn samples was calculated with Equation 1. The results are shown in Table 2. The bulk factor of textured yarn from Trial 1 (apron system) is higher than that of Trial 2 (godet system). However, in Trial 3, the bulk factor improved and rose to 18.7, the highest among all. This was due to low draw ratio and yarn tension in Trial 3.

3.8 Properties of woven fabrics prepared from textured yarns

The yarn samples prepared from Trial 1 (apron system), Trial 2 (godet system) and Trial 3 (godet system) were used as weft in a waterjet loom to prepare plain woven fabrics. The speed of manufacturing (550 rpm), reed (72/3), picks/meter (3150), ends/meter (4252) and warp yarn linear density (80 den, 72 intermingling filaments) was kept similar for the preparation of fabric samples. Areal density (g/m^2), air permeability, drape and tearing strength were measured and compared for all three fabric samples. The results are shown in Table 3. It can be seen that there is no significant variation in the areal density and tearing strength of the woven fabrics prepared with yarns from three different trials. However, the air permeability and drape coefficient of the fabrics differ significantly. The air permeability of the fabrics prepared from yarn textured in the apron system (Trial 1) was higher than that of the godet systems, which may be due to the differences in fabric porosity. The drape coefficient of the fabric from Trial I is lower than that of the godet systems due to comparatively loose or open fabric structure.

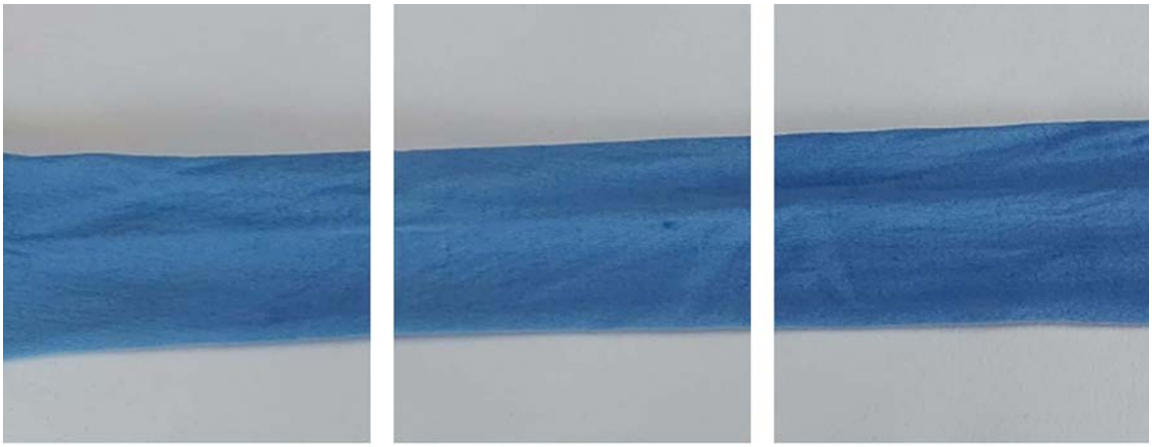
Table 3: Comparison of fabric properties

Sl. no.	Fabric property	Trial 1 (apron system)	Trial 2 (godet system I)	Trial 3 (godet system II)
1	Areal density (g/m^2)	73.4 (2.3)	71.6 (2.5)	72.8 (2.8)
2	Air permeability (cm^{3}cm^{-2}s^{-1})	19.13 (1.23)	14.32 (1.11)	16.67 (1.25)
3	Drape coefficient	56.43 (2.14)	71.45 (3.57)	72.37 (3.98)
4	Tearing strength warp × weft (N)	17.502 × 17.061 (1.23, 1.56)	17.112 × 17.121 (1.45, 1.68)	17.282 × 17.8 (1.41, 1.61)

(Standard deviation is shown in brackets.)

3.9 Dyeability of knitted fabrics prepared from textured yarns

The yarn samples prepared from Trial 1 (apron system), Trial 2 (godet system) and Trial 3 (godet system) were used in a circular knitting machine to prepare single jersey fabrics using the same machine parameters. The knitted fabrics were prepared continuously and later dyed with a disperse blue dye, keeping the same dyeing conditions in an HTHP dyeing machine. The appearance of the fabric samples is shown in Figure 7. The darkest shade was found in the case of Trial 1, followed by Trial 3 and Trial 2. The *K*/*S* values obtained from the computer colour-matching instrument for all these samples are shown in Table 4. The dye sorption of the yarn can deeply affect the end-product quality and can show the texturing process parameter variations. A small alteration in orientation and crystallinity may change dye diffusion. Dye sorption increases with increasing mobility of the amorphous chains, and dye diffusion depends on the orientation of the amorphous chain segments [9]. The decrease in the colour strength (*K*/*S*) in the godet system (Trial 2 and Trial 3) in comparison to the apron system (Trial 1) can be attributed to the higher amorphous orientation due to increased yarn tension during the texturing in the godet systems. Between Trial 2 and Trial 3, colour strength is lower in the case of Trial 2 sample, which is due to the increased drawing ratio, resulting in better amorphous orientation. Oriented amorphous material inhibits dye molecule diffusion, thus lowering the dye uptake [3].



Trial 1 (Apron system) Trial 2 (Godet system I) Trial 3 (Godet system II)

Figure 7: Dyed knitted fabrics prepared from textured yarns

Table 4: K/S values of knitted fabrics

Sl. no.	Fabric name	K/S value
1	Trial 1 (apron system)	3.232
2	Trial 2 (godet system I)	1.218
3	Trial 3 (godet system II)	2.132

4 Conclusion

The linear density of the yarn decreased significantly after the texturing of the control POY. The decrement of linear density was found to be higher in the case of the apron system than that of the godet system of drawing. If the draw ratio decreased, the linear density of yarns increased. The tenacity of yarn produced in the godet system was better than that of the apron system. If the draw ratio decreased, the tenacity of yarn decreased. The breaking elongation of yarn after texturing drastically reduced. In the case of the godet system, the reduction was even greater than that of the apron system. The initial modulus of the yarn increased significantly after the texturing. The initial modulus in the apron system was found to be higher than that of the godet system. The boiling water shrinkage was greater in the godet system than in the apron system. Yarn bulk was found to be higher in the apron system than that of the godet system. No significant variations in areal density and tearing strength of the woven fabrics prepared with yarns from three different Trials were found. However, the air permeability and drape coefficient of the fabrics differed significantly. The air permeability of fabrics prepared with yarn textured in the apron system was significantly higher, and the drape coefficient was significantly lower than that of the godet systems. The dyeability of the knitted fabric prepared with yarns from the apron system was significantly better than that of the godet system.

Therefore, it can be concluded that the tensile strength and flexibility of textured yarn prepared with the godet system is better than the one prepared with the apron system. Though the bulk of the yarn in the godet system is inferior to the apron system, it can be improved by altering texturing parameters such as the draw ratio, D/Y ratio, heater temperature etc. Overall, better quality of yarn and fabrics can be prepared in the godet system, which is energy saving, of higher speed and requires low maintenance technology in comparison to the apron system.

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The Determination of Functionalized Textile Materials Durability Based on Copolymers of Acrylonitrile to Thermal and Thermal-Oxidative Degradation

Določanje obstojnosti funkcionaliziranih tekstilij na osnovi kopolimerov akrilonitrila na toplotno in toplotno-oksidativno razgradnjo

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Abstract

Acrylonitrile is widely used to produce carbon fibres, household textiles, artificial fur, etc. The modification of polyacrylonitrile fibres in an alkaline medium is extended in the production of textile sorbents. The scientific direction of fibre modification through surface activation using hydrogen peroxide is of scientific interest. However, the thermal and thermophysical properties of the samples are not examined. Therefore, interest arises when analysing the effect of polyacrylonitrile textile material functionalization on the resistance of fibres to thermal oxidation and thermal degradation. The study of thermogravimetry and differential thermogravimetry thermooxide of polyacrylonitrile – modified fibres is carried out using thermogravimetric analysis to research the thermal oxidation and thermal degradation of modified polyacrylonitrile fibre samples. A change in the rate of thermal oxidative-degradation in the process of functionalization was identified in this research. A change in the loss of mass of the sample under different conditions of functionalization was also identified. The total glass transition of the polyacrylonitrile was achieved by heating the polymer to 130 °C. The intensification self-regulation of the structure of the polymeric material through the formation of the mesophase was released at the temperature of around 100 °C. During the heating of the initial polyacrylonitrile textile material to the temperature of 70–80 °C, a weakening of intermolecular contacts was observed, which led to an increase in the mobility of macromolecular segments. The temperature of 78 °C was considered to be the initial glass transition temperature $T_{g,t1}$ and $T_{g,t2}$ – 121 °C as the final temperature for the original sample. However, if the temperature exceeded 130 °C, chemical changes in the polymer occurred, in particular, the process of cyclization. The analysis of the thermogravimetry data of thermally oxidized samples resulted in the retention of the complex stepwise nature of decomposition inherent in the initial fibrous material based on acrylonitrile copolymers. The conducted analysis showed the absence of significant changes

in the reasonable conditions of chemical modification and practical operation of textile materials.
The physical and mechanical properties of functionalized textile materials based on acrylonitrile copolymers were studied. As a result of surface functionalization, an insignificant strength reduction of functionalized textile materials occurred.
Keywords: superficial modification, polyacrylonitrile fibre, glass transition temperature, physical and mechanical properties of textile materials

Izvleček

Akrilonitril se na široko uporablja za izdelavo ogljikovih vlaken, gospodinjskih tekstilij, umetnega krzna ipd. Modificirana poliakrilonitrilna vlakna so v alkalnem mediju razširjena za izdelavo tekstilnih absorbentov. Površinska aktivacija vlaken z vodikovim peroksidom je znanstveno zanimiva, pri čemer njihove toplotne in toplotno-fizikalne lastnosti niso raziskane. Zanimal nas je vpliv funkcionalizacije poliakrilonitrilnega tekstilnega materiala na odpornost proti toplotni oksidaciji in toplotno razgradnjo. Študij termogravimetrije in diferencialne termične analize termooksidiranih poliakrilonitrilnih – modificiranih vlaken je bil izveden s pomočjo termogravimetrične analize za proučevanje termooksidativne in termične razgradnje vzorcev modificiranih poliakrilonitrilnih vlaken. V tej raziskavi je bila ugotovljena sprememba hitrosti toplotne oksidativne razgradnje v procesu funkcionalizacije. Zaznana je bila tudi sprememba v izgubi mase vzorca pri različnih pogojih funkcionalizacije. Popoln steklast prehod poliakrilonitrila je bil dosežen pri segrevanju polimera do 130 °C. Pospešeno samourejanje strukture polimernega materiala s tvorbo mezofaze se je začelo pri temperaturi okoli 100 °C. Med segrevanjem izhodnega poliakrilonitrilnega tekstilnega materiala do temperature okoli 70–80 °C sta bila opažena oslabitev medmolekulskih interakcij in povečanje gibljivosti makromolekulskih segmentov. Temperatura 78 °C je veljala za začetek steklastega prehoda ($T_{g,T1}$) oziroma 121 °C za konec steklastega prehoda ($T_{g,T2}$) v izvirnem vzorcu. Pri temperaturi nad 130 °C so nastopile kemične spremembe v polimeru, predvsem ciklizacija. Analiza termogravimetričnih meritev toplotno oksidiranih vzorcev je pokazala, da se je ohranila kompleksna postopna narava razgradnje, ki je značilna za začetni vlaknati material na osnovi kopolimernega akrilonitrila. Analiza je pokazala, da v sprejemljivih pogojih kemijske modifikacije in praktičnega manipulacije ni prišlo do bistvenih sprememb tekstilnih materialov. Proučene fizikalno-mehanske lastnosti funkcionaliziranih tekstilnih materialov na osnovi kopolimerov akrilonitrila niso pokazale pomembnega znižanja trdnosti funkcionaliziranih tekstilnih materialov zaradi površinske funkcionalizacije.
Ključne besede: površinska modifikacija, poliakrilonitrilno vlakno, temperatura steklastega prehoda, fizikalne in mehanske lastnosti tekstilnih materialov

1 Introduction

Polyacrylonitrile textile materials are among the most promising synthetic fibres. The creation of acrylonitrile textile materials with an improved set of properties that bring products closer to natural ones is an urgent and promising direction in the development of the textile industry.

The modification of polyacrylonitrile fibres in an alkaline medium is widely used in the production of textile sorbents [1−5]. To a large extent, the properties of sorbents are determined by a set of functional groups and the density of the spatial mesh caused by polymer crosslinking [3, 4, 6−9].

The reaction of polyacrylonitrile (PAN) fibres with alkali is characterized by the appearance of several types of functional groups. This is due to the successive transformations of nitrile groups into heterocyclic, amide and carboxylate-ionic groups [3, 5]. In this case, the reaction does not end with complete transformation. Some of the remaining intermediate structures have ionogenic properties [3].

It should also be noted that during modification, textile materials with functional features are obtained without changing the properties of the fibre bulk. Saponification of polyester and triacetate textile materials is a simple method for alkaline fibre surface treatment. As a result of saponification, carboxyl and hydroxyl groups are "liberated".

Surface alkaline hydrolysis can be applied to polyester materials prior to dyeing. Such processing improves the colour characteristics and quality of finished products [10-15]. Namely, the capillarity of the materials increases, the rigidity decreases, the drape is improved and the soiling of fabrics decreases [14]. A positive effect due to the hydrolysis of the polymer is achieved only when the mass of the textile material is reduced by 10–30% [10-14]. As a result, the mechanical strength of the fibre decreases.

In a scientific study conducted by the authors of the paper [14], information is provided on the modification of polyacrylonitrile fibres by activating the surface of the fibres with hydrogen peroxide. The scientific direction of fibre modification through surface activation using hydrogen peroxide is of scientific interest. A positive effect on the sorption properties of PAN fibres after their surface modification was shown. It is a known fact that polyacrylonitrile fibres are used mainly as a textile or raw material for the production of carbon fibres [15–18]. The latter can be used at elevated temperatures (1,600–2,000 °C). Therefore, interest arises from studying the effect of functionalization of a PAN-textile material on the resistance of fibres to thermal oxidation and thermal degradation. It is also possible to use modified fibres as technical textiles, where their thermal stability is necessary.

Amides are obtained through the partial hydrolysis of nitriles. The Radziszewski reaction mechanism provides for a nucleophilic attack of the nitrile group by a hydroperoxide anion. The result is an unstable intermediate that is an oxidizing agent. Subsequently, there follows the hydride transfer from the second water molecule to the intermediate formation of the hydroperoxide carboximide (Figure 1). In an alkaline solution, hydrogen peroxide restores the intermediate to the amide through the release of oxygen [14].

Mechanical properties represent some of the most important basic characteristics of fibres as textile materials. During the process of fibrous material functionalization based on acrylonitrile copolymers, a change in the surface occurs due to the formation of amide and carboxyl groups. This leads to the rapid and intense degradation of the surface layers of the polymer material. This work determined the relative strength of the textile material by comparing the strength of the original sample and samples after functionalization.

2 Materials and methods

For the manufacture of samples for functionalization, nitron D yarn ("Polymir" plant; Republic of Belarus) was used. The linear density of yarn was 15 tex. Samples of knitted fabrics were made on a class 10 flat knitting machine. The composition of the copolymer was: acrylonitrile 91%, methyl acrylate 8% and AMPS (2-acrylamide-2 methyl-propanesulfonic acid) 1%. A hydrogen peroxide solution (35%) in presence of tetraborate (pH 8.0) buffer systems was used for the processing of fibre material.

Assuming that the PAN sample before functionalization was designated as PAN-0, the concentration of hydrogen peroxide would then be as follows: 50 g/l - PAN-50, 100 g/l - PAN-100, 120 g/l - PAN-120 and 180 g/l - PAN-180.

The functionalization of the test samples was carried out according to the Radziszewski reaction. The concentration of hydrogen peroxide (35%) varied accordingly: 50 g/l, 100 g/l, 120 g/l and 180 g/l. The temperature was 98 °C, while the material to liquor ratio was 1:20. The duration of processing was 60 minutes. Samples of textile materials: nitron D (Polimir plant; Republic of Belarus), with a direct linear density of 15 tex. The composition of the copolymer was: acrylonitrile – 91%, methyl acrylate – 8% and

AMPS (2-acrylamide-2-methyl-propanesulfonic acid) – 1%.

The thermophysical properties of the samples were studied using differential scanning calorimetry (DSC). A TA Instruments Q100 calorimeter was used for this purpose. It allows measurements to be made in a nitrogen atmosphere in a temperature range from -55 to 240 °C and a heating rate of 20 °C/minutes. To do this, mass of samples 0.01–0.015 g were placed in aluminium capsules, which were then hermetically sealed.

The heating-cooling-heating scanning mode was used for the studied samples. In this case, for the analysis of thermophysical properties, as a rule, DSC curves obtained during reheating were chosen. The middle of the endothermic transition on the curve of the temperature dependence of the heat capacity C_p = f(T) corresponded to the glass transition temperature ($T_{g,t}$) of the textile material based on the acrylonitrile copolymer.

The resistance of textile materials to thermal (in an atmosphere of dry nitrogen) and thermal-oxidative (in air) degradation was determined in dynamic mode using a Setaram TG TDA92 instrument in an inert atmosphere and in air in the temperature range of 20 °C to 700 °C and a temperature increase rate of 10 °C/minute with the constant removal of degradation products. The mass of the samples was 0.01–0.015 g. For each sample, thermogravimetry (TG) and differential thermogravimetry (DTG) curves were simultaneously recorded. The accuracy of measuring the temperature parameters of degradation was ± 3 °C, while the error in determining the mass loss was < 1.0%.

All used methods are defined by the current international or national standards of Ukraine for the relevant textile products.

To assess the mechanical properties of yarn, which determine their behaviour during operation, a range of indicators was used, including breaking force and elongation at break [19].

In this work, physical and mechanical indicators were determined using a pendulum-type tensile testing machine RM-3-1. The clamping length of the sample was 500 mm, the lowering speed of the lower clamp was 500 mm/min, the pre-tension force (based on the nominal linear density of the yarn is 15 tex) was 10 cN.

The results of the research are presented in relative units in order to compare and contrast the influence of functionalization conditions on the physical and mechanical properties of fibrous materials, which made it possible to limit the influence of instrument error and yarn thickness variation, as well as other systematic factors. The confidence interval was 95%, with 30 measurements for each sample.

3 Results and discussion

The analysis of thermo-oxidative degradation indicators shows the possibility of expanding the scope of the modified fibre for technical use.

Mechanical properties represent important characteristics of fibres and textile materials. The specific feature of fibres as polymeric materials is that they represent oriented systems. One of the most important properties of fibrous materials is the anisotropy of their mechanical behaviour due to the specificity of fibre structure. The elementary units of macromolecules are bonded by covalent chemical bonds. The interaction between the units of two neighbouring macromolecules is caused by weaker intermolecular bonds. As a result, the work required to break chemical bonds exceeds the work required to break intermolecular bonds by several times. Fibrous materials based on acrylonitrile copolymers have a rather high strength. During the functionalization of fibrous material based on acrylonitrile copolymers, there is a change in the surface due to the generation of amide and carboxyl groups.

Data regarding changes in breaking force and the elongation of fibrous material are shown in the table below Table 1.

Table 1: Effect of functionalization conditions on changes in breaking force and the elongation of PAN-based fibrous material

№	Functionalization conditions (of 35% H_2O_2) (g/l)	Relative strength in relation to the original sample, relative units	Relative root-mean-square error (%)	Relative extension (%)	Relative root-mean-square error (%)
1	Original sample	1.0	11.8	1.0	15.5
2	50	0.937	14.3	0.998	19.3
3	100	0.995	15.4	0.940	20.3
4	120	0.873	14.1	0.938	21.2
5	180	0.911	15.0	1.11	21.0

However, with an increasing concentration of hydrogen peroxide, the loss of strength characteristics does not exceed 5–8%. The formation of this kind of "threshold" can presumably be caused by changes in the internal structure of the fibrous material. With a further increase in concentration, it is possible to form "semi-cross-linked" structures due to further transformations of amide groups. Since the changes directly on the surface of the fibrous material are of interest, functionalization using hydrogen peroxide concentrations of up to 100 g/l is recommended for the textile industry with the least loss of breaking strength. For samples of fibrous materials based on acrylonitrile copolymers, functionalized at pH = 8.0 for samples № 3, 4 and 5 (Table 1) in relation to the original sample, a slight increase in elongation is observed. Thus, the changes could be determined by changes within the structure of the fibrous material. Therefore, surface functionalization is associated with an insignificant change in strength characteristics, which does not lead to a change in the consumer properties of the fibrous material.

For a two-phase textile material based on acrylonitrile copolymers, two temperature transitions (glass transitions) $T_{g,T1}$ and $T_{g,T2}$ are inherent. The $T_{g,T1}$ transition occurs at a temperature of ~100 °C, above which the vitrified mesophase turns into a mesophase melt. The $T_{g,T2}$ transition at a temperature of ~150 °C is the transition of a glassy amorphous phase to an elastic state. The transition of the ordered phase from the glassy state to a fluid state occurs at a lower temperature than the softening of the amorphous phase.

Similar to other linear polymers, fibre-forming acrylonitrile copolymers are characterized with several stages of polymer at the initial stage of fusion, which is associated with the manifestation of mobility or substitution of functional groups, i.e. conformational transitions. Based on the well-known Flory-Huggins model, the glass transition temperature should be directly proportional to the energy required to change the mobility of a segment.

The purpose of this study was to investigate and compare the changes in indicators of physical and mechanical properties and glass transition temperature of textile materials based on thermogravimetry (TG) and differential thermogravimetry (DTG) curves using the differential scanning calorimetry (DSC) method. In Figure 1, DSC curves characterizing heat release during heating of the original PAN fibre samples (curve 1) and after their functionalization (curve 2) are depicted. Summary parameters are shown in Table 2.

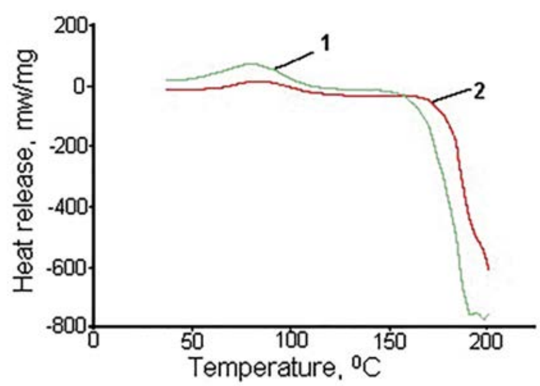


Figure 1: DSC thermograms for PAN: curve 1 is PAN-0; curve 2 is PAN-180

When PAN was heated to 130 °C, the polymer completely fused. At a temperature of around 100 °C, self-ordering of the structure of the polymeric material was intensified with the formation of a mesophase.

When the sample PAN-0 was heated to the temperature of 80 °C (Figure 1, curve 1), the significant weakening of intermolecular contacts was observed. This caused an increase in the mobility of macromolecules segments.

The temperature of 78 °C can be considered the initial glass transition temperature $T_{g,T1}$. Accordingly, $T_{g,T2}$ - 121 °C can be considered the final temperature for the initial sample (Table 1). When heated above the temperature of 130 °C, chemical changes in the polymer occur, i.e. the process of cyclization.

When functionalized PAN-180 is heated, the temperature of 82 °C can be considered the initial glass transition temperature $T_{g,T1}$, while $T_{g,T2}$ - 132 °C can be considered the final temperature (Table 1). The glass transition temperature is 92 °C.

Table 2: Thermophysical characteristics for samples of textile material based on acrylonitrile copolymers

Samples	$T_{g,T1}$ (°C)	$T_{g,T2}$ (°C)	$\Delta T_{g,T}$ (°C)	$T_{g,T}$ (°C)	$\Delta C_{p'}$ (Wg^{-1} K^{-1})
PAN–0	78	121	43	85	0.398
PAN-50	76	125	44	84	0.404
PAN-100	75	130	43	82	0.385
PAN-120	78	128	48	85	0.432
PAN-180	82	132	50	92	0.447

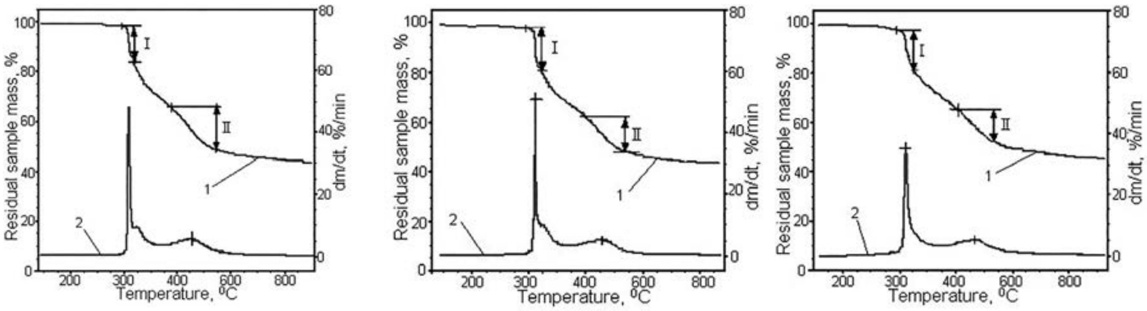
Thus, the value of $T_{g,T}$ is shifted to higher temperatures. In this case, the temperature range of the glass transition process ($\Delta T_{g,T}$) expands slightly. The change in the glass transition temperature is affected by the presence of polar groups, as well as the location thereof.

The glass transition temperature increases with an increase in the number of CN-groups and with an increase in the size of substituents. A decrease in the size of substituents occurs if the polymer chains have sufficient kinetic flexibility. Obviously, the decrease in $T_{g,T}$ is associated with the transformation of nitrile groups into amide and carboxyl groups, which confirms the passage of the Radziszewski reaction. Carboxyl groups are effective catalysts for the cyclization process. Their presence in the polymer leads to a decrease in the temperature level of its manifestation and an increase in the glass transition temperature. This is observed for samples after treatment with a high concentration of hydrogen peroxide (above 100 g/l).

As mentioned earlier, polyacrylonitrile has two glass transition temperatures. It is the second temperature that is determined by the shift of the equilibrium of the dipole interaction of nitrile groups [20]. The second glass transition temperatures of the original sample based on acrylonitrile and functionalized copolymers can differ by 10 degrees or more.

The TGA method was used to determine the thermal characteristics of the studied samples based on acrylonitrile copolymers. The method is most sensitive to the loss of mass of samples under the influence of temperatures, as well as the loss of water, the content of which varies with surface changes, in particular, with functionalization.

The TGA curves have clear inflection points (Figure 2). The character of polymer decomposition rate curves can be described as bimodal. This indicates the occurrence of the thermolysis process with an increased rate of decomposition in two areas.



a) b) c)

Figure 2: Typical TGA curves (1) in an inert medium and the corresponding differential DTG curves (2) for samples: a) PAN-0, b) PAN-100 and c) PAN-180

As the results of the study show, when using different amounts of hydrogen peroxide, the temperature ranges of degradation and the corresponding temperature of the rate of degradation are practically unchanged (Table 3).

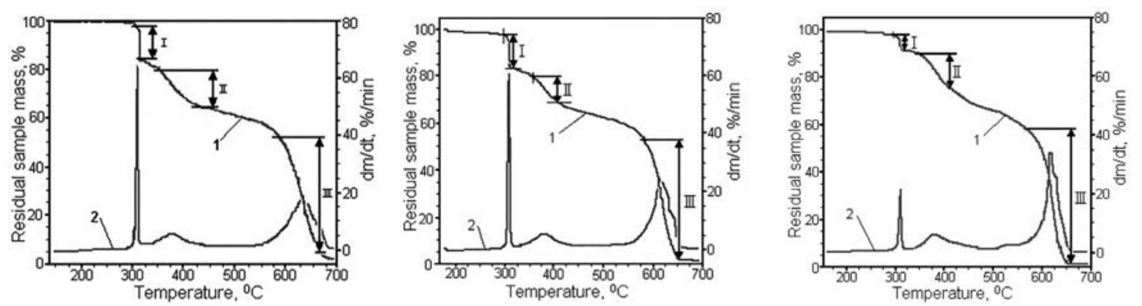
Table 3: Influence of chemical modification of textile materials based on PAN on their resistance to thermal degradation

Sample	Stage	Temperature ranges of degradation (°C)		Temperature of the max. rate of degradation, T_{dmax} (°C)	The rate of degradation, v_{dmax} (%/min)	Mass loss, Δ*m* (%)
		T_{dS} [a)]	T_{dF} [b)]			
PAN–0	I	295	322	312	50.7	14.3
	II	397	470	427	5.0	17.3
PAN-100	I	294	318	309	47.0	14.6
	II	388	471	429	5.3	17.5
PAN-180	I	295	326	312	35.1	13.5
	II	403	468	435	4.9	16.3

[a)] Starting temperature; [b)] Final temperature

The temperature of the rate of degradation, which for the first stage (I) lies in the range of 294–326 °C, is 309–312 °C. At the second stage (II), with practically unchanged temperature limits, the increase in the temperature of the rate of degradation is observed. In this case, the degradation rate at the first stage decreases, while the mass loss remains constant for each stage (Table 3).

Figure 3 depicts TGA and the corresponding DTG curves showing the effect of thermal-oxidative degradation on the properties of textile materials.



a) b) c)

Figure 3: Typical TGA curves (1) in air and corresponding differential DTG curves (2) for samples: a) PAN-0, b) PAN-100 and c) PAN-180

The analysis of the TGA data of thermally-oxidized samples shows that they retain the complex stepwise nature of decomposition in the initial fibrous material based on acrylonitrile copolymers (Table 4).

Table 4: Influence of chemical modification of textile materials based on acrylonitrile copolymers on their resistance to thermal-oxidative degradation

Sample	Stage	Temperature ranges of degradation (°C)		Temperature of the max. rate of degradation, $T_{d\,max}$ (°C)	Temperature of rate of degradation, v_{dmax} (%/min)	Mass loss, Δm (%)
		T_{dS} [a)]	T_{dF} [b)]			
PAN – 0	I	295	317	310	68.4	15.2
	II	334	416	377	5.5	15.6
	III	563	682	634	17.2	55.2
PAN-100	I	297	316	309	64.9	14.2
	II	341	419	379	5.3	14.1
	III	560	657	613	24.0	55.7
PAN-180	I	296	319	310	20.6	6.2
	II	344	485	383	6.0	23.0
	III	570	659	613	24.0	55.7

[a)] Starting temperature; [b)] Final temperature

Another well-defined interval appears with the maximum decomposition temperature. Thus, the curves are trimodal with three corresponding stages. A shift in the temperature ranges of decomposition is observed. The rates of mass drop of the samples differ by increasing the temperature: higher in the initial section and smoother, slower in the final section (Table 4). As the amount of amide compounds in the samples increases, the shift of the inflection point to the region of high temperatures may indicate the interaction of macromolecules and the formation of semi-crosslinked systems.

For the PAN-0 sample, a broader peak is observed at the third stage of degradation. The situation is similar to the PAN-180 sample at the second stage (Table 4). With an increase in the amount of H_2O_2 during processing, the maximum rate of degradation in the first stage also decreases. It is 68.4%/min for PAN-0, 64.9%/min for the PAN-100 sample and 20.6%/min for the PAN-180 sample. In this case, the second stage is accompanied by an increase in mass loss: 15.6% for the PAN-0 sample and 23.0% for PAN-180.

As evident from Table 4, the thermal stability of textile materials increases in the process of functionalization, as seen by higher values of degradation temperatures ($T_{d(5\%)}$, $T_{d(50\%)}$, $T_{d(max)}$).

Table 4: Thermal characteristics (in an inert atmosphere and in air) of initial and functionalized samples of textile materials based on acrylonitrile copolymers

Environment	Sample	$T_{d(5\%)}$ (°C)	$T_{d(50\%)}$ (°C)	$T_{d\,(max)}$ (°C)
N_2	PAN-0	304.13	456.16	679
	PAN-100	307.6	462.23	685
	PAN-180	309.64	494.44	692
O_2	PAN-0	304.26	590.66	676
	PAN-100	307.92	591.74	680
	PAN-180	314.46	596.94	687

The following changes were also noted during the course of the study: the rate of thermal-oxidative degradation and the index of sample mass loss. This confirms the change in fibre structure and testifies to changes in the surface under various functionalization conditions.

4 Conclusion

The study of the thermogravimetry and differential thermogravimetry thermooxide of PAN-modified fibres was carried out using additional thermogravimetric analysis. The study of the thermal oxidation and thermal degradation of samples of modified PAN fibres was performed. Thermogravimetric analysis was used for this purpose. It was established that in the process of functionalization there was a change in the rate of thermal-oxidative degradation. There is a change in the loss of the mass of the sample under different conditions of functionalization. When the PAN is heated to 130 °C, the complete glass transition of the polymer occurred. At a temperature of around 100 °C, the self-regulation of the structure of the polymeric material structure intensified with the formation of the mesophase.

When the initial PAN textile material was heated to a temperature of ~70–80 °C, a weakening of intermolecular contacts was observed, which led to an increase in the mobility of macromolecular segments. The temperature of 78 °C can be considered the initial glass transition temperature $T_{g,T1}$, while $T_{g,T2}$ - 121 °C can be considered the final temperature for the initial sample. When heated above a temperature of 130 °C, chemical changes in the polymer occur, in particular, the process of cyclization.

The analysis of the TGA data of thermally oxidized samples shows that they retain the complex stepwise nature of decomposition inherent in the initial fibrous material based on acrylonitrile copolymers. The conducted analysis shows the absence of significant changes in the reasonable conditions of chemical modification and the practical operation of textile materials.

The influence of the surface functionalization of polyacrylonitrile textile material was researched, with results showing insignificant changes in strength characteristics. The absence of the deterioration of consumer properties of fibrous material was observed. Thus, the conducted research highlights the possibility of practical application of functionalized textile polyacrylonitrile materials in domestic and technical applications (production of knitwear, fabrics for various purposes, carpets, curtain products, filter pads, etc.), where the influence of thermal characteristics on functional properties is an important factor.

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Viruses and Bacteria – Antiviral and Antibacterial Textile Materials: A Review

Virusi in bakterije - protivirusni in protibakterijski tekstilni materiali - pregled

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Abstract

Protective textiles, such as antiviral and antimicrobial textiles, are essential for daily human health during pandemics. This paper focused on different studies of bacteria, the classification of viruses and features, different antibacterial and antiviral agents, and the manufacture of antibacterial and antiviral textiles and masks. This review primarily considered the representative specifications of ideal antiviral agents compatible with antimicrobial textile purposes.
Keywords: virus classifications, antibacterial agents, pandemic, fabric finishing

Izvleček

Zaščitne tekstilije, kot so protivirusne in protimikrobne tekstilije, so v pandemičnih razmerah bistvenega pomena za človekovo zdravje v vsakdanjem življenju. Prispevek obravnava različne raziskave bakterij, razvrstitev in značilnosti virusov, različna protibakterijska in protivirusna sredstva ter izdelavo protibakterijskih in protivirusnih tekstilij in mask. Ta pregled se osredinja predvsem na specifikacije idealnih protivirusnih sredstev, združljivih s protimikrobnimi tekstilnimi sredstvi.
Ključne besede: razvrstitev virusov, protibakterijska sredstva, pandemija, plemenitenje tekstilije

1 Introduction

The global spread of COVID-19 has had serious economic, social and political consequences around the world. Some vaccines against COVID-19 were listed by the World Health Organization (WHO) for emergency use, while many people around the world have been vaccinated. However, personal protective measures should be taken in public places, and there is a growing need to produce antiviral and protective textiles against COVID-19 and other viruses. Textiles and materials are a breeding ground for the transmission of infectious diseases by microorganisms and viruses [1]. The world today faces some extraordinary challenges in managing viral emergencies with the outbreak of COVID-19. With an ever-increasing death toll, COVID-19, the latest of three pandemics in the past two decades in addition to the SARS epidemic in 2002 and the MERS epidemic in 2012, has claimed millions of lives in many countries, according to the latest report of the WHO [2]. It is important therefore to have antiviral textiles to protect people from unknown viruses before the development of a vaccine or a drug. This paper reviews different classes of bacteria and viruses, as well as different types of antibacterial and antiviral agents for textiles.

2 Viruses and bacteria

2.1 Virus

2.1.1 Virus features

Viruses originally caused disease. Viruses are small, from a few nanometres to larger than some bacteria, and can be 20,200 nm in length, while some can be 1,000 nm in length. Human cells are typically around 1,030 μm (microns) in diameter. For example, influenza and human immunodeficiency virus are approximately 100 nm in diameter. Poxviruses, such as the variola virus can be around 400 nm in length, while the dangerous Ebola and filoviruses are only 80 nm in diameter but spread in elongated threads that can reach lengths of over 1,000 nm. Megaviruses are about 400 nm in diameter and Pandoraviruses are about 1,000 nm long. All viruses are no smaller than bacteria; the size of the bacteria is typically around 2,000–3,000 nm, but some, known as mycobacteria, can be 10 times smaller and within the reach of these large viruses [3]. Viruses need the internal environment of the cell to create new infectious virus particles. Viruses use cells' energy and machinery to make and collect new virions. Humans, plants, animals, bacteria and all living cells have double-stranded DNA (dsDNA) through their genetic material. Viruses have genomes, or genetic material, created from DNA or RNA (but not both). Genomes are not essentially double-stranded, and different virus types can have single-stranded DNA (ssDNA) genomes, while viruses with RNA genomes can be single-stranded or double-stranded. A particular virus will have some type of nucleic acid genome. The size of the genome can vary in different viruses.

2.1.2 Virus structure

The nucleic acid genome plays an important role in the production of progeny virions. In order to protect the fragile nucleic acid from a serious situation, the virus surrounds its nucleic acid with a capsid, which is a small protein shell that is difficult to break. A capsid has one or more diverse models of proteins that can be repeated to make it flexible. Nucleic acid and a capsid together form the nucleocapsid of a virion. Viral genomes are generally very small. Genes encode the information to make proteins, while tiny genomes cannot encode different proteins. In addition, viruses have a lipid membrane surrounding the capsid referred to as an envelope, which derives from one of the cell membranes such as the plasma membrane [3].

2.1.3 Virus classification

In the 1970s, David Baltimore classified viruses into seven classes based on the type of nucleic acid genome and viral repetition strategy (Figure 1). The seven classes of the Baltimore classification are as follows: dsDNA viruses, ssDNA viruses, dsRNA viruses, positive-sense ssRNA viruses, negative-sense ssRNA viruses, RNA viruses that reverse transcribe and DNA viruses that reverse transcribe [4].

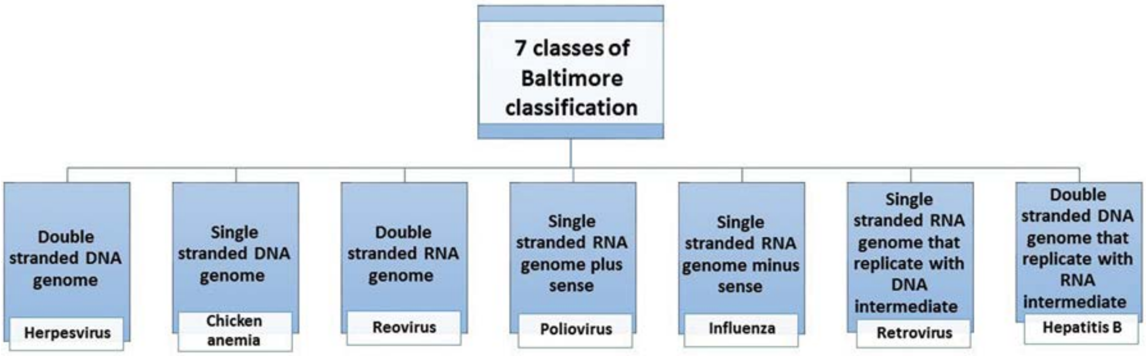

Figure 1: Baltimore classification for viruses and examples

Class I: Double stranded DNA (dsDNA) viruses

A double-stranded DNA virus that is extremely dependent on the host cell cycle, invades the host nucleus before beginning replication. Adenoviridae, Herpesviridae, and Papoviridae are some examples of class I viruses.

Class II: Single stranded DNA (ssDNA) viruses

These ssDNA viruses often have circular genomes and replicate within the cell nucleus through a rolling circle method. Circoviridae, Anelloviridae and Parvoviridae are some examples of these viruses.

Class III: Double stranded RNA (dsRNA) viruses

Double-stranded RNA viruses affect host polymerases like DNA viruses and duplicate in the nuclear capsid of the host cell cytoplasm. The genomes of these viruses are divisible and each individual gene encodes only one protein. Rheoviridae and Birnaviridae are examples of class III viruses.

Class IV: Positive-sense single-stranded RNA (ssRNA) viruses

Class IV ssRNA viruses can be read by ribosomes for decoding into proteins and have positive-sense RNA genomes. These viruses are separated into polycistronic mRNA and complex transcription viruses. Polycistronic mRNA is a polyprotein that is cleaved into different proteins. Astroviridae, Flaviviridae, Coronaviridae and Picornaviridae are some examples of this class.

Class V: Negative-sense single-stranded RNA (ssRNA) viruses

Single-stranded RNA (ssRNA) viruses have a negative RNA genome and must be copied by a viral polymerase to obtain a clear and readable mRNA strand. The genomes of these viruses may or may not be segmented. Paramyxoviridae, Orthomyxoviridae and Rhabodviridae are some examples of ssRNA viruses.

Class VI: Positive-sense ssRNA reverse transcriptase viruses

These viruses replicate via a DNA intermediate, have a positive sense and have a single-stranded RNA genome. RNA is converted into DNA by a reverse transcriptase, before which the DNA is inserted into the host genome and then translated by the enzyme integrase. Retroviruses such as HIV, Pseudoviridae and Metaviridae are some examples of ssRNA viruses.

Class VII: Double-stranded DNA (dsDNA) reverse transcriptase viruses

These viruses have a double-stranded DNA genome and replicate via ssRNA mediators. The dsDNA genome has gaps and could be a template for making mRNA. Conversely, RNA can be transcribed back into DNA for genome reproduction. The hepatitis B virus is an example of a dsDNA virus. On the other hand, the International Committee on the Taxonomy of Viruses (ICTV) was asked to assign viruses to a taxonomic hierarchy (Figure 2). The taxonomy used family, genus, order and species to categorize viruses. Viruses are not classified under the same taxonomic tree as living organisms because they are not living [3–4].

The International Committee on the Taxonomy (ICT) of Viruses classified coronaviruses into the Coronaviridae family and the Nidovirales order. Toroviruses and coronaviruses are the two typical genera of the Coronaviridae family; they were also classified to the Coronavirinae subfamily. Subfamilies are formed based on rooted and unrooted genetic trees and partial nucleotide sequences of RNA-dependent RNA polymerase. So far, Coronavirinae have been recognized and divided into five genera: alpha (α) coronavirus, beta (β) coronavirus, gamma (γ) coronavirus, delta (δ) coronavirus and omicron coronavirus [5–7].

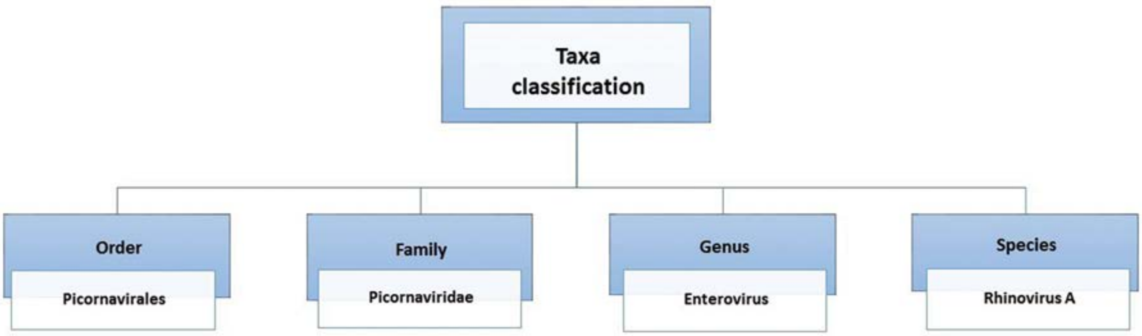

Figure 2: Taxonomy classification of viruses and examples

2.1.4 Virus spread and transmission

Viruses can be transmitted directly from one animal to another (sexual, respiratory, faecal-oral and blood), or via vertical transmission from parent to children, or through contaminated water and food. Some viruses, such as the measles mumps, polio, rubella and chickenpox viruses, are host-specific and only infect just humans. However, some viruses, such as influenza viruses, can be spread between humans and animals [8].

2.2 Bacteria

Bacteria are small single-celled organisms that are found everywhere on earth and are essential to ecosystems. Various strains of bacteria are harmless and some are even helpful and beneficial. Bacteria are classified and identified according to the interests of microbiologists and other scientists. The classification of bacteria may be done using different grouping methods, such as gram stain and bacterial cell wall, shape, mode of nutrition, temperature requirement, oxygen requirement, pH of growth, osmotic pressure requirement, number of flagella and spore formation (Figure 3). Amongst different classifications systems, the Gram stain, which was discovered by Danish microbiologist Hans Christian Gram in 1884, remains an important and useful technique until the present [9]. It allows a large proportion of clinically important bacteria to be classified as either Gram positive or negative based on their morphology and differential staining properties [10]. In 1872, Cohn classified bacteria to four major types depending, on their shapes:

A. **Cocci (spherical)**: These types of bacteria are unicellular, spherical or elliptical shape. Either they may remain as a single cell or may aggregate together for various configurations. They are classified as follows:
   - **Monococcus:** they are also called micrococcus and are represented by a single round shape. Example: *Micrococcus flavus.*

- **Diplococcus:** the cell of the Diplococcus divides in a particular plane and after division, the cells remain attached to each other. Example: *Diplococcus pneumonia*.
- **Streptococcus:** here the cells divide repeatedly in one plane to form a chain of cells. Example: *Streptococcus pyogenes*.
- **Tetracoccus:** this consists of four round cells, which divide in two planes at right angles to one another. Example: *Gaffkya tetragena*. *Staphylococcus* – here the cells divide into three planes forming structured-like bunches of grapes, giving an irregular configuration. Example: *Staphylococcus aureus*.
- **Sarcina:** in this case, the cells divide in three planes but form a cube-like configuration consisting of eight or sixteen cells of regular shape. Example: *Sarcina lutea*.

B. **Bacilli (rod):** these are rod-shaped or cylindrical bacteria that either remain singly or in pairs. Example: *Bacillus cereus*.

C. **Vibro (comma):** the vibro are the curved, comma-shaped bacteria and represented by a single genus. Example: *Vibro cholerae*.

D. **Spirilla (spiral):** these types of bacteria are spiral or spring-like with multiple curvature and terminal flagella. Example: *Spirillum volutans* [11].

Actinomycetes are branching filamentous bacteria, so called because of their fancied resemblance to the radiating rays of the sun when seen in tissue lesions (from actis meaning ray and mykes meaning fungus). **Mycoplasmas** are bacteria that are cell-wall deficient and thus do not possess a stable morphology. They occur as round or oval bodies, and as interlacing filaments [12].

On the basis of mode of nutrition, bacteria can be classified to Phototrophs, Chemotrophs, Autotrophs, and Heterotrophs [13]. On the basis of temperature requirement, they can also be classified to Psychrophiles, Psychrotrops (facultative psychrophiles), Mesophiles, Thermophiles and Hypethermophiles [14]. Bacteria classified on the basis of the pH of growth are divided into Acidophiles, Alkaliphiles and Neutrophiles [15].

Bacteria classified based on osmotic pressure requirement are divided into Halophiles, Extreme or Obligate Halophiles and Facultative Halophiles [16]. Bacteria can also be classified as Atrichos, Monotrichous, Lophotrichous, Amphitrichous and Peritrichous based on flagella.

Based on spore formation, bacteria can be divided into spore-forming bacteria (endospore-forming bacteria and exospore-forming bacteria) and non-sporing bacteria [17].

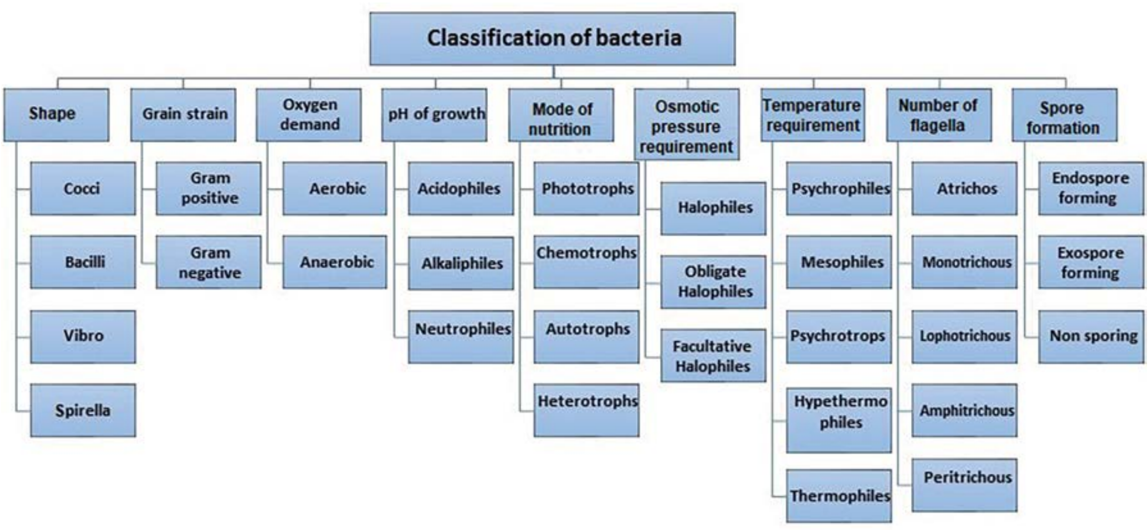

Figure 3: Classification of bacteria

3 Antiviral and antibacterial agents

An antimicrobial agent kills microorganisms or inhibits their growth. Antimicrobial agents may be antibacterial, which work against bacteria; antifungal, which fight against fungi; microbiocides, which kill microbes; microbiostatic, growth inhibitors of microbes; and antiviral, which kill viruses [18].

3.1 Natural sources and plants

Common medicines created based on therapeutic plants have been used by man for the treatment of numerous diseases in the past. Plants have active naturally compounds [19–20]. Today, partial chemicals are presented for viral diseases, and the potential antiviral properties of natural sources should be considered [21]. Therapeutic plants can stop the repeat cycle of different types of DNA or RNA viruses, such as HIV, HSV influenza virus, human rhinovirus, hepatitis B and C virus (HBV and HCV), and Dengue virus. Daidzein (soybean), Naringin (grape), hesperetin (citrus), and quercetin (foods and fruits, such as green and black tea, apples, onions, citrus fruits, tomatoes and some other plants) are some examples of therapeutic plants [21]. In 2005, Berrin Özcelik et al. investigated the antibacterial, antifungal and antiviral activities of the lipophilic extracts of *Pistacia vera* L. from the Anacardiaceae family, native to Asia and typically distributed in the Mediterranean region and the United States. HSV and PIV have been used to study the antiviral activity of lipophilic extracts and potent antiviral activity against aciclovir and oseltamivir has been reported [22].

The antiviral activity of Hawaiian medicinal plants against human immunodeficiency virus type 1 (HIV-1) was investigated by Locher in 1996. Hawaiian medicinal plants have antiviral properties against HIV-1. They reported that aqueous extracts of Eugenia malaccensis and the leaves of Pluchea indica, methanol and water extracts of the leaves and bark of Pipturusalbidus (grey), plant extracts of Aleurites moluccana, Psychotria hawaiiensis (grey), Clermontia aborescens, and Scaevola sericea demonstrate good antiviral activity [23].

Dichloromethane extracts from three Artocarpus species from Purwodadi Botanical Garden (East Java, Indonesia) – Artocarpus altilis, Artocarpus camansi and Artocarpus heterophyllus – were reported by Hafid et al. and tested for their antiviral activity against the hepatitis C virus. Simple extract samples were prepared from three Artocarpus species. They concluded that extracts of Artocarpus altilis and Artocarpus camansi demonstrated hepatitis C virus inhibition of more than 90%, while extracts of Artocarpus heterophyllus demonstrated hepatitis C virus inhibition of more than 80% inhibition [24]. In addition, cyanovirin N, and 11 kDa protein from blue-green algae deactivates HIV-1, while sulfated polysaccharides from algae and algae have anti-HSV and anti-HIV properties [25].

In other research, the effect of carrageenan/cyclodextrin hydrogel/honey bee propolis extract on cationized cotton fabric was studied by Sharaf & Naggar in 2019. Propolis has therapeutic, antifungal, antibacterial, antiviral, anti-inflammatory, antioxidant and antitumor properties. An innovative biodegradable and eco-friendly hydrogel was made from β-cyclodextrin, Kappa carrageenan encapsulated and honey bee propolis extract. They reported that treated fabric have antimicrobial activity and can be used as wound healing fabrics [26].

Sneezing micro-droplets can be easily inhibited. The most active compound in liquorice root in inhibiting the virus associated with SARS is glycyrrhizin. Glycyrrhizic acid (GLR), a triterpenoid saponin isolated primarily from liquorice root, is active against a variety of human viruses. Glycyrrhizic acid isolated from liquorice has antiviral activity and can deactivate the virus and stop replication. Droplet microbes are bound to the agent and infectious droplets are rapidly opened by hydrophilic action, resulting in virus exposure. The purifying and inhibitory properties of liquorice root quickly inactivate the virus. GL and GA can damage biomolecules, such as lipids, parts and DNA [27].

The antiviral, antibacterial and antifungal activities of some flavonoids were studied by Deliorman Orhana et al. in 2010. Flavonoids are natural elements with different phenolic structures found in fruits, vegetables, bark, grains, roots, flowers, stems, tea and wine. They reported that flavonoids effectively inhibited HSV-1 and isolated strains of E. faecalis [28].

In 2020, Fakharani et al. studied extracts from Spirulina platensis that exhibit antiviral activity against numerous viruses. Calcium spirulan is a natural sulfated polysaccharide. They reported that sulfoglycolipids have good antiviral activity against human immunodeficiency virus (HIV) rather than preventing reverse transcriptase activity. Moreover, many peptides, such as cyclic ichthyopeptins A, depsipeptides and ichthyopeptins B extracted from Microcystis ichthyoblabe cultures, showed antiviral activity against the influenza A virus. Cyanobacterial lectins show antiviral activity against hepatitis virus, HSV, influenza virus and Ebola virus [29]. Solanum rantonnetii methanol (80%) is non-toxic in cell culture and has antiviral activity against HCV. This extract is active at low concentrations. In 2014, Rashed et al. reported that quercetin 3-methyl ether and kaempferol 8-methyl ether produced from Solanum rantonnetii extracts have antiviral activity against HCV at high concentration [30].

3.2 Nanoparticles

In preventing the transmission of a virus, the principal purpose is to stop the virus from reaching healthy people. Nanomaterials have distinctive physical and chemical properties and have been applied to create recent antiviral agents [2]. Nanotechnology uses many beneficial nanoparticle-based antiviral agents, together with nanomaterial coating strategies to prevent the virus from contaminating sensitive individuals. It can decrease viral spread exceptionally through satisfactory and easy-to-maintain results and solutions. Antiviral nanomaterials can inactivate multiple types of microbes through a specific platform. In addition, due to the nature of nanomaterials, they can inhibit virus attachment and inhibit virus entry into the cell [2].

Recently, several well-designed nanoparticles such as gold, silver, titanium and zinc nanoparticles, carbon dots, graphene oxide, quantum dots, nanoclusters, silicon materials, polymers and dendrimers have been shown to have significant antiviral ability. They have different antiviral activity and mechanism, and inhibition effectiveness [31–32].

Nanomaterials have large modifiable surface areas and can be functionalized with various molecules that can be used as nanocarriers, nanomedicines and nano-based vaccines to effectively engineer appropriate immunological memory [33]. The use of nanoparticles and nanomaterials has been applied in many industries such as textiles, cosmetics, electronics and medicine [34]. Functional carbon dots and carbon quantum dots can be used as antiviral agents [2].

In 2021, Li et al. reported that coating cell membrane with nanostructures, where the membrane is secured by a nanocore, may result in the avoidance of undesirable membrane fusion. They reported that cell membranes coated with nanobait successfully capture and divert Zika virus (ZIKV) away from healthy cells. To reduce the fusion property of the membrane, coating the lipid membrane with a nanoparticle core stabilizes the cell [33].

3.3 Metal and metal oxide-based nanoparticles (NPs)

Metal and the metal oxide-based NPs show antibacterial activity alone, but demonstrate superior antibiotic activity when combined with metal nanoparticles or metal oxide-based nanoparticles or composites with other metal nanoparticles or antibiotics or biomolecules [18].

There are some studies on the antimicrobial properties of metal nanoparticles, which are affected by reactive oxygen species (ROS) generation, the physical abrasion of the membrane due to interaction with nanoparticles, the loss of membrane integrity owing to nanoparticle binding, or by the release of metal ions from the nanoparticles.

Metal-based nanoparticles have impressive physico-chemical properties. Due to their tiny size and high specific surface, they can interact with microorganisms and viruses. Various metal and metal oxide-based nanoparticles, such as copper, silver, gold, zinc and titanium, have been provided as antibacterial. In general, host cell infection by viruses occurs through attachment, penetration, replication and budding mechanisms [35].

In contrast, metal-based nanoparticles may interact with a microorganism in three streps: first by attaching to the virus and inhibiting the entry of virus attachment into the cell; second by the generation of active oxygen and other ions and radicals sticking to the wall and completing the structure of viral proteins and nucleic acids; and finally by simulating the cell nucleus to strengthen the immune system to enhance host-cell response and inhibit viral potential and spread.

Antimicrobial nanomaterials can be applied as a coating through different processes, such as the electrophoretic deposition of lysozyme silver nanoparticles for medical purposes [2]. Silver nanoparticles (Ag NPs) can conveniently interact with the outer layers of a virus, circumventing their attachment and entry into the host cells. The typical particle size of Ag NPs can compromise antiviral activity. Some therapeutics, such as oseltamivir (OTV), zanamivir, aminoadamantane and amantadine, can be adopted as surface ligands for Ag NPs to boost antiviral properties. Other silver compounds, such as Ag_2S, silver bis(citrato)germinate, $AgNO_3$ and silver acesulfame, are also considered effective antiviral materials [36].

Gold nanoparticles (Au NPs) have exceptional stability, biocompatibility and the ability to bind with biological ligands (bioconjugation), and can be used as antiviral agents. Au NPs can block viral particles and inhibit virus entry or attachment, and control the spread of a virus [32].

Copper oxide nanoparticles have great stability, broad antibacterial properties, are cost-effective and are used extensively in antibacterial materials [37].

Copper ions that are released from CuO nanoparticles can produce reactive oxygen species (ROS). They can collapse HSV capsid integrity, damaging the entire genome. Cuprous oxide (Cu_2O) nanoparticles also have antiviral properties. They can attach and enter to HCV virions.

The antiviral ability of Cu_2O is better than other Cu-based compounds. CuI particles demonstrated a noticeable antiviral reaction against influenza A viruses (HIN1). CuI creates hydroxyl radicals in aqueous solutions, and can deactivate a virus by oxidizing surficial lipid groups. Different cuprous combinations like CuCl and Cu_2S have anti infections properties [38].

Zinc oxide and titanium oxide have been effective in biological valuations. ZnO nanoparticles can easily surround the herpes virus and prevent the infection of the host cells. The mechanism of inhibition is based on the damaging of the lipid membrane and the blocking of virus attachment.

Moreover, some other metals and metal oxide-based anti-viruses, such as gallium and iron oxide or tin oxide (SnO_2), can be used for protective fabrics [39–40].

Nanoparticles have antiviral activity through various mechanisms, such as hepatitis B virus inactivation, virus capture and retention, the prevention of virus cell entry, and the blocking of virus replication and reproduction.

Ag-, Ti- and carbon-based nanomaterials have direct interaction with viruses and cause virus inactivation through various ways, depending on the nature of viruses and nanomaterials. A multi-walled carbon nanotube, negatively charged graphene oxide (GO), TiO_2 NPs, GO-conjugated AgNPs, AgNP-MHCs (aminopropyl-functionalized Fe_3O_4-SiO2 core-shell magnetic hybrid colloid-decorated AgNPs), copper ions in NPs and Au/CuS core-shell NPs can inactivate viruses.

Metal-based NPs and metal oxide-based NPs have antibacterial, antiviral and antifungal properties. In particular, copper oxide (CuO) and zinc oxide (ZnO) NPs are exceptionally effective against viruses and multiple bacterial strains, and can be applied on textiles and medical devices. Antibacterial CuO and ZnO nano metal oxides are generally safe on undamaged epidermis [34, 41]. Silver (Ag) has antimicrobial properties against many bacteria, fungi and viruses. Ag nanoparticles (AgNP) are utilized in fabrics, wound dressings, medical devices and deodorant sprays [6]. Many researchers reported the effective antiviral activity of AgNPs against several human pathogenic viruses, such as respiratory syncytial virus (RSV), influenza virus, norovirus, hepatitis B virus (HBV) and human immunodeficiency virus (HIV). In 2020, Jeremiah et al. reported that AgNPs are extremely powerful microbicides against SARS-CoV-2. AgNPs have cytotoxic effects and should be used with caution and can harm environmental ecosystems in the event of improper preparation and disposal. They concluded that the antiviral effect of AgNPs with a size of 2 to 15 nm was most effective [6].

Solid-state copper oxide (Cu_2O) deactivate influenza A virus and bacteriophage Q beta well, but copper oxide (CuO) and silver sulfide (Ag_2S) show little antiviral activity. Copper ions from copper chloride ($CuCl_2$) have a slight impact on the activity of bacteriophage Q beta, while copper ions deactivate influenza A. Silver ions from silver nitrate ($AgNO_3$) and silver (I) oxide (Ag_2O) in solution demonstrate the good inactivation of influenza and the weak inactivation of bacteriophage Q beta. Solid-state Cu_2O is more effective against both kinds of viruses, enveloped and non-enveloped, compared to silver compounds, owing to excellent an inactivation mechanism aided by direct contact. In addition, Cu_2O is commonly available and inexpensive. Cu_2O can also be combined with other biocidal chemicals, such as photocatalytic titanium oxide nanoparticles [42]. In 1998, Puddua et al. investigated the antiviral impact of bovine lactoferrin saturated with metal ions (ferric, manganese or zinc ions) on the early steps of human HIV-1 infection. They reported that HIV-1 replication and syncytium formation were effectively inhibited by lactoferrins at a certain dose [43].

3.4 Carbon-based materials

Carbon atoms bind to each other in many ways with different binding energies, generating them to form different allotropes, such as carbon dots, single-wall or multi-wall carbon nanotubes and 2D graphene oxide. Graphene oxide has antipathogenic and antiviral properties against pseudorabies virus, which is a DNA virus, and porcine epidemic diarrhoea virus, which is an RNA virus. Graphene oxide and decreased graphene oxide demonstrated interesting antiviral properties due to their negative charges and monolayer structure. Negatively charged graphene oxide shows more electrostatic interaction with viruses, and enters the cell and destroys the structure of the virus.

Organic antiviral materials destroy pathogens by reacting on surface proteins or nucleic acids, or by terminating pathogen morphology or spreading through the generation of reactive oxygen species upon external stimulation. The antimicrobial properties of organic antiviral materials are separated into antiviral and photodynamic antiviral materials. Intrinsic antiviral material have a special chemical structure that can inactivate a virus. Numerous natural and synthetic compounds have intrinsic antiviral properties [35].

3.5 Povidoneiodine

The use of povidoneiodine (PVPI) is recognized in medical education. In vitro reviews of cell cultures infected with HIV and H_5N_1 virus have revealed that PVPI has an antiviral implication, while the cell hosts were unchanged and survived. The utilization of PVPI has no toxic influence on thyroid function. Used intravenously, it has demonstrated substantial results against microbial, viral, fungal and parasitic infections, and has anti-inflammatory activity, especially in cases where antibiotics are ineffective. Its potential uses are as a blood disinfectant, to treat burns, to prevent cancer or to treat the H_5N_1 avian influenza virus after it has been mutated, while there are other possible uses [44].

3.6 Chitosan

Chitosan, a biopolymer, has valuable properties, such as biorenewability, biodegradability, biocompatibility and non-toxicity, and has been studied extensively for its therapeutic and medicinal uses. The antibacterial and antifungal activities of chitosan have been the subject of a great deal of research. Chitosan only shows its antibacterial activity in an acidic media due to its poor solubility at pH values above 6.5. Chitosan derivatives such as carboxymethylchitosan (CMCS) also have good antimicrobial activity [45]. Chitosan-based particles have been described as promising vehicles for ocular drug delivery, mainly due to their ability to bring the corneal and conjunctival surfaces into close contact, and because of their negligible toxic effects [46]. To utilize the biocidal effect of some metal nanoparticles for the production of antibacterial textiles and fibres, an aqueous emulsion of chitosan nanoparticles encapsulating metal oxide can be prepared [47].

3.7 Photodynamic antiviral and antibacterial materials

Photodynamic antiviral materials are effective, broad-spectrum and long-acting pathogen killers, and are environmentally friendly. They are generally powered by light to generate reactive oxygen species that can selectively kill pathogens. Some photodynamic materials have immediate biocidal properties under dark conditions and low light [48].

4 Antimicrobial fabric and textile

Due to the presence of microorganisms, such as viruses, bacteria and fungi, antimicrobial textile materials have been created that effectively protect against these pathogens. Antimicrobial textiles are active textiles that can kill microorganisms or prevent their growth. Recently, various types of antimicrobial textiles, such as antibacterial, antifungal and antiviral textiles, have been studied and manufactured (Figure 4). Modified methods are used to determine the antimicrobial properties of textiles against bacterial and fungal particles. These antimicrobial textiles are utilized in a range of applications, such as healthcare, hygiene, medicine, filtration, packaging and storage, sportswear, ventilation and water purification systems [49–50]. In clinical and hospital environments where the mainly problem is virus transmission, it is necessary to use appropriate textiles that form a good barrier against the transmission of microorganisms, especially when wet.

There are two main procedures for producing antimicrobial and antiviral textiles. The first method is to mix the antiviral material with the polymer spinning solution and then spin it. The second method is through finishing, where the antiviral material is added to the fabric finishing agent via impregnation or the padding method to produce a fabric's antiviral function [51]. Padding, grafting, spraying and cross-linking are some of the most applicable methods for producing antimicrobial textiles. The development of antimicrobial textiles made of synthetic fibres has facilitated new methods, such as compounding extrusion and melt blending. At the same time, the use of plasma treatments, colloidal solutions, magnetron sputtering, sol–gel processes, microencapsulation techniques, or even the *in situ* synthesis of different antimicrobials onto textile materials are new, effective and stable methods [52].

Different chemicals, such as mineral compounds (oxides, metal ions and photocatalysts), organic compounds (amines or quaternary ammonium compounds, phenols, biguanide, alcohols and aldehydes), natural compounds and organometallic compounds, can be used for the antimicrobial finishes of textile materials [53]. In addition, antibacterial active protective technologies developed by blending antibacterial fibres into textiles could be another method for integrating antibacterial properties into textiles [54].

Using proper raw materials, suitable yarn constructions, appropriate weaving model and effective and ecofriendly antimicrobial finishing can reduce microorganism problems and virus transmission

[55]. Fabrics have three-dimensional structures and the antiviral treatment of them can reduce microorganism, disease transmission and the risk of infection in hospitals. Primarily in the hospital environment, there are many concerns about exposure to various microorganisms that can be easily transmitted from the environment to humans and cause various diseases. Innovative textile products can act as a barrier to reduce the risk of infection for people with compromised immune systems. In the hospital environment, there are many factors for human infection, despite the observance of hospital protocols. Using the suitable fabrics can reduce the risk of pathogens that cause discomfort to patients [55–56].

Textile fabrics, such as gowns and drapes, are used to care for and protect humans by inhibiting the transfer of microorganisms. Gowns are items of protective apparel designed to ensure the protection of the wearer from the spread of infection should they come into contact with potentially infectious liquids and solid materials. Gowns can also prevent the transfer of pathogens to vulnerable patients with compromised immune systems [57].

Textile products for medical use can be reusable or disposable. Non-woven textiles with different compositions, such as viscose/polyester or polypropylene, are frequently used for disposable products. Alternatively, cotton/polyester blends, polyester or cotton are used for reusable textile materials. Reusable surgical gowns are more effective and ecological because of their superior water vapor transmission and the fact that they generate less solid waste. For some products, it essential to use laminates for better repellence. Textile fibres are generally classified as natural fibres (animal fibre, vegetable fibre and mineral fibres) and man-made fibres (regenerated fibres and synthetic fibres) [55].

Consequently, antibacterial finishing is carried out to give textiles improved resistance to microorganisms, to avoid the destruction and discoloration of the fibres, and to improve the durability and extended life of the textile materials, which plays an important role in hospitals and medical centres by minimizing the microbial colonization of textiles and the potential for transmission from fabric surfaces [58]. Public awareness of infectious diseases has increased, and researchers in the textile industry have developed antimicrobial fabrics by adding various antibacterial and antiviral compounds [59].

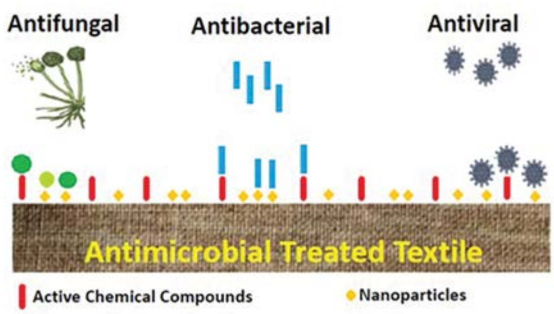

Figure 4: Antimicrobial treated textile; antibacterial agents inhibit the growth of bacteria, antifungal agents prevent the growth of fungal and spore germination, and antiviral agents modify the surface structures of viruses [50]

In a 2018 research paper by Ren et al., non-woven fabrics were coated with 1-chloro-2,2,5,5-tetramethyl-4-imidazolidinone (MC, a variety of N-halamines) using the pad-dry process. They reported that MC can successfully inactivate the AI virus in the suspension and interfere with the RNA of the AI virus. Fabrics used for air filtration can be coated with MC due to their actual microbial activity [60]. In 2021, Garren et al. studied nitric oxide and its effect on viral infection. They reported that nitric oxide is a significant therapeutic choice for treating virus-based illnesses, such as skin infections and respiratory viral infections. Gaseous nitric oxide, as an extensive antiviral agent, and other nitric oxide donor therapies for viral infections are helpful and effective. Nitric oxide releasing materials relieve complications associated with viral infections [61].

In a review paper, Norrahim et al. discussed the fabrication of nanocellulose-based antimicrobial materials against viruses, bacteria, fungi, algae and protozoa by employing variable functional groups, including aldehyde groups, quaternary ammonium, metal, metal oxide nanoparticles and chitosan. Nanocellulose alone cannot protect human beings from developing a wound infection as it is not an antimicrobial agent and should be used with antimicrobial agents through surface modification using biocidal agents, making them effective against wound infection [62].

In 2017, Ustaoglu Iyigundogdu et al. studied the application of sodium pentaborate pentahydrate and triclosan on cotton fabrics to produce antimicrobial textiles. They concluded that treating cotton fabric with 3% sodium pentaborate pentahydrate, 0.03% triclosan and 7% glucapone exhibited antibacterial and antifungal properties. In addition, treated cotton fabrics demonstrated good antibacterial and antiviral activity against adenovirus type 5 and poliovirus type 1, while sodium pentaborate pentahydrate and triclosan solution can be used for antimicrobial textile finishing. They reported that sulfated polysaccharides and copolymers of acrylic acid with vinyl alcohol sulfate demonstrate antiviral activity against human cytomegalovirus (CMV) [63].

N-halamine is an active organic synthetic antibacterial agent. It is generally used for the antibacterial modification of fibres, fabrics and non-wovens. N-halamine deposition is stable, non-volatile and effective. N-halamine can kill AI viruses in a short time and disrupt their genetic and repetition abilities. Many antiviral agents could be employed to develop protective clothing and bedding with antiviral activity against viruses.

5 Antiviral protective material - mask

In 2020, Macintyre and Chughtai reported that the use of masks by healthy people can be beneficial and prevent the spread of COVID-19. It also prevents the infection of health care worker and deaths from COVID-19, as aerosolization has been reported in the hospital environment [64].

Research on antimicrobial face masks started gaining momentum after the SARS-2003 epidemic. With the onset of COVID-19, the spike in demand for antimicrobial face masks has resulted in a spike in market share [65–66].

Like many diseases, COVID-19 can be spread by an infected and sick person through the emission or exhalation of bodily fluids or aerosol particles that carry the virus, and can attach to multiple sites and surfaces and thus be touched by the recipient [67]. Aerosol pathogens are a main source of respiratory diseases and body-to-body transmission. Respiratory protection and air transfer parameters are integrated in a complex system that can be divided into different two-way mechanisms, such as release, infection, filtration and protection. Aerosol particles vary in size and play an important role in the spread of airborne viruses. Therefore, further studies are urgently needed to curb the spread of viral infections. The use of ventilators can be an actual non-pharmaceutical intervention to reduce the spread of viruses, primarily through use by people in surrounding locations who come into contact with a person showing pandemic-like signs.

The rapid spread of COVID-19 led to an international quarantine in numerous countries. The COVID-19 epidemic has caused significant financial damage around the world. Researchers were very curious about how best to protect people before vaccines were available. The corona virus spreads primarily via saliva droplets. Controlling the spread of the virus in the early stages thus represents a great opportunity. A face mask can limit the spread of the virus inside and outside the mask [68]. The main material of the mask is non-woven fabric, which can prevent the virus through filtration. Conventional masks cannot kill the viruses and, after use and disposal, are prone to cross-infection and the development of another source of infection. By adding antiviral effects to masks, they last longer, are more efficient and cause fewer disposal problems [48]. Medical protective masks usually consist of fleece layers, such as spunbonded and melt-blown fleece. Interception, inertial impact and electrostatic precipitation are the mechanisms of filtration in protective masks.

The maximum filter performance of normal filter materials is 85%. Electret treatment can be used to improve the filtration efficiency of surgical masks. Electret treatment gives filter material, such as a mask, a positive charge and can increase filter efficacy to as much as 95%. Bacteria, viruses and aerosols are adversely charged and are blocked by the positively charged fibres in the masks. Different parameters, such as fibre diameter, fibre charge, filtration thickness, packing density and particles diameter, density, and velocity can affect protection performance. Proper use and handling are also very important, as improper use and handling could increase the risk of pathogens transmission, especially during the COVID-19 epidemic [68]. The filtration systems of masks can be functionalized by adding antiviral agents and fabricating reusable virus inactivating devices. The utilization of antiviral protective masks can minimize the threat of transmission of infectious agents through contaminated masks. Both inorganic and organic materials and composites can be employed to manufacture antiviral masks and fabrics [48]. Pathogenic viruses are small in size and cause diseases, such as measles, the common cold, flu, mumps, rubella, pneumonia and chickenpox, and these viruses should be removed from the air to increase public health and protect people from epidemics or pandemics [69].

The utilization of face masks can protect the wearer's nose and mouth from vapor droplets that contain viruses or other infectious pathogens. However, improper use and disposal can increase the danger of pathogen transmission significantly. On the other hand, copper oxide demonstrates excellent antiviral properties. Copper oxide can be incorporated into polymeric materials, giving them strong antibacterial activity and biocidal properties. Borkow et al. reported the incorporation of copper oxide into textile fibres, latex and other polymer products. Products treated with copper oxide retain their broad spectrum of antimicrobial and antiviral properties. They reported impregnating N95 disposable respirators (masks that filter 95% of 0.3 micron particles) with copper oxide, giving them effective biocidal anti-influenza properties without altering their physical properties. The utilization of biocide masks can significantly reduce the threat of contamination of hands or surroundings and after infection [70]. Commercial medical masks are inexpensive, but do not protect against airborne viruses. The surface of inexpensive filters can be modified with antiviral agents to give them antiviral properties [69]. "PU30" is developed by a group of Hong Kong Polytechnic University (PolyU) researchers. It is an antiviral, washable and reusable face mask that can be used 30 times. This anti-virus 3D printing material can kill the most common viruses, bacteria and the COVID-19 virus on surfaces. The main components of the material are resins and antiviral agents, such as cationic compounds, which can damage the membrane of the virus and eradicate its structure to kill the virus and bacteria. The research team states that PU30 can kill 70% of the COVID-19 virus and other viruses/bacteria surviving on a surface within two minutes, eliminates more than 90% of viruses within 10 minutes, and kills almost all viruses and bacteria in 20 minutes.

The PU30 face mask consists of 1) an outer layer containing cotton fabric treated with a hydrophobic cationic antiseptic coating, 2) a middle layer that contains a PTFE membrane with high filtration efficiency, and 3) an inner layer that is made of skin-friendly cotton Lycra fabric. They found that Bacterial Filtration Efficiency (BFE) was more than 95% after 30 washes in boiling water [71–72]. The disinfection components of the material are embedded in the products rather than coated on the surface, while daily cleaning with disinfectants such as bleach does not compromise its anti-virus performance. In 2020, Ka-Po Lee et al. from the PolyU team investigated the key aspects affecting the comfort of reusable face masks, but did not calculate antimicrobial or antiviral potential. Seven different mask types were selected and subjected to multiple tests, such as air and water vapor permeability, thermal conductivity and a wearing test. They concluded that washable face masks generated from thin layers of low-density knit fabric and a permeable filter are more breathable.

Mask comfort and breathability depend on various factors, such as fabric thickness, structure and density, fibre content, filter permeability, microclimate and fit. A low-density, thin-knit washable mask with a filter with good permeability is more breathable. It was also found that masks with sufficiently good heat-conducting materials, such as copper, and good water vapor permeability are more comfortable to wear. This allows moisture and heat to be released into the environment more easily. Proper mask fitting plays an essential role in measuring the quality of a mask, as it affects the breathability and benefit of the mask. Tight masks can irritate the skin [73].

There are different classes of antibacterial agents that can be properly used in various combinations to produce an innovative and effective antimicrobial face mask. Among several antibacterial agents, Ag and Cu [70] pervaded antimicrobial face masks are more popular due to their high reactivity and excellent antimicrobial efficacy in nano-forms, although the detachment of nanoparticles from the face mask and associated nanotoxicity are concerns. Metal and metal oxide nanoparticles incorporated through the electrospinning and melt-blowing techniques have shown less leaching and more stability. New classes of antibacterial agents, such as antimicrobial polymers (with active moieties, such as antimicrobial peptides, QACs, iodine and N-halamine compounds), NaCl, and natural compounds, such as mangosteen extracts, Folium Plectranthii amboinicii oil, extracts of Scutellaria baicalensis extracts, Vitex trifolia, Punica granatum, Allium sativum, are recognized as effective against various microorganisms including viruses. Active moieties, such as N-halamines, QACs, PEI, BP, polypyrrole and inorganic groups (mostly metals), have been incorporated to yield various antimicrobial polymers suitable for making a reusable face mask. Among these, N-halamine and QACs have proven very effectives against a broad spectrum of microorganisms. Bath coating, spray coating and immobilisation via carriers have been employed to yield QAC-modified antimicrobial fabrics.

The efficiency of antimicrobial face masks should be evaluated for both antibacterial and antiviral activities to establish the claim of "antimicrobial face mask" on more substantial grounds for the development of protective face masks. There should be a thorough evaluation of the biotoxicity and ecotoxicity associated with antimicrobial agents and the antimicrobial face masks. The risk of unknown toxicity calls for the proper assessment of the skin compatibility and stability of antimicrobial coatings. Therefore, proper use, reuse and disposal protocol should be designed to avail the full benefits. In short, there are ample opportunities for various stakeholders who deal with antimicrobial masks to develop affordable, safe, and efficient antimicrobial face masks that can overcome the challenges present with single-use face masks [65, 74].

6 Methods for testing the antimicrobial and antiviral activities of textile fabrics

Some standard methods for measuring evaluating antimicrobial activity on textile materials have been issued. The main standards include both qualitative methods (AATCC 147:2004, ISO 20645:2004 and JIS L 1902:2008 halo method) and quantitative methods (AATCC 100:2004, ISO 20743:2007 absorption method and JIS L 1902:2008 absorption method) to determine the antibacterial effect of textiles with an antibacterial finish. Qualitative or agar diffusion methods are easy to perform, rapid and beneficial for testing a large amount of samples. Textile samples should be contacted with bacterial cells using nutrient agar plates. The bacterial activity of qualitative methods is calculated using halo formation, where missing bacteria immediately grow around the edges of samples. The halo size embodies the potential for the antimicrobial characteristics of samples, but cannot be used as a quantitative method. Quantitative or absorption methods take more time and material than qualitative methods. In quantitative methods, a tiny volume of bacteria comes into contact with swatches, permitting all of the liquid to be absorbed. After incubation, bacteria are eluted from the tissue and the total bacterial count is fixed by serial dilution. Antimicrobial activity is determined via percentage reduction, and validated together with a control sample that is untreated and without an antimicrobial agent [75].

Their purpose is to check the ability of antibacterial-treated textiles to avoid microbial growth and to kill microorganisms over a specified period time. The absorption, printing and transfer methods are three types of quantitative tests set out in the ISO 20743 standard. The AATCC 100 test method is a for antimicrobials. The AATCC 100 test method quantitatively tests the capacity of fabrics and textiles to inhibit the development of microorganisms or kill them over a 24-hour contact period. To calculate the antiviral properties of treated textile fabrics, a virus suspension was first dropped onto textile fabrics. After a pre-defined period of time, the fabrics were washed, and the infectious viral titer was determined using the PFU test method. The adsorption of a virus by a textile and the virus inactivation caused by the textile are fundamentally important. The antiviral properties of treated fabrics depend on treatment conditions, such as temperature, contact time, EMEM concentration and the type of fabric, as well as the test virus type.

In 2017, Imoto et al. found that experimental conditions had a material affect on virus infectivity titers. Antiviral properties should be evaluated under stable conditions for viruses, at a lower temperature (4 °C) and at a lower EMEM concentration (1/10 EMEM) [76]. In 2007, Shahidi et al. studied the antibacterial properties of fabrics and testing methods. They reported that two types of tests are available to evaluate the antibacterial properties of textiles: agar-based inhibition zone tests and bacterial count tests. The agar test (halo method) is a well-established approach for semi-quantitative analysis. A specific piece of cloth was placed on a bacterial culture spread on a medium. Various gram-positive and gram-negative bacteria can be selected for an antibacterial test. The dish was then incubated at 37 8 °C for 24 hours. Also used was a medium comprising the peptone mixture: 1.5, neutral red: 0.03, crystal violet: 0.001 and agar: 13.5. Samples were incubated under regulated conditions. The area around the sample, called the halo, indicates that bacterial growth has been inhibited and demonstrates the usefulness of the antibacterial sample.

Bacterial count tests are technical and time consuming compared to the halo method. There is, however, a quantitative evaluation of the usefulness of antibacterial treatment. Bacterial growth medium such as Luria-Bertani medium (LB) broth can be utilized in a bacterial count test. Bacteria was dropped into 10 ml of LB broth to reach a cell concentration of 10^8 (CFU)/mL and then diluted to a cell concentration of 10^6 (CFU)/mL. The swatches (size 1×1 cm^2) were placed in a 1 ml bacterial suspension and all samples were incubated at 37 °C for 24 hours. Previously, 100 µL of solution was sought from each incubated sample and spread onto an agar plate. All plates were incubated again for 24 hours and the colonies formed on them were counted [59, 77].

Recently, some viruses, such as SARS-CoV-1, MERS and SARS-CoV-2, have affected human life, and various antiviral products have been produced on the market. Antiviral textiles were also produced, while there was a need for an integrated test method to evaluate the antiviral effect of textile products. ISO 18184, a test method for evaluating the antiviral activity of textile products, was first introduced in 2014 and then revised in 2019 [78].

ISO 18184 is used for textile products that are hydrophilic in nature and can be used to calculate the antiviral activity of textile materials, such as woven, non-woven and knitted fabrics, yarns, active wear, socks, daily wear, health care products, such as scrubs, masks, and surgical clothing, and other home textiles [50].

For sample preparation, nine sterilized control samples (untreated) are required to determine the infectious titer of the virus immediately after inoculation to determine the residual infectious titer of the virus after inoculation for the duration of contact (between two and 24 hours), while Cytotoxicity analysis is also used. In addition, six sterilized test samples are used to determine the residual infectious titer of the virus after inoculation with the treated sample, which is used in contact with the control sample and for cytotoxicity analysis.

For the test, control and treated samples are placed in separate sterile plates and 200 μL of virus is inoculated on both control and treated samples. After virus inoculation, 20 ml of SCDLP (used as neutralizing solution) is added to three control samples. After the pre-defined contact period, 20 ml of SCDLP broth is added to three treated and three untreated samples to recover residual virus.

The washing solution is serially diluted up to 10 dilutions and the infectious titer of recovered virus is determined either by plaque assay or using the TCID50 method. Other assays can also be used based on the virus strain.

The antiviral activity is determined using the following equation:

$$M_v = Log_{10}(V_a) - Log_{10}(V_c) \quad (1)$$

where, M_v represents the antiviral activity value, Log10 (V_a) represents the logarithm average of three infectivity titer values immediately after inoculation of the control specimen, and Log10 (V_c) represents the logarithm average of three infectivity titer values after specific contact time with the test specimen.

In ISO 18184, the antiviral performance of the textile product is considered good if the log value is between 2 and 3. If the log value is greater than or equal to 3, the antiviral performance of textile product is considered excellent [74]. For hydrophobic textiles, ISO 21702 is used to evaluate antiviral activity. ISO 21702 is a unified test protocol that measures antiviral activity on non-porous and plastic surfaces, designed to provide protection against viruses.

In 2023, Nefedova et al. investigated the antiviral properties of knitted polyester textiles treated by CeO_2 nanoparticles and SiO_2 nanoparticles with quaternary ammonium surfactant CTAB (CTAB@ SiO_2) using the spray depositing method. The antiviral effect of treated textiles was evaluated against porcine transmissible gastroenteritis viruses TGEV and SARS-CoV-2. The antiviral effect of the used nanomaterials was measured in colloidal form. They concluded that the antiviral effect of nanomaterials decreased after their deposition on the textile surface compared to the colloidal state.

They concluded that the antiviral activity of textiles cannot be predicted from the antiviral efficacy of the deposited compounds in a colloid state, and that additional attention should be given to the prolonged efficacy of antiviral treated textiles [79].

In 2022, Shen et al. studied antibacterial and antiviral cotton fabric treated with diphenolic acid (DPA) using the pad-dry-cure method. They demonstrated that diphenolic acid molecules were covalently linked onto cotton fibre surfaces through an esterification reaction between their carboxyl groups and the hydroxyl groups of cellulose on the fibre surfaces. The DPA phenolic groups induced onto the cotton fibres facilitated the destruction of pathogens via protein affinity interaction. They concluded that DPA modified fabrics have high bacteriostatic reduction rates against *Escherichia coli* and *Staphylococcus aureus*, and also have excellent antivirus effect that facilitate rapid virus inactivation in less than 20 minutes, without any damage to the cotton fibre structure. The treated cotton fabrics were also deemed safe for human skin [80].

7 Durability

Durability against simulated healthcare washing is an important property for sport and medical textiles. Durability can be achieved by optimizing the textile finishing methods. Antibacterial finishing is usually carried out to give textiles improved resilience against microorganisms to prevent the destruction of fibres and discoloration, and the increased durability of textiles with a longer life, which plays an important role in addressing hygiene in clinical and sensitive environments by minimizing the microbial colonization of textiles and the potential for transfer from fabric surfaces.

In 2020, Wang et al. studied the antimicrobial agent polybiguanide derivative - poly(hexamethylenebiguanide). The pad-dry-cure method was used to apply PHMB to cotton fabrics. They concluded that the optimum finishing conditions can impart excellent durability to fabrics expected to undergo repeated simulated healthcare washing. The fabric samples showed 100% bactericidal effect after 52 washing cycles, and 104 washings slightly reduced the bactericidal activity. They reported that both simulated healthcare washing and coating treatment have a negative effect on the hand feel behaviour and tearing strength of cotton fabric. Antibacterial textile finishing should not have a negative effect on textile materials [1].

In 2022, Novi et al. studied antimicrobial zinc nanocomposite textiles, fabricated using a novel Crescoating process. Zinc nanoparticles were grown *in situ* within the bulk of different natural and synthetic fabrics to form safe and durable nanocomposites. The zinc nanocomposite textiles showed an unprecedented microbial reduction of 99.99% (4 log10) to 99.9999% (6 log10) within 24 hours on the most common gram-positive and gram-negative bacteria, and fungal pathogens. Additionally, the antimicrobial activity remained intact even after 100 laundry cycles, demonstrating the high longevity and durability of a textile that was non-irritating and hypoallergenic [81].

8 Conclusions and future trends

Today, the need for antiviral and antimicrobial textiles is becoming important. Undoubtedly, antimicrobial textiles are a very important field of research, and a cause of market expansion due to societal needs. Factors that prove the importance of this category includes: different textile substrates, such as natural, synthetic and blends thereof, varied antimicrobial finishing materials, such as organic and synthetic compounds, synthetic polymers, natural and naturally-derived compounds, metals and metal oxides, raw or functionalized silica micro- and nanoparticles, the broad range of processing techniques, such as grafting, microencapsulation, coating and copolymerization, plasma processing, electrospinning, sol–gel methods, exhaustion and the pad-dry-cure method, and final consumption and applications, such as personal protective clothing and masks, wound dressings, water and air filtration media, sports- and footwear, hospitals and hotels beddings.

Textiles with different synthesized chemicals, such as nanoparticles, metal compounds, triclosan, povidone iodine, acidic polymer and some surfactant, or natural extracts, have been treated to impart antiviral properties. Most bio-extract-treated or chemical-treated textiles demonstrate exceptional antiviral property. These antiviral agents and antiviral finishing processes can be used on various textile materials to fight the SARS-CoV-2 virus and other viruses, and thus protect human health. Antiviral textiles are very important, and this area requires additional research for the development of unique and new technologies. Currently, there is a fundamental need to produce cost-effective, environmentally friendly, safe and high-performance antiviral textiles and masks. Cooperation between experts in textile science, microbiology and pharmaceuticals is necessary for the realization of industrial production and the manufacture of antiviral textiles, and plays an important role in the protection of people. Hence, future research should focus on identifying the potential for natural antimicrobial agents. Given that the use of masks and antimicrobial textiles is increasing, the disposal of antimicrobial textiles should be properly managed, so that it does not become a problem like plastic waste.

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