Industria Textilă

ISSN 1222–5347

5/2025

ISI rated journal, included in the ***ISI Master Journal List*** of the Institute of Science Information, Philadelphia, USA, starting with vol. 58, no. 1/2007, with ***impact factor 0.9 and AIS 0.116 in 2024.***

The journal is indexed by CrossRef, starting with no. 1/2017 having the title DOI: https://doi.org/10.35530/IT.

Edited in 6 issues per year, indexed and abstracted in:
Science Citation Index Expanded (SCIE), Materials Science Citation Index®, Journal Citation Reports/Science Edition, World Textile Abstracts, Chemical Abstracts, VINITI, Scopus, Toga FIZ technik, EBSCO, ProQuest Central, Crossref
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Aknowledged in Romania, in the Engineering sciences domain, by the National Council of the Scientific Research from the Higher Education (CNCSIS), in group A
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Investigating the heat measurement techniques of sewing needle

DOI: 10.35530/IT.076.05.202539

ADNAN MAZARI FUNDA BUYUK MAZARI

ABSTRACT – REZUMAT

Investigating the heat measurement techniques of sewing needle

Industrial lockstitch sewing machines have an unavoidable issue with the heat generated by the sewing needle during high-speed sewing. This needle heat causes thread breakage, burn spots on fabric and poor seam strength. Garment manufacturers and technical textile producers are forced to slow down production or use expensive cooling techniques, such as needle coating, thread lubrication, and forced cooling. In this research, the techniques used in needle heat measurement are summarised and show why the classical technique of thermal camera shows false readings. The research work shows repeatable results from a unique technique of embedded thermocouple technique to measure sewing needle temperature and compares with other techniques. The overall setup of this technique, including the types of thermocouples and receiver, is deeply explained in the article. This technique shows significant improvement in the needle temperature measurement methodology, which is tested at different sewing speeds and with the most common sewing threads used in the market. The article is useful for researchers and also for the industry to know exactly the needle heat before sewing and consider the machine parameters accordingly for better seam quality.

Keywords: *needle heat, garment, heat transfer, sewing, lock stich*

Investigarea tehnicilor de măsurare a efectului de încălzire a acului de cusut

Mașinile industriale de cusut au o problemă inevitabilă legată de încălzirea acului de cusut în timpul coaserii la viteză mare. Încălzirea acului provoacă ruperea firului, apariția de pete de arsuri pe materialul textil și rezistența slabă a cusăturii. Producătorii de îmbrăcăminte și de textile tehnice sunt obligați să încetinească producția sau să utilizeze tehnici de răcire costisitoare, cum ar fi tratarea acului, lubrifierea firului și răcirea forțată. În această cercetare, sunt rezumate tehnicile utilizate pentru măsurarea efectului de încălzire a acului și se prezintă de ce tehnica clasică a camerei termice afișează valori eronate. Cercetarea prezintă rezultate repetabile obținute cu ajutorul unei tehnici unice de termocuplu încorporat pentru măsurarea temperaturii acului de cusut și le compară cu alte tehnici. Configurația generală a acestei tehnici, inclusiv tipurile de termocuplu și receptor, este explicată în detaliu în articol. Această tehnică prezintă o îmbunătățire semnificativă a metodologiei de măsurare a temperaturii acului, fiind testată la diferite viteze de coasere și cu cele mai utilizate fire de cusut de pe piață. Articolul este util pentru cercetători, dar și pentru industria de profil, pentru a cunoaște cu exactitate temperatura acului înainte de coasere și pentru a lua în considerare parametrii mașinii în consecință, pentru o calitate superioară a cusăturii.

Cuvinte-cheie*: încălzirea acului, îmbrăcăminte, transfer de căldură, coasere, cusătură simplă*

INTRODUCTION

Over the last 2 decades, there has been a huge demand for the sewing of garments, technical textiles, and highly functional apparel. This forces the garment producers to run the sewing machine at the maximum possible sewing speed, but a key issue of needle heat forces the producers to decrease overall production. A classic lock stitch machine, which is commonly used for sewing in the apparel industry, can easily run at a speed of 5000–6000 r/min, but just because of unavoidable needle heat, it is recommended to run the machine at 2500 r/min or lower. Many of the producers use expensive techniques of forced air cooling or thread lubrications, but still the exact needle temperature is unknown because it depends on multiple factors, including speed, ambient conditions and material properties. Knowing the needle temperature range, considering classical textiles will still provide useful information for the producer, but unfortunately, there is no trustworthy technique to provide repeatable results.

Depending on the sewing conditions, the maximum needle temperature ranges from 100°C – 300°C [1]. This high temperature weakens the thread because the tensile strength of the thread is a function of temperature [1] and leads to a decrease in production [2]. Furthermore, the final sewn thread has 30–40% less strength than the comprehensive thread [3]. Various methods were used to measure needle temperatures, such as infrared thermometers, thermocouples, and temperature-sensitive waxes. The needle moves very quickly during the sewing process, making it extremely difficult to measure accurate temperatures [4]. Although only a few theoretical models are available to predict sewing needle temperatures [4, 5], the experiments conducted by thermal cameras are affected by emission as well [7]. Sondhelm [8] used paint applied to the needle to observe colour changes over temperature. Laughlin [9] attempted to measure needle temperature by infrared measurements from needles using Lead-Sulfide cells. Another technique with a thermal element was later developed by Dorkin and Chamberlain [10]. Many technological developments have been undertaken over the years, including needle design [11, 12], fabric conductors, thread lubricants [13], needle coolers [14] to cool down the needle at speed sewing, but knowing the exact needle temperature still needs a more research and technological advancement.

Experimental techniques of measurement

A flow chart of the needle heating approach by multiple researchers is shown in figure 1. The collection of techniques is mainly divided into experimental and theoretical approaches. In all the fields, multiple research studies have been performed in the last decade. The chart gives a general overview of what researchers have worked on in the last years and how it will be improved in the author's work [15]. Generally, the contactless techniques of thermal cameras are very famous for experimental techniques; on the other hand, the finite element method using simulation software like Ansys is popular to obtain the prediction of needle temperature with respect to time.
It is briefly explained below how the needle temperature is measured and how it is used.

Contact method

This technique involves any method of needle temperature in which there is physical contact of the measuring device to the needle, like thermocouple and heat-sensitive colours, etc. [16]. The sewing process goes through enormous roughness between the needle, fabric and the sewing thread, and any attachment of colour, waxes and coatings does not last long. Touching the needle with the measurement device after finishing the sewing process brings human error and time delay. The needle with a small mass and thin size can cool down before the measuring device can be touched. Inserting a thermocouple inside the needle groove has been tested in the past, but due to the thick size of the sensor, low fragility and slow response measurement, it was never practical. But now with the new K and C type thermocouple, it's possible to measure with a very thin wire with better fragility and quick response measurement by wireless data loggers.

Contactless method of needle temperature measurement

These methods include techniques in which the temperature of the needle is measured without contact with the needle. Thermal camera, pyrometers and infrared techniques can be used for this approach. Most of the researchers have either used this technique or they have used the results from this method to compare with their theoretical models. The principle of contactless measurement depends on the emissivity of the object. Generally, for a stationary object with high emissivity, like a wall, human body or rigid structure, this technique is an excellent choice, but in the case of thin shining metal moving at high speed, like a sewing needle, there are complications to achieve repeatable results.
The main goal of the article is to measure the needle temperature with the latest thermal camera and see if it's really possible to measure needle temperature at high speeds of sewing speeds. Later, a unique technique of embedding the thermocouple in the needle groove will be experimented with to see if this technique is practical for measuring needle heat under different sewing conditions. A variety of sewing threads will be tested to see the overall change in needle heat during the sewing process and the performance of the thermocouple.

Experimental part

In this research latest thermal camera, "Infratec 9400", and the embedded thermocouple technique will be used to determine the sewing needle temperature at high speeds. The 9 most commonly used sewing threads are selected to sew denim fabric at high speeds of sewing on an industrial lockstitch machine. The properties of denim fabric are shown in table 1, followed by the thread details in table 2.
The testing is performed on an industrial Lock stitch machine at different speeds of sewing with 100% Cotton, Denim fabric of 290 g/m^2 and two layers of fabric. Each stitch is performed for 15 seconds of time. The Lock stitch machine "Brother Company, DD7100-905" is run at different sewing speeds. The sewing needle of size 100/16 from the company Groz-Beckert is selected for all experiments.

Thermal camera setup

In this research, the high-speed thermal camera "Infratec 9400" is used to measure the needle temperature at different speeds of sewing speeds. To start the measurement process, it's important to know the exact emissivity of the sewing needle. All thermal cameras work on the principle of the emissivity of the object. For this

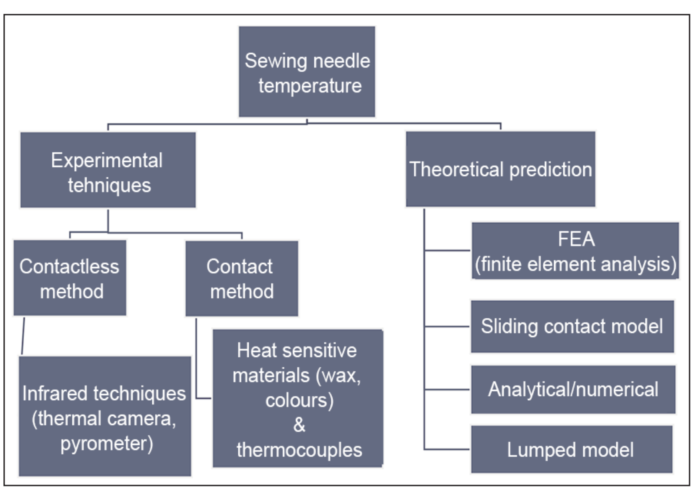

Fig. 1. Techniques to measure needle of sewing needle

Table 1

FABRIC USED FOR THE EXPERIMENTS					
Fabric type	**Weave**	**Weight (g/m^2)**	**Ends/cm**	**Picks/cm**	**Fabric thickness (cm)**
100% cotton Denim	2/1 Twill	290	26	18	0.035

Table 2

SEWING THREAD USED FOR THE EXPERIMENTS			
Trade name	**Composition**	**Thread (density) count (tex)**	**Coef. of friction, μ**
(C80) Saba	PET-PET corespun (CS) thread	40	0.13
(C50) Saba	PET-PET corespun (CS) thread	60	0.16
(C35) Saba	PET-PETcorespun (CS) thread	80	0.31
(75) Rasant	PET-COTTON corespun(CS)	40	0.14
(50) Rasant	COTTON-PET corespun(CS)	60	0.17
(35) Rasant	PET-COTTON corespun (CS)	80	0.31
(24/2) Merciful	Mercerised cotton (long staple)	70	0.4
(40) Mercifil	Mercerised cotton (long staple)	50	0.2
(50) Mercifil	Mercerised cotton (long staple)	40	0.13

test, the emissivity of the needle was calculated by ASTM standard E 1933-99a and determined to be 0.08 for a chromium-polished needle. As the needle is thin and shiny, it is complicated to determine the exact emissivity, and most researchers adopt the emissivity of the needle as that for polished chromium, which is 0.06 [9]. All the tests are performed in a dark room to avoid external heat sources reflecting from the shining needle. The “InfraTec 9400” high-speed thermal imaging camera is intended for recording fast events during which temperature excitation occurs on the observed object. The camera is set up as shown in figure 2, with a Basic lens 100 mm FOV (Field of View): 7.3 × 5.9° and a 20 mm Macro lens NWIR f/3.0 with a maximum frame rate binning mode: 622 Hz. The camera is placed 20 cm away from the needle tip on a separate vibration-free tripod to avoid focus change during high-speed sewing. Firstly, sewing is performed without thread and later with different thread types. The experiments are repeated 10 times, and each sewing is performed for 15 seconds.

Embedded thermocouple setup

This technique involves the technique of needle temperature in which there is physical contact of the measuring device to the needle, like a thermocouple and heat-sensitive colours, etc. The sewing process goes through enormous roughness between the needle, fabric and the sewing thread, and any attachment of colour, waxes and coatings does not last long. Touching the needle with the measurement device after finishing the sewing process brings human error and time delay. The needle with a small mass and thin size can cool down before the measuring device can be touched. The scientific idea by Prof. Hes [15] is modified to use the K type and C type thermocouple (Company: Omega®) which is soldered near the eye of the needle in the groove, the groove is designed for the thread to hide itself during needle insertion time but has enough space of a thin needle to be embedded K type thermocouple was used which are relatively slower in measurement and are more rigid with bigger thickness, the thermocouple was replaced with C type with much quick response, size of 0.076 mm shown in figure 3 and connected to fast wireless device for obtaining the temperature

Fig. 2. Thermal camera setup

Fig. 3. The thermocouple is attached by soldering and welding techniques

each second wirelessly. The thermo-couple is selected according to as thinnest available with the measurement range. In thin size, the range of the K type is less than 300°C, whereas the C type can measure a much higher range in the same thinness. The other important property required was better flexibility to not break the thermocouple during high-speed sewing, and also the remote connectivity with the data receiving unit. After multiple tries, the whole system from Omega® Company was useful for this technique. The tip is soldered in the groove of the needle (the space is enough for the wire to sit inside the groove during the insertion of the needle in the fabric), just next to the needle eye, as this is possibly the maximum hot point of the needle.

The collector is connected to a sewing machine, which remotely sends the temperature measurement to the computer via Bluetooth. This is accepted that these kind of sensor attachments causes a possible change in the thermal disturbance. It was made to keep this impact to a minimum, and comparing the results with other techniques, this method shows better accuracy, and the results were repeatable and reproducible.

The needle size of 100 or above is most suitable for this kind of measurement (normally size 90–140 is used for Denim or technical apparel), as the groove is big enough for the thermocouple to easily be fixed. The thermocouple is soldered, firstly precleaning with HCl solution and later attached with Sn-Ag-Cu-Zn using a soldering rod at 480°C. To achieve a higher range of melting, later spot welding and Tungeten Inert Gas (TiG) is used to attach the needle next to the needle eye. TiG welding showed excellent attachment properties. Argon gas is used during welding to avoid oxidation. A fine electrode tip of 0.5 mm was used for the welding. The attachment of the thermocouple to the needle eye by TiG welding is shown in figure 4.

After multiple experiments and optimisations, for low speed of sewing speeds, the soldering technique worked perfectly and for higher sewing speeds, the TiG welding performed perfectly. Both techniques can be used to solder the thermocouple inside the needle groove. The needle with attached thermocouple can be seen in figure 5.

The classical communication of the thermocouple sensors provided a slow response, in which it's possible to have the peak temperature, but overall gain and loss of needle temperature is very important with respect to short time intervals. As the needle gains above 200°C within the first 3 seconds of sewing, and similarly, the trend of heat loss gives us better knowledge of the heat loss when the machine is decelerating. For this experiment, the special wireless connector from the company Omega® was ordered. Initially the MWTC wireless device with K type thermocouple (5SC-TT-(K)-36-(36)) is used, with the improvement in the thermocouple technology the latest device of wireless connectivity UWTC-2 from Omega® company can work with thermocouple of type C (W5%Re-W26%Re) which are finer, around 0.076 mm and can

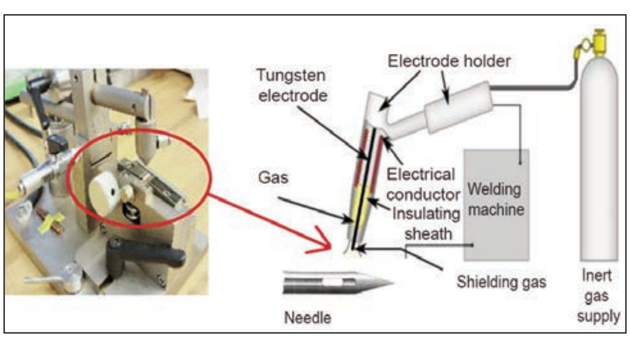

Fig. 4. Thermocouple attachment by the TiG welding technique

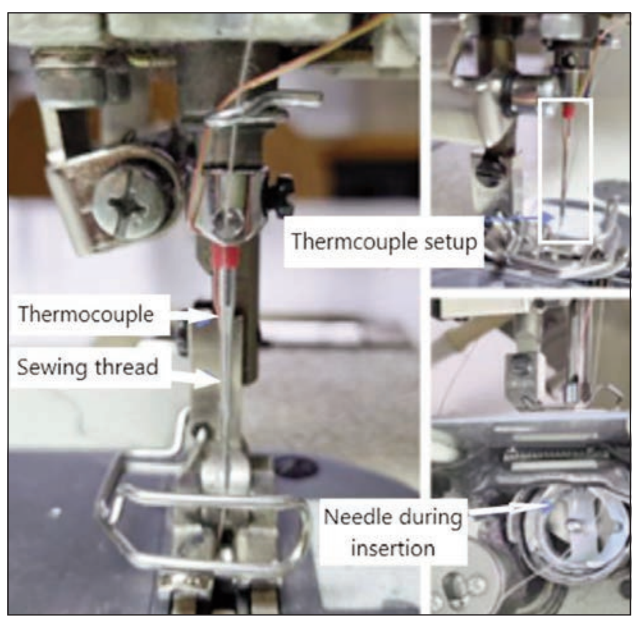

Fig. 5. A thermocouple attached to the sewing needle of an industrial lock stitch machine

Fig. 6. Data logger and wireless connection device for K and C type thermocouple

work till range of 2300ºC, special connector OSTW-C-M-S were used for the connectivity of the thermocouple to the sender device.

The testing is performed on an industrial Lock stitch machine at different speeds of sewing with 100% Cotton, Denim fabric of 290 g/m^2 and two layers of fabric. Each stitch is performed for 15 seconds of time.

RESULTS AND DISCUSSION

Firstly, testing is performed at different speeds of sewing with a classical Chrome needle of size 100; the thread Saba C80 is used for the experiments. The results are shown in table 3. At a lower speed of sewing of 250 r/min, the thermal cameras showed repeatable results, whereas at a higher speed, there was a huge standard deviation, which is mainly due to error in the exact needle temperature. The experiment is performed only with Polyester core spun thread of 80 tex, due to high variability in the results and poor repeatability, other threads were not tested as the thermal camera technique was not suitable.

It is observed that the thermal cameras, even at their fastest frame rate and optimum lens, it was able to measure the needle temperature with acceptable deviation only till 500 r/min or lower speeds. In the case of a needle with thread, even speeds of 500 r/min bring a significant change in the mean temperature of the needle. This is mainly due to the focus point being larger than the needle size, and impossible to avoid the thread's impact on the measurement of sewing needle temperature. Another issue is the change of emissivity of metals with the rise of temperature. This change is still insignificant for temperatures less than 100ºC but later on, there must be a dynamic change of emissivity level according to the material surface properties at different temperatures. Whereas when the classic thread of 40 tex is used during sewing, the error percentage was much higher, and the main reason was that the thread's emissivity was much larger compared to the shining needle, which causes error in the measurement.

Table 3

SEWING NEEDLE TEMPERATURE MEASURED WITH THERMAL CAMERA					
Object	Sewing speed (r/min)				
	250	500	1000	2000	3000
Needle without thread	32	44	59	81	87
Standard Deviation (±)	3.8	4.2	5.8	12.7	18.4
Needle with thread (40 Tex)	38	59	76	125	158
Standard Deviation (±)	4.8	5.9	13.9	22.1	41.2

Secondly, the thermocouple setup is prepared to measure the needle at a vast range of sewing speeds from 1000 r/min to 4700 r/min. This technique showed an error of 5–7% but overall, it is the only technique in which needle temperature can be measured at such a high speed. The results of different threads at different speeds of sewing are shown in figure 7.

Results show that above 4000 r/min the needle temperature ranges to nearly 300ºC, which is not possible to measure using any other technique, and secondly, the repeatability of the results makes it a good choice to know needle temperature considering a defined set of parameters like sewing thread, machine speed and textile fabric. The needle temperature was the highest of the cotton-based thread, which is also connected to a higher coefficient of friction and directly causes more needle heat. The gain and loss of the needle heat are shown in the figure below for the speed of 4700 r/min. It is obvious that the needle reaches the maximum temperature within

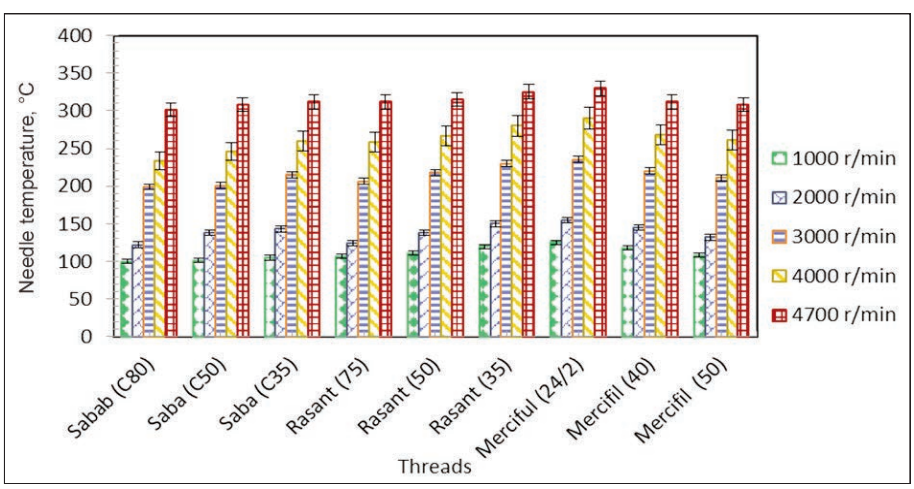

Fig. 7. Needle temperature by the embedded thermocouple approach

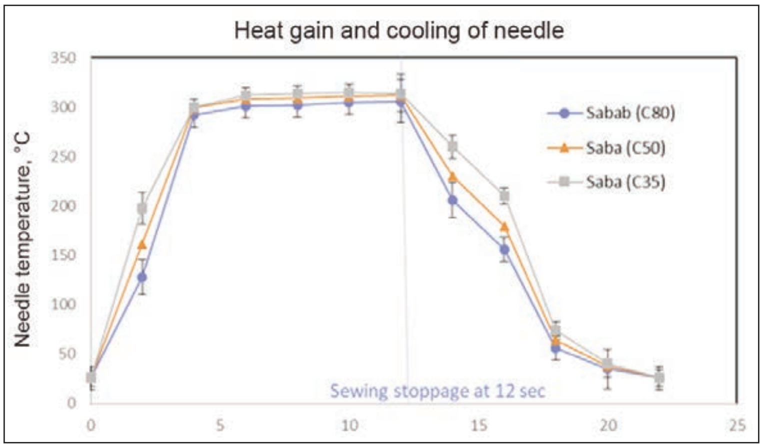

Fig. 8. Needle heat gain and loss

in first few seconds of sewing and takes nearly 10 seconds to cool down to room temperature.

The heat gain and loss at very small intervals of time were not possible with a K K-type thermocouple and a manual data logging approach; the wireless connectivity and C-type thermocouple provided much more reliable results, as shown in figure 8. It is seen that the rise of needle temperature is within the first 3–5 seconds of sewing, and after stoppage, the needle cools down within in few seconds.

CONCLUSIONS

It is concluded that a thermal camera or contactless approach that works with emissivity is not a practical solution for the sewing needle temperature measurement. The small size of the needle, low emissivity and high frequency make it impossible to measure needle temperature. The needle temperature with thread was even more complicated because of the high emissivity level of the thread as compared to a thin, shiny needle. There was more than 30% error at even speeds of 500 r/min. Whereas the inserted thermocouple approach showed repeatable results and even with 5–7% of error, this technique is the only method to measure needle temperature at the speed of sewing of 4000 r/min. The needle temperature at this speed is around 300ºC which is much more than the melting temperature of polymeric threads. The research provided the latest knowledge of the thermocouple attachment setup with the sewing needle and how to measure needle temperature at higher speeds for sewing. The technique provided unique information for the industrial partners as well, to know the exact needle temperature before the sewing process to obtain high-quality seams. In future, with better, thinner and more flexible thermocouples, it might be possible to decrease this error of measurement. But still, this technique shows one of the lowest standard deviations as compared to other techniques.

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The dual high phenomenon and corporate innovation capabilities: Empirical evidence from Chinese textile enterprises

DOI: 10.35530/IT.076.05.2024137

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ABSTRACT – REZUMAT

The dual high phenomenon and corporate innovation capabilities: Empirical evidence from Chinese textile enterprises

"Dual high" describes a situation where a firm simultaneously holds a high proportion of monetary funds and a high proportion of short-term loans. Using a sample of 1,796 textile companies in China, this paper explores the impact of the dual high phenomenon on a firm's innovation capabilities. The study finds that the more pronounced the dual high characteristics of a firm, the stronger the inhibitory effect on its innovation capabilities. The underlying mechanisms suggest that dual high characteristics increase financial risk, leading firms to reduce R&D investment to mitigate these risks, thereby inhibiting innovation. Moreover, digitalisation significantly moderates the relationship between the dual-high phenomenon and innovation capabilities, implying that a higher level of digitalisation reduces the adverse effects of dual high characteristics on innovation capabilities of Chinese textile enterprises. Further analysis shows that non-state-owned enterprises experience a stronger inhibitory effect on innovation capabilities compared to state-owned enterprises. Additionally, the lower the proportion of digitalisation in a firm, the stronger the inhibitory effect of dual high characteristics on innovation capabilities. This research enriches the theoretical understanding of the dual high phenomenon and provides practical insights for mitigating its negative impacts.

Keywords: *Dual High, short-term borrowings, monetary funds, corporate innovation, corporate financial risk, digitalisation*

Fenomenul "dual high" și capacitățile de inovare ale întreprinderilor: dovezi empirice din întreprinderile textile din China

Fenomenul „dual high" descrie o situație în care o firmă deține simultan o proporție mare de fonduri monetare și o proporție mare de împrumuturi pe termen scurt. Folosind un eșantion de 1.796 de companii textile din China, această lucrare explorează impactul fenomenului „dual high" asupra capacităților de inovare ale unei firme. Studiul constată că, cu cât caracteristicile „dual high" ale unei firme sunt mai pronunțate, cu atât efectul inhibitor asupra capacităților sale de inovare este mai puternic. Mecanismele care stau la baza acesteia sugerează că aceste caracteristici „dual high" cresc riscul financiar, determinând firmele să reducă investițiile în cercetare și dezvoltare pentru a atenua aceste riscuri, inhibând astfel inovarea. Mai mult, digitalizarea moderează semnificativ relația dintre fenomenul „dual high" și capacitățile de inovare, ceea ce implică faptul că un nivel mai ridicat de digitalizare reduce efectele adverse ale caracteristicilor „dual high" asupra capacităților de inovare ale întreprinderilor textile din China. Analizele ulterioare arată că întreprinderile private experimentează un efect inhibitor mai puternic asupra capacităților de inovare în comparație cu întreprinderile de stat. În plus, cu cât proporția de digitalizare este mai mică într-o firmă, cu atât efectul inhibitor al caracteristicilor „dual high" asupra capacităților de inovare este mai puternic. Această cercetare îmbogățește înțelegerea teoretică a fenomenului „dual high" și oferă perspective practice pentru atenuarea impactului său negativ.

Cuvinte-cheie*: „Dual High" , împrumuturi pe termen scurt, fonduri monetare, inovare corporativă, risc financiar corporativ, digitalizare*

INTRODUCTION

The report of the 20th National Congress of the Communist Party of China emphasised the need to strengthen and improve modern financial regulation and enhance the economic stability guarantee system. Before 2017, dual high was considered a sign of low capital utilisation efficiency. However, recent scandals involving dual high firms, such as Kangde Xin and Kangmei Pharmaceutical, have brought this phenomenon into the spotlight, turning it into a red flag for investors and negatively impacting these firms' reputations and growth [1]. In September 2023, President Xi Jinping introduced the concept of "new productive forces" during an inspection in Heilongjiang, which was further defined in January 2024 to emphasise innovation, quality, and the representation of advanced productive forces. Innovation capability is a key factor in a firm's sustainable development and relies heavily on consistent and sufficient cash flow to support both innovation input and output [2]. Firms with pronounced dual high characteristics are vulnerable to cash flow shortages as they allocate substantial monetary funds to repay short-term debts, thereby undermining the sustainability of their cash flows. Consequently, the more pronounced a firm's dual high characteristics, the stronger the potential inhibitory effect on its innovation capability.

The textile industry is a cornerstone of China's economy, contributing nearly 7% of the country's GDP and accounting for approximately 35% of global textile exports. Given its massive scale, the industry faces significant pressure to innovate while managing the financial risks and ensuring a strong liquidity position. Explaining how financial constraints could impact innovation in this sector, particularly in a rapidly digitalising environment, can offer crucial insights for policymakers to enhance the sustainability and competitiveness of Chinese textile enterprises. The "dual high" phenomenon results from two types of factors: superficial and substantive [3]. Superficial factors do not pose economic consequences, and they are mainly observed in capital-intensive firms, which require large cash reserves for daily operations while borrowing externally [4, 5]. On the other hand, substantive factors are those leading to significant economic consequences. Firms may hold substantial non-liquid cash or other monetary funds that cannot be used freely, resulting in large interest-bearing debts [6]. Additionally, significant amounts of cash held by major shareholders or other parties also exacerbate the dual high situation [7]. When firms do not manage their cash holdings and short-term borrowings efficiently, they risk not allocating resources in alignment with sustainability requirements. This can be explained by the fact that when firms maintain a high ratio of cash holdings and short-term borrowings, most of the cash remains outside of business operations. This scenario may result in fewer resources being allocated to innovation capabilities, thereby compromising their sustainability goals.

Innovation capability is a critical measure of a firm's sustainable development, reflected in both innovation input and output. Sustained and ample cash flow is essential to support the R&D activities and innovation capabilities of firms [8]. However, firms with pronounced dual high characteristics are prone to cash flow shortages because they allocate substantial monetary funds to repay short-term debts. This dynamic undermines the sustainability of cash flows and inhibits their ability to innovate. The inhibitory effects of dual high characteristics on innovation capabilities can be explained through the lens of financial risk theory, which posits that a high level of debt increases a firm's financial risk, necessitating a more conservative approach to resource allocation [9]. Firms that are unable to manage their cash holdings and short-term borrowings experience high financial risks, and to mitigate these risks, they reduce their R&D investments, thereby limiting their innovative capability. This risk-averse behaviour is particularly pronounced in firms with high short-term debt obligations, as they prioritise liquidity management over long-term strategic investments.

Despite extensive research on the dual high phenomenon, the majority of previous literature has focused on its causes and governance strategies, leaving a significant gap in understanding the economic consequences, particularly regarding firm-level innovation capabilities. For example, Lian and Xu [3] examined factors resulting in dual high characteristics but did not explain their connection with innovation. In the same stride, Ma [5] investigate governance strategies to mitigate risks associated with dual high firms, but does not present their potential link with innovation capabilities. Studies on financing constraints and corporate innovation, such as Brown and Fazzari [10] and Aghion and Bloom [11], mainly focused on external financing difficulties rather than internal financial mismanagement framed by the dual high phenomenon. Additionally, prior literature on state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs) examined the connection between performance and governance [12], completely ignoring the potential impact of the dual high phenomenon on innovation capabilities.

Furthermore, the role of digitalisation to mitigate financial constraints and promote innovation, explained by Brynjolfsson and McAfee [13] and Hanelt and Bohnsack [14], has not been linked to dual high context. Thus, this study fills these gaps by examining the impact of dual high phenomenon on innovation capabilities and showing the moderating effects of digitalisation and ownership structure.

There are numerous contributions presented by this paper. First, this paper extends research on the economic consequences of the dual high phenomenon in firms with a focus on their innovation capabilities. This paper, under the backdrop of new productive forces, examines how the dual high phenomenon could be linked to the innovation capabilities of textile enterprises of China, and thus enriches the understanding of the economic consequences of China's textile industry. Second, this paper complements economic research related to corporate innovation by incorporating the moderating effects of financial risk in the nexus between the dual-high phenomenon and corporate innovation capabilities. Current literature exclusively explains the factors affecting innovation from technological perspectives. However, it remains unexplored how financial aspects related to the dual high phenomenon could influence corporate innovation. Third, this study shows that digitalisation significantly moderates the nexus between the dual-high phenomenon and corporate innovation capabilities, showing that high levels of digitalisation in Chinese textile enterprises may reduce the adverse effects of dual high characteristics on innovation capabilities. The interaction between dual high and digitalisation underscores the potential for digitalisation to foster innovation capabilities, even in financially constrained enterprises. Fourth, this paper holds several policy implications as its findings introduce policymakers to new productive forces brought by corporate innovation. This paper offers ways to tackle the dual high phenomenon, a challenging issue for today's firms, and explores its relationship with innovation, and thus its findings may help regulatory bodies strengthen oversight of such firms, mitigate the negative impacts of dual high on innovation capability, and support sustainable operations of Chinese textile enterprises.

The remainder of this paper is structured as follows: 2nd section covers empirical literature and theoretical framework to show the nexus between explanatory and explained variables, and develops hypotheses; 3rd section presents the empirical model, data and variables of study; 4th section reports empirical results, and 5th section presents the conclusion and policy implications.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

Before 2017, dual high was seen as an indicator of inefficient capital use. Following the scandals of Kangde Xin and Kangmei Pharmaceutical, dual high has become a red flag for investors. The causes of dual high can be categorised into two types. The first type includes superficial factors, which generally do not result in actual economic consequences. Capital-intensive firms require sustained and ample cash flow to sustain daily activities and thus tend to hold large amounts of cash while borrowing externally [4, 5]. During China's economic transition period, evident "financial discrimination" made it easier for state-owned enterprises to receive government support and low-cost loans, leading to dual high [15]. The second type includes substantive factors, which generally result in actual economic consequences. Firms may have a large amount of non-liquid cash or other monetary funds that are not freely usable, leading to large interest-bearing debts [6]. Additionally, significant amounts of cash may be occupied by major shareholders or related parties, resulting in dual high [7].

Inefficient fund allocation results in increased financial risk and decreased financial flexibility, which significantly inhibits a firm's ability to invest in long-term strategic initiatives such as research and development (R&D). High debt level increases financial risk by imposing fixed obligations on the firm, which can strain cash flow and limit fund availability for innovation [16, 17]. When a substantial portion of a firm's resources is tied up in servicing debt, it reduces the capital available for investing in innovative projects, which are critical to maintain a strong competitive advantage [18]. Furthermore, decreased financial flexibility limits a firm's ability to adapt to changing market conditions and to be ready to invest in new technologies. High cash reserves coupled with high debt signal poor financial management and inefficient capital allocation, making it difficult for firms to respond to emerging market opportunities and threats [19]. This lack of flexibility can be detrimental in industries characterised by rapid technological change, where continuous innovation could be essential to survive [20]. Empirical evidences show that firms having constrained financial flexibility are less likely to engage in R&D activities, as they are not able to absorb the high costs and risks associated with innovation [21, 22]. Consequently, the dual high phenomenon creates a vicious cycle of financial distress and underinvestment in innovation initiatives, ultimately hindering a firm's long-term growth and competitiveness [23, 24].

Innovation is the primary driver of development, and the continuous operation and growth of enterprises inevitably require innovation. Currently, numerous studies have delved into the innovation capabilities of firms: There exists an inverted U-shaped relationship between internal control and corporate innovation [11]. The Shanghai-Hong Kong Stock Connect policy enhances corporate innovation capability [25]. The proportion of state ownership inhibits corporate innovation [26]. Strengthening government enforcement of intellectual property protection enhances corporate innovation capability [27]. Excessive financialization in the manufacturing sector suppresses innovation capability [28]. Yang and Xiong [29] found that dual high (high cash holdings and high debt levels) suppresses patent applications related to corporate innovation expenditures, but did not discuss its relationship with innovation input and patent grants. Therefore, this paper will explore the relationship between dual high and corporate innovation expenditures and inputs, thereby enhancing the existing literature and further elucidating the factors influencing corporate innovation capability.

The agency theory posits that a conflict of interest may arise between managers and shareholders regarding this issue, as managers tend to prioritise short-term financial stability over long-term innovation to secure their positions [30, 31], while shareholders strive for long-term economic success of firms to maximise their wealth. It can be explained that firms with substantial cash holdings and short-term loans have sufficient cash flow to ensure daily operations. However, due to the high proportion of short-term loans and the long timeline and uncertain returns associated with innovation, firms are less likely to invest heavily in innovation resources. Similarly, although a high proportion of short-term loans can provide additional funding, it may increase financial pressure and risk-bearing capacity. Consequently, firms may focus more on debt repayment and reduce investment in innovation activities. Drawing on these views and findings of previous literature, this hypothesis can be proposed:

Hypothesis 1: High volume of monetary funds and short-term borrowings impede firms' innovation capabilities.

China is among the forefront countries, adopting digital technologies to gain productivity and economic goals. Digitalisation is a critical factor to moderate the influence of short-term borrowings and monetary funds on corporate innovation by enhancing operational efficiencies, improving financial management, and facilitating access to new technologies for Chinese listed enterprises. Previous studies show that digitalisation enables firms to optimise their financial resources and reduce the adverse effects of high short-term debt. For example, Bardhan and

Krishnan [32] explain that digital capabilities improve firm performance via streamlining operations and reducing transaction costs, which can free up resources to invest in innovation initiatives. Similarly, Rao and Pan [33] demonstrate that digitalisation helps firms in managing their financial risks, enabling them to allocate more resources to R&D activities, despite high levels of short-term debt and monetary funds in hand.

Moreover, digitalisation improves the liquidity management of firms with substantial monetary funds, thereby improving their innovation capabilities. Khin and Ho [34] showed that digitalisation facilitates better cash flow management and financial planning, thus firms are able to maintain adequate liquidity while investing in innovative projects. Vial [35] supported this finding and indicated that digital tools and platforms provide more accurate and timely financial reporting, providing firms with better insights into their financial positions and enabling more strategic investment decisions. By leveraging digital technologies, firms are able to mitigate constraints imposed by short-term borrowings and high cash holdings, thus fostering a more conducive environment for innovation.

From a theoretical perspective, the Resource-Based View (RBV) explains the moderating effects of digitalisation on the nexus of high short-term borrowings and monetary funds with innovation capabilities. The RBV posits that firms achieve competitive advantage via leveraging unique resources and capabilities [36], and digitalisation is a valuable resource that can enhance a firm's strategic capabilities, including its innovation capability. According to this theory, firms with advanced digital capabilities can better utilise their financial resources, manage risks, and respond to market changes, thereby reducing the negative impact of high short-term borrowings and monetary funds on corporate innovation [37, 38]. The moderating effect of digitalisation is evident as it enables firms to overcome financial constraints and allocate resources more efficiently towards R&D and other innovative projects.

Hypothesis 2: Digitalisation moderates the influence of high volumes of monetary funds and short-term borrowings on firms' innovation capabilities.

Financial risk is a significant factor directly linked to short-term borrowings and monetary funds, and it may mediate their impact on a firm's innovation capability. Empirical literature suggests that high levels of short-term debt increase financial risk via imposing substantial fixed costs and principal repayment obligations, which can hinder a firm's liquidity and financial stability, and thus influence the move toward innovation initiatives. For instance, Almeida and Campello [37] found that firms with high leverage are more susceptible to financial distress, which forces them to adopt the strategies of debt servicing instead of innovation. Similarly, Wade and Hulland [38] suggested that financial constraints negatively influence a firm's capacity, as the need to meet short-term borrowings limits fund availability for R&D investments.

Additionally, holding substantial monetary funds can also result in financial risk, especially when these funds are not being utilised efficiently. Excessive cash holdings might signal poor financial management and lead to inefficiencies, as highlighted by Jensen [30], who argued that managers of cash-rich firms might engage in value-destroying activities instead of investing in profitable projects. This misallocation of resources may exacerbate financial risk, reducing the firm's ability to invest in innovative initiatives. Brown and Petersen [8] demonstrated that firms with high cash reserves but poor investment strategies tend to underperform in terms of innovation output compared to their peers with better financial management strategies and practices.

The financial risk theory by Modigliani and Miller [9] presents a robust framework to understand the mediating role of financial risk in influencing the nexus of high short-term borrowings and monetary funds. According to their proposition, the capital structure of a firm directly influences its financial risk and cost of capital. Firms with a high volume of short-term borrowings (high leverage) face higher financial risk because of the fixed nature of debt obligations, which may limit their flexibility in investing in innovative projects. Conversely, excessive cash holding without productive use may also increase financial risk by leading to inefficient capital allocation and agency problems [30]. Additionally, constrained by the nature of dual high, firms need to ensure timely repayment of deposits and loans, leading to short-term operational and profit-seeking pressures. This can cause firms to focus more on short-term gains, neglecting the cultivation and development of long-term innovation capabilities. Therefore, to reduce financial risk, firms may adopt more cautious and conservative measures, being unwilling to bear the uncertainties and risks associated with innovation, and on these views, this study posits this hypothesis:

Hypothesis 3: Financial risk mediates the nexus of high volume of monetary funds and short-term borrowings with firms' innovation capabilities.

RESEARCH DESIGN

Data sources and sample selection

This study primarily selects small, medium, and large-sized companies of the textile industry as the research sample. The corporate data is sourced from the CSMAR database, spanning the period from 2011 to 2022. To improve data quality and ensure research accuracy, the data is processed using Stata 17.0 econometric software as follows: removing ST and *ST companies from the sample; excluding firms with missing values for key variables; applying a 1% winsorization on both ends for continuous variables to avoid biases in regression estimates due to extreme values.

Variables selection

Dependent variables

Referring to the study by Yao and Zhu [39], this paper measures corporate innovation on two levels: innovation input (RD) and innovation output (Patent1 and Patent_Award1). Innovation input is measured by the ratio of R&D expenditure to operating revenue, while innovation output is measured by the number of patents. Given the lag in patents, relying solely on the number of applications does not adequately reflect a firm's actual innovation output. Therefore, this study also includes the number of granted patents for further refinement.

Independent variables

Dual High (DH1): The dual high phenomenon (DH1) is exhibited by firms maintaining high levels of monetary funds and short-term borrowings relative to their total assets. For the current study, we employ two thresholds to capture dual high characteristics. The first definition considers a firm as dual high if the ratio of monetary funds to total assets, and the ratio of short-term borrowings to total assets, exceed 15%. This serves as the benchmark definition (DH1), and the dual high phenomenon is measured in this study for baseline analysis. This threshold of 15% ensures a broader representation of firms with dual high characteristics, offering insights into how moderate levels of monetary funds and borrowings could impact the corporate innovation [40, 41].

The second definition of dual-high phenomenon (DH2) is stricter and classifies a firm as dual high only if both the ratio of monetary funds to total assets and the ratio of short-term borrowings to total assets exceed 20% [42]. This definition is used as a proxy variable (DH2) to measure the dual-high phenomenon in robust analysis. This definition captures more pronounced cases of dual high characteristics, and the proportion of firms meeting these criteria could be relatively low, potentially leading to small sample size representation. Firms meeting the criteria for either DH1 or DH2 are assigned a value of 1; otherwise, the value is 0.

Control variables

Referring to prior literature [43, 44], this study also controls for variables such as net profit margin of total assets, company size, etc. The definitions of the main variables in this paper are detailed in table 1.

Model construction

Based on the results of the Hausman test, this paper employs a two-way fixed effect model (1) to test the impact of the dual high phenomenon on corporate innovation capability:

$$\text{Innovation}_{i,t} = \alpha_0 + \alpha_1 \text{DH1}_{i,t} + \alpha_2 \mathit{control}_{i,t} + \\ + \theta_i + \mu_t + \varepsilon_{i,t} \quad (1)$$

where Innovation$_{i,t}$ includes the dependent variables RD$_{i,t}$, Patent1$_{i,t}$, Patent_Award1$_{i,t}$, DH1$_{i,t}$ is the core independent variable. The control variables include net profit margin of total assets (ROA), company size (Size), revenue growth rate (Growth), the shareholding ratio of the largest shareholder (TOP1), years since the company's establishment (FirmAge), board size (Board), and cash flow ratio (Cashflow). $\varepsilon_{i,t}$ is the random disturbance term, α is the parameter to be estimated, θ_i represents firm fixed effects, and μ_t represents time fixed effects.

Table 1

VARIABLES DEFINITIONS

Variable category	Variable name	Variable code	Calculation method
Dependent variables	Innovation input	RD	R&D investment / Operating revenue
	Innovation output	Patent1	The natural logarithm of the total number of patent applications plus 1
		Patent_Award1	The natural logarithm of the total number of patents granted plus 1
Independent variables	Dual High effect	DH1	Proportion of short-term borrowings and monetary funds to total assets both exceeds 15%
		DH2	Proportion of short-term borrowings and monetary funds to total assets both exceeds 20%
Control variables	Return on total assets	ROA	Net profit / Average total assets
	Firm size	Size	Natural logarithm of total assets
	Operating revenue growth rate	Growth	Current year operating revenue/Last year operating revenue – 1
	Shareholding ratio of the largest shareholder	TOP1	Number of shares held by the largest shareholder / Total shares
	Firm age	FirmAge	ln(Current Year – Year of Establishment + 1)
	Board size	Board	Natural logarithm of the number of directors
	Cash flow ratio	Cashflow	Net cash flow from operating activities / Total assets

Table 2

DESCRIPTIVE STATISTICS					
Variable	**Obs**	**Mean**	**Std. dev.**	**Min**	**Max**
RD	21,552	4.671	6.582	0	424.9
Patent1	21,552	3.095	1.620	0	9.406
Patent_Award1	21,552	2.786	1.554	0	8.965
DH1	21,552	0.0852	0.279	0	1
ROA	21,552	0.0376	0.0762	–1.859	0.880
Size	21,552	22.25	1.301	17.81	28.64
Growth	21,552	0.392	13.57	–0.952	1878
TOP1	21,552	33.46	14.58	2.197	89.99
FirmAge	21,552	2.872	0.347	1.099	4.159
Board	21,552	2.122	0.196	1.099	2.890
Cashflow	21,552	0.0452	0.0685	–0.704	0.664

EMPIRICAL RESULTS

Descriptive statistics

The descriptive statistics results of this paper are shown in table 2. It is shown that the mean value of corporate innovation input (RD) is 4.671, with a minimum value of 0 and a maximum value of 424.9. The mean values of innovation output (Patent1 and Patent_Award1) are 3.095 and 2.786, respectively, with minimum values of 0 and maximum values of 9.406 and 8.965. This indicates a significant disparity in innovation capability among firms. The mean value of dual high (DH1) is 0.0852, indicating that 8.52% of the sample firms exhibit dual high characteristics. The distribution of control variables is generally consistent with the previous literature.

Multicollinearity test

To identify whether there is a multicollinearity problem among the variables in the model, we analyse the variance inflation factors (VIF) of the variables. As shown in column 1 of table 3, the maximum VIF for the model variables is 1.480, and the average VIF is 1.150. Generally, it is considered that when the VIF value does not exceed 5, the model does not have a serious multicollinearity problem. Therefore, there is no severe multicollinearity issue among the variables in this study, and it will not affect the accuracy of the model estimates.

Table 3

MULTICOLLINEARITY TEST RESULTS		
Variable	**(1)**	**(2)**
	VIF	**1/VIF**
Size	1.480	0.674
Patent_Award1	1.260	0.797
ROA	1.180	0.845
Cashflow	1.170	0.853
FirmAge	1.100	0.909
TOP1	1.090	0.916
RDSpendSumRatio	1.080	0.927
Board	1.070	0.933
DH1	1.010	0.989
Growth	1	0.996
Mean VIF	1.150	-

Baseline results

To explore the impact of dual high (DH1) on corporate innovation in depth, we conduct a regression analysis. The regression results are shown in table 4. The coefficient of dual high (DH1) on innovation input

Table 4

BASELINE REGRESSION RESULTS			
Variable	**(1)**	**(2)**	**(3)**
	RD	**Patent1**	**Patent_Award1**
DH1	–0.900***	–0.100***	–0.156***
	(0.104)	(0.029)	(0.028)
ROA	–4.183***	0.915***	0.209*
	(1.238)	(0.130)	(0.117)
Size	–0.439***	0.661***	0.622***
	(0.029)	(0.008)	(0.008)
Growth	0.021	–0.002***	–0.001***
	(0.027)	(0.000)	(0.000)
TOP1	–0.019***	–0.001*	–0.001
	(0.003)	(0.001)	(0.001)
FirmAge	–1.771***	–0.114***	–0.126***
	(0.267)	(0.028)	(0.027)
Board	–0.065	0.160***	0.098**
	(0.185)	(0.046)	(0.043)
Cashflow	–0.603	0.352**	0.522***
	(1.032)	(0.147)	(0.135)
_cons	20.538***	–11.624***	–10.909***
	(1.115)	(0.192)	(0.183)
Firm FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
N	21,552	21,552	21,552
r2	0.199	0.449	0.458
F	64.793	954.146	903.450

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are reported in parentheses.

(RD) is –0.900, and it is significant at the 1% level, indicating a significant negative correlation between dual high and innovation input. The coefficients of dual high (DH1) on innovation output (Patent1 and Patent_Award1) are –0.100 and –0.156, respectively, and both are significant at the 1% level, indicating a significant negative correlation between dual high and innovation output. In summary, dual high is significantly negatively correlated with corporate innovation capability, thus validating the hypothesis. The significantly negative correlation of dual high with both innovation input and innovation output suggests that when companies face dual high, they tend to reduce their investment in innovation, and their innovation output is also negatively affected. This may be because high-interest rates increase the financing costs for companies, thereby reducing the funds available for R&D and innovation. Additionally, high-interest rates might mean that companies, facing higher financial pressure, become more cautious and may choose to reduce risk investments, including innovation projects. Overall, findings presented by baseline regression support hypothesis 1.

Testing the robustness of baseline results

Changing the model

To eliminate the differences in results due to different regression models, this study retests the main hypothesis using a Tobit model.

As shown in table 5, dual high (DH1) is significantly negatively correlated with both innovation input and innovation output at the 1% level, and the conclusion remains unchanged.

Table 5

RESULTS WITH THE ALTERNATIVE MODEL

Variable	(1) RD	(2) Patent1	(3) Patent_Award1
DH1	-1.236^{***}	-0.152^{***}	-0.203^{***}
	(0.156)	(0.035)	(0.034)
_cons	30.737^{***}	-8.043^{***}	-7.588^{***}
	(0.899)	(0.202)	(0.195)
var(e.Patent1)		2.040^{***}	
		(0.020)	
var(e.RD)	40.341^{***}		
	(0.389)		
var(e.Patent_Award1)			1.899^{***}
			(0.018)
N	21,552	21,552	21,552
Control Var.	Yes	Yes	Yes

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are reported in parentheses.

Changing the explanatory variable

This study redefines "dual high" as the ratio of short-term loans and monetary funds to total assets exceeding 20% for two consecutive years and being higher than the industry average [45]. Under this definition, it is labelled DH2; if the condition is met, DH2 is 1, otherwise, it is 0. After regression, the results are shown in table 6. The redefined dual high (DH2) is significantly negatively correlated with both innovation input and innovation output at the 1% level, and the conclusion remains unchanged.

Table 6

RESULTS WITH PROXY OF EXPLANATORY VARIABLE

Variable	(1) RD	(2) Patent1	(3) Patent_Award1
DH2	-0.885^{***}	-0.274^{***}	-0.315^{***}
	(0.141)	(0.055)	(0.053)
_cons	20.567^{***}	-11.628^{***}	-10.911^{***}
	(1.117)	(0.192)	(0.183)
Firm FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Control var.	Yes	Yes	Yes
N	21,552	21,552	21,552
r2	0.198	0.450	0.458
F	61.033	956.643	905.492

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are reported in parentheses.

Further analysis

Moderating effect of digitalisation

Digitalisation can, to some extent, suppress the dual high phenomenon in enterprises [46], and digital transformation can promote the improvement of corporate innovation performance [47]. Therefore, we believe that corporate digitalisation acts as a moderating variable between dual high and innovation capability. To this end, we introduce the interaction term between the moderating variable of corporate digitalisation and dual high (DH1), labelled DH_DCG. Before interaction, the explanatory and moderating variables are centred. The constructed model is as follows:

$$\text{Innovation}_{i,t} = \alpha_0 + \alpha_1 \text{DH1}_{i,t} + \alpha_2 \text{DH\_DCG}_{i,t} + \alpha_3 control_{i,t} + \theta_i + \mu_t + \varepsilon_{i,t} \quad (2)$$

where $\text{Innovation}_{i,t}$ includes the explained variables $\text{RD}_{i,t}$, $\text{Patent1}_{i,t}$, $\text{Patent\_Award1}_{i,t}$. The regression results are shown in table 7. The results indicate that the interaction term DH_DCG exhibits a significant negative correlation with enterprise innovation at the 1% level, suggesting that the interactive effect between the level of enterprise digitalisation and the explanatory variable (DH1) significantly influences enterprise innovation, thereby we accept hypothesis 2.

Mediating effect of financial risk

If a company's financial risk is relatively high, it may exacerbate the impact of high deposits and high loans (DH) on its innovation capability. Firstly, financial risk may lead to investment constraints for the company, especially in the field of innovation. High debt ratios and high-interest expenses can limit a

Table 7

MODERATING EFFECTS OF DIGITALIZATION			
Variable	**(1)**	**(2)**	**(3)**
	RD	**Patent1**	**Patent_Award1**
DH1	-0.913^{***}	-0.102^{***}	-0.156^{***}
	(0.105)	(0.029)	(0.028)
DH_DCG	-0.310^{***}	-0.079^{***}	-0.056^{***}
	(0.076)	(0.021)	(0.021)
DCG	0.286^{***}	0.113^{***}	0.105^{***}
	(0.043)	(0.008)	(0.007)
_cons	20.866^{***}	-11.494^{***}	-10.788^{***}
	(1.098)	(0.191)	(0.182)
Firm FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Control Var.	Yes	Yes	Yes
N	21,552	21,552	21,552
r2	0.201	0.455	0.463
F	60.712	796.759	756.987

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are reported in parentheses.

company's cash flow, making it difficult to obtain sufficient funds for innovation activities. These investment constraints may hinder the company's R&D and other innovation activities, thereby reducing its innovation capability. Secondly, as mentioned earlier, signalling theory suggests that financial risk can send negative signals to the company's shareholders and investors, reducing their confidence and support for the company. Investors may worry that the company cannot bear the high debt burden, thereby decreasing their willingness to invest in the company. This could limit the company's financing capacity, further weakening its innovation capability. Finally, financial risk may cause the company to focus more on risk aversion rather than pursuing innovation. The company might become more cautious in innovation projects, avoiding taking on excessive risks, which could cause the company to miss out on potential innovation opportunities. Based on this, we use the "Oscore" proposed by Ohlson [48] to reflect the company's financial risk and construct the following model:

$$OScore_{i,t} = \alpha_0 + \alpha_1 DH1_{i,t} + \alpha_2 control_{i,t} + \theta_i + \mu_t + \varepsilon_{i,t} \quad (3)$$

$$Innovation_{i,t} = \alpha_0 + \alpha_1 OScore_{i,t} + \alpha_2 DH1_{i,t} + \alpha_3 control_{i,t} + \theta_i + \mu_t + \varepsilon_{i,t} \quad (4)$$

where $Innovation_{i,t}$ includes the dependent variables $RD_{i,t}$, $Patent1_{i,t}$, $Patent\_Award1_{i,t}$. The results are shown in table 8. After adding the mediation variable, the relationship between DH and corporate innovation remains significantly negatively correlated at the 1% level, and the absolute value is smaller than the regression results without the mediation variable, indicating that the mediation effect is established, and this finding led us to accept hypothesis 3.

Heterogeneity analysis: Firm level

Due to possible differences in financing structures between state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs), SOEs may rely more on traditional financing methods such as bank loans, while non-SOEs may prefer diversified financing channels, including equity financing, bond financing, etc. Therefore, DH may have different impacts on the financing costs and available funds for the two types of enterprises, thereby affecting their innovation input and output. The inhibitory effect of DH on the innovation capability of non-SOEs is stronger compared to SOEs. Based on this, we divided the sample into SOEs and non-SOEs for regression analysis, as shown in table 9. The regression results show that DH has a significantly negative correlation with the innovation capability of non-SOEs at the

Table 8

MODERATING EFFECTS OF FINANCIAL RISK				
Variable	**(1)**	**(2)**	**(3)**	**(4)**
	OScore	**RD**	**Patent1**	**Patent_Award1**
DH1	0.879^{***}	-0.453^{***}	-0.081^{***}	-0.140^{***}
	(0.030)	(0.099)	(0.031)	(0.030)
OScore		-0.396^{***}	0.008	0.010^{*}
		(0.029)	(0.006)	(0.005)
_cons	-13.379^{***}	13.863^{***}	-11.524^{***}	-10.746^{***}
	(0.254)	(0.840)	(0.218)	(0.209)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Control Var.	Yes	Yes	Yes	Yes
N	19761	19761	19761	19761
r2	0.548	0.274	0.452	0.460
F	651.483	69.686	781.872	737.934

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are reported in parentheses.

Table 9

MODERATING EFFECTS OF FINANCIAL RISKFIRM OWNERSHIP HETEROGENEITY ANALYSIS RESULTS						
Variables	**SOEs**			**Non-SOEs**		
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	RD	**Patent1**	**Patent_Award1**	**RD**	**Patent1**	**Patent_Award1**
DH1	–0.522***	–0.061	–0.114**	–1.036***	–0.101***	–0.160***
	(0.142)	(0.052)	(0.051)	(0.179)	(0.036)	(0.034)
_cons	13.735***	–11.780***	–11.481***	22.993***	–10.496***	–9.785***
	(0.960)	(0.370)	(0.354)	(1.782)	(0.276)	(0.262)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Control Var.	Yes	Yes	Yes	Yes	Yes	Yes
N	6576	6576	6576	14615	14615	14615
r2	0.325	0.546	0.550	0.204	0.390	0.402
F	22.153	400.218	388.997	27.883	385.449	366.020

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are reported in parentheses.

1% level, indicating heterogeneity in the impact of DH on the innovation capability of SOEs and non-SOEs.

CONCLUSIONS AND POLICY IMPLICATIONS

Using data of 1,796 textile companies of China spanning over 2011–2022, this paper examines the nexus between the dual high (DH) phenomenon and corporate innovation capabilities. Using a two-way fixed effects model, this study confirms that the DH phenomenon significantly hinders corporate innovation capabilities of Chinese textile enterprises, mainly through its impact on corporate financial risk and resource allocation. The mediation effect of financial risk necessitates effective financial risk management strategies, as high financial risk arising from the DH phenomenon could divert resources away from long-term strategic investments like innovation. Textile enterprises with pronounced DH characteristics could face higher financial risks, compelling them to adopt conservative financial strategies that may reduce their R&D investments, ultimately inhibiting the corporate innovation potential. Digitalisation is found to be a significant factor in reducing the DH phenomenon on the innovation capabilities of Chinese textile enterprises. Additionally, this paper identified significant differences in the impact of the DH phenomenon on innovation capabilities across ownership structures. Non-state-owned enterprises (non-SOEs) experience stronger inhibitory effects of DH on innovation capabilities compared to the state-owned enterprises (SOEs). This disparity indicates that non-SOEs would lack the institutional support and financial flexibility that could allow them to amplify the adverse effects of DH.

There are several policy implications presented by this paper: Specifically, findings presented for hypothesis 1 highlight the negative impact of the dual high phenomenon on corporate innovation capabilities, and push the Chinese regional government to support textile companies by offering tax incentives, subsidies, and policies that can encourage diversified financing channels, such as equity financing or bond issuance. These measures may help these enterprises to reduce their reliance on bank loans and thus mitigate financial constraints linked with the dual high phenomenon, thereby fostering corporate innovation capabilities of textile enterprises. Findings indicated by hypothesis 2 encourage textile companies of China to promote digital transformation so they can have efficient resource allocation and improved innovative performance. Findings based on hypothesis 2 push Chinese textile enterprises to adopt effective financial risk management strategies so they can mitigate the adverse effects of dual high characteristics on corporate innovation. Additionally, Diversified financing channels can provide textile companies with more options, lessening the suppressive effect of DH on innovation capability. Regulatory authorities should require textile companies to enhance information disclosure and transparency, including key information about their financial status, borrowing activities, and asset-liability structure. This transparency facilitates the assessment and monitoring of a company's risk status by regulatory authorities and investors. By improving information disclosure and transparency, regulatory authorities can better understand a company's risk status and take necessary regulatory measures promptly.

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Iterative development of flexible textile composites for naval emergency shuttles in oil spill recovery

DOI: 10.35530/IT.076.05.2024106

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ABSTRACT – REZUMAT

Iterative development of flexible textile composites for naval emergency shuttles in oil spill recovery

Maritime oil spill accidents should not be regarded as irreversible disasters, as hydrocarbons are recoverable and economically valuable resources that, when efficiently processed, can be reintroduced into the economic value chain. Currently, five principal strategies are employed to mitigate hydrocarbon pollution: natural biodegradation, transfer to storage barges, in situ combustion, dispersion within the water column, and surface concentration followed by recovery. This paper focuses on the fifth strategy – concentration and recovery of hydrocarbons from the water surface – by presenting an iterative development approach for two composite materials intended for use in a naval emergency response unit. This unit is specifically engineered to improve the efficiency of hydrocarbon collection, concentration and recovery during maritime spill incidents, particularly under emergency conditions. The composite materials comprise a textile matrix structure made from 100% polyester yarns, obtained through a weaving process and subsequently coated with polyvinyl chloride (PVC) to enhance mechanical durability and resistance to water and oil. To optimise the structural performance of the composites in marine environments, textile engineering methodologies were applied, including advanced Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) tools.

This research highlights the critical role of the textile structure and the intrinsic properties of polyester fibres, including their tensile strength, flexibility, and chemical resistance to oil, saltwater, and ultraviolet (UV) degradation. An iterative design methodology supported by virtual prototyping was employed to evaluate how textile construction techniques – such as weaving and coating – affect the deployment of the composite material's overall mechanical performance and suitability for deployment in emergency oil spill response operations.

Keywords: *marine pollution, oil spill recovery, functional textiles, composite materials, naval emergency unit, computer-aided design (CAD), computer-aided engineering (CAE)*

Dezvoltarea compozitelor textile flexibile pentru unități navale de intervenție destinate recuperării hidrocarburilor din poluări marine

Accidentele maritime de poluare cu hidrocarburi nu trebuie considerate dezastre ireversibile, întrucât acestea reprezintă resurse recuperabile și valoroase din punct de vedere economic care, printr-o procesare adecvată, pot fi reintegrate în lanțul valoric. În prezent, cinci strategii majore sunt utilizate pentru atenuarea poluării cu hidrocarburi: biodegradarea naturală; transferul către barje de stocare; arderea in situ; dispersia în coloana de apă; precum și concentrarea la suprafață urmată de recuperare.

Prezenta lucrare se concentrează asupra celei de-a cincea strategii – concentrarea și recuperarea hidrocarburilor de la suprafața apei – prin propunerea unei metodologii iterative de dezvoltare pentru două materiale compozite destinate utilizării într-o unitate navală de intervenție de urgență. Această unitate este proiectată în mod special pentru a crește eficiența proceselor de colectare, concentrare și recuperare a hidrocarburilor în cadrul incidentelor de poluare marină, în particular în condiții critice de urgență. Materialele compozite investigate sunt constituite dintr-o matrice textilă obținută prin țeserea firelor de poliester 100%, ulterior acoperită cu policlorură de vinil (PVC), pentru a conferi rezistență mecanică crescută, impermeabilitate și protecție împotriva hidrocarburilor. Optimizarea performanțelor structurale ale acestor compozite în medii marine a fost realizată prin aplicarea metodologiilor de inginerie textilă, cu utilizarea instrumentelor avansate de proiectare asistată de calculator (CAD) și de inginerie asistată de calculator (CAE).

Lucrarea evidențiază rolul critic al structurii textile și a proprietăților intrinseci ale fibrelor de poliester – rezistența la tracțiune, flexibilitatea și rezistența chimică la hidrocarburi, apă sărată și radiații ultraviolete (UV). O metodologie de proiectare iterativă, susținută de prototipare virtuală, a fost implementată pentru a evalua modul în care tehnicile de obținere și finisare ale structurilor textile – precum țeserea și acoperirea – influențează performanța mecanică globală a materialelor compozite și compatibilitatea utilizării lor în operațiuni navale de intervenție de urgență în cazul poluărilor marine cu hidrocarburi.

Cuvinte-cheie: *poluare marină, recuperarea hidrocarburilor, textile funcționale, materiale compozite, unități navale de intervenție de urgență, proiectare asistată de calculator (CAD), inginerie asistată de calculator (CAE)*

INTRODUCTION

Oil spills have long-lasting and dramatic impacts on marine ecosystems, threatening biodiversity and harming marine life. Such incidents may arise from a variety of sources, including tanker accidents, offshore drilling platforms and routine maritime operations. Although the precise quantification of global oil inputs into marine environments remains challenging, studies estimate that approximately 35% of marine pollution originates from tanker traffic, while an additional 45% is attributed to industrial discharges and offshore extraction activities. Crude oil and petroleum products contain volatile organic compounds (VOCs) that readily evaporate, contributing to atmospheric pollution and exacerbating the overall environmental burden [1–3]. Several physical factors affect the behaviour of oil spills once they reach the water surface. These include surface tension, which influences the spread of oil, specific gravity (which changes as lighter components evaporate), and viscosity (which determines the oil's tendency to remain in place) [4–6].

Two principal strategies are employed in the development of materials and systems for effective oil spill response: oil concentration and recovery [7]. *Concentration* is commonly facilitated by the use of floating barriers, such as booms, which serve to confine and limit the dispersion of oil on the water surface. Recovery operations, on the other hand, involve various types of equipment, including booms, skimmers, and sorbents, that are designed to extract and collect the contained oil [8, 9]. The design of these recovery systems typically integrates critical components such as a freeboard to prevent oil from splashing over, flotation elements to ensure buoyancy, and support structures to maintain stability during operation. Once captured, the oil is pumped into storage tanks for subsequent transport and disposal [10–14].

Various types of composite textile structures are employed in the fabrication of flexible oil containment tanks designed for emergency response in maritime disaster scenarios. These materials are selected based on their ability to withstand harsh environmental conditions and to perform accordingly. Common configurations include: (a) polyester (PES) fabrics coated with polyvinyl chloride (PVC) or thermoplastic polyurethane (TPU); (b) polyester or polyamide fabrics vulcanised with rubber and coated with an external layer of Hypalon® to enhance resistance to abrasion and puncture; and (c) polyester fabrics coated with ethylene-vinyl acetate (EVA). Each material combination is tailored to ensure mechanical robustness, chemical resistance, and operational reliability under demanding field conditions [15–17].

The primary advantage of these composite structures lies in their enhanced resistance to a range of aggressive environmental and chemical stressors, including exposure to petroleum products, extreme temperatures, ultraviolet (UV) radiation, high-salinity seawater, industrial detergents, and, where applicable, various chemical agents.

This study investigates technologies for oil spill concentration and recovery through the conceptual design of a naval emergency shuttle, an innovative, floating, collapsible unit intended for rapid deployment in the immediate aftermath of a spill. The proposed shuttle is required to be lightweight, compact, and portable, with the ability to function effectively in strong sea currents while facilitating efficient oil collection and temporary storage. The design process critically considers the physicochemical properties of petroleum hydrocarbons, such as volatility and solubility, which influence material selection and structural integrity [18–22]. To meet these performance criteria, an iterative development approach was employed to engineer a flexible composite material based on a textile matrix. The research emphasises the optimisation of key material properties, namely flexibility, mechanical durability, and resistance to the harsh marine environment, for application in naval emergency shuttles [23–26]. Leveraging advanced digital design tools, this work aims to enhance the operational performance and overall effectiveness of oil spill response and recovery systems.

MATERIALS AND METHODS

In the design and development of a flexible composite material with a textile matrix for the proposed naval emergency transport unit, several key functional characteristics were taken into account to ensure its effectiveness in oil spill response scenarios. The naval emergency shuttle was required to:

- operate efficiently under moderate sea state conditions, corresponding to a minimum of Force 4 on the Beaufort scale (wind speeds of 11–16 knots and wave heights of approximately 1.0–1.5 m), during oil spill recovery operations;
- support transport and storage, with a minimum speed of 2 knots for the vessel-shuttle assembly;
- enable rapid deployment within a maximum response time of one hour, in conjunction with conventional oil spill recovery equipment such as vessels, booms, and skimmers;
- possess a hydrodynamic configuration that ensures stability and secure storage of recovered oil;
- incorporate additional design features to facilitate oil clean-up and phase separation;
- lightweight, compact, and highly portable to allow for ease of transport and deployment in emergencies.

Designing the naval emergency shuttle

Based on the defined operational requirements, a specialised structure for the naval emergency shuttle was developed. The design consists of the following primary components: 1 – central unit: a right circular cylinder structure forming the above-water freeboard, intended to concentrate the spilled oil and prevent wave-induced splashing; 2 – fine prow: a truncated conical element positioned at the front, equipped with

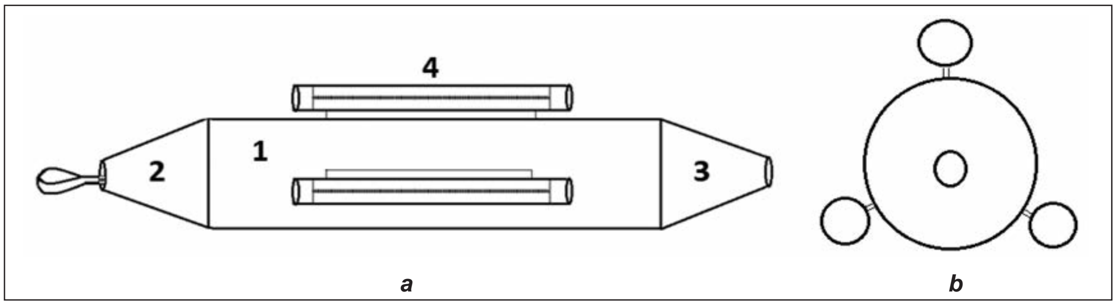

Fig. 1. Naval emergency shuttle design: *a* – frontal view; *b* – lateral view

Table 1

COMPONENT CHARACTERISTICS AND SUBASSEMBLIES				
Subassembly	**Shape**	**Dimensions (mm)**		
		Height/Length	Bottom diameter	Top diameter
Central unit	right circular cylinder	1800	600	
Fine prow/Stern	truncated cone	400	600	200
Floating structures	right circular cylinder	1200	150	

an anchoring eyelet; 3 – stern: a similarly shaped truncated cone, positioned at the rear for hydrodynamic balance and directional stability; 4 – floating structures: three right circular cylinders, aligned longitudinal along the central unit to provide buoyancy and support. These elements are illustrated in figure 1, which presents both the frontal and lateral views of the shuttle configuration.

The manufacturing process of the naval emergency shuttle involves the precise assembly of these components using a reinforced stitching technique, which ensures structural integrity while preserving the defined geometry and functional dimensions outlined in table 1.

Incremental development of the flexible composite materials with a textile matrix

To meet the specific requirements of the naval emergency shuttle – intended for the collection, concentration, and recovery of hydrocarbons from the water surface – two tailored composite materials based on PVC-coated polyester fabric were developed:

- CM1 (composite material 1): used for the central unit and the floating support;
- CM2 (composite material 2): used for the fine prow and stern.

The incremental development and optimisation of these composite structures were achieved using specialised CAD–CAE (Computer-Aided Design and Engineering) software tools. This digital approach enables detailed structural analysis and material adaptation according to the operational stress loads and marine environment constraints.

To generate the 3D models required for the structural analysis, the following steps must be completed:

a) 3D simulations and modelling

The Generative Structural Analysis module was used to define the model and to visualise the components of the shuttle, before the numerical simulation. Each subassembly was independently modelled in 3D, as illustrated in figure 2.

b) Geometry discretisation

The 3D models were discretised into finite elements using linear tetrahedral elements (four nodes, one Gauss point, three degrees of freedom per node). A meshing tolerance of 0.01 mm was applied to ensure high fidelity of the model geometry before simulation, as shown in figure 3.

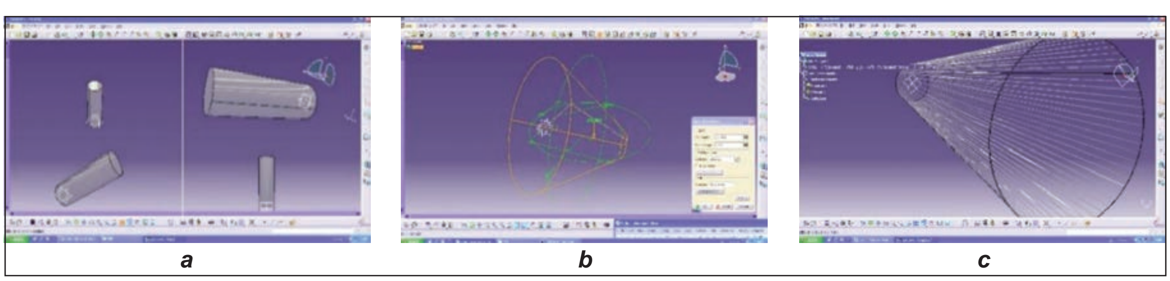

Fig. 2. 3D simulation of the naval emergency shuttle design:
a – central unit, *b* – thin prow and stern; *c* – floating structures

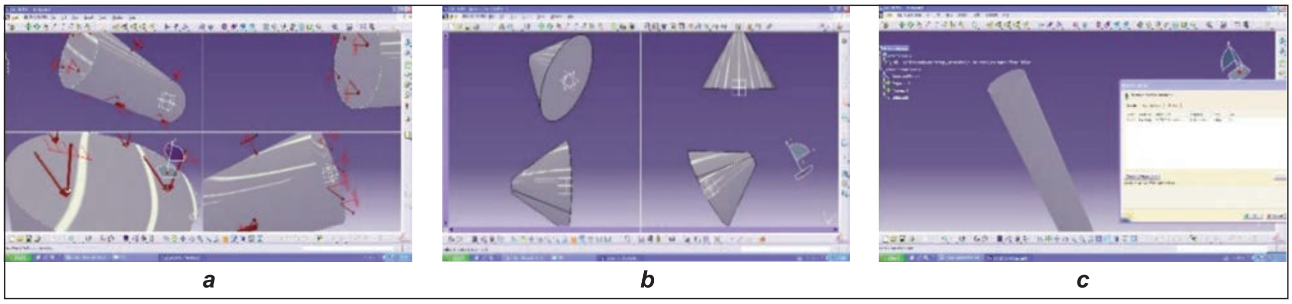

Fig. 3. Geometry discretisation: *a* – central unit, *b* – thin prow and stern; *c* – floating structures

RESULTS AND DISCUSSIONS

Structural models analysis

The structural behaviour of the naval emergency shuttle components was evaluated using finite element simulations conducted within the Generative Structural Analysis environment. The models were solved using the integrated solver, and deformation results were analysed through section-plane visualisation (Cut Plane Analysis). The internal deformation of the composite material subassemblies ranges from 0.0 to 10.5 mm, confirming that the structural integrity of the system is maintained under operational conditions corresponding to sea states of up to Beaufort 6 (figure 4).

In particular, the central unit showed a maximum displacement of 25.3 mm under simulated load. Despite this higher deformation, the structure remains within safe operational limits, without risk of collapse, validating its suitability for open-sea intervention scenarios.

Von Mises stress analysis

The results of the von Mises stress analysis for each subassembly are summarised below:

- Central unit: Stress value ranged from 0 to 2.13×10^8 N/m^2, remaining well below the value of the admissible stress limit of CM2 (3.45×10^{10} N/m^2);
- Fine prow and stern:
  Fine prow: 6.96×10^7 to 5.38×10^9 N/m^2;
  Stern: 6.41×10^5 to 4.96×10^7 N/m^2;
  Both remain below the admissible limit of CM1 (9.45×10^9 N/m^2).
- Floating structures: Stress values ranged from 0 to 1.27×10^7 N/m^2, also below CM1's resistance threshold, ensuring structural stability under operational marine conditions (figure 5).

Principle stress (main stress tensor)

The analysis of principal stress values further confirmed the material's structural adequacy:

- Central unit: range of -5.21×10^8 to 4.92×10^8 N/m^2 (below CM2's threshold);
- Fine prow and stern:
  Fine prow: -7.68×10^9 to 5.51×10^9 N/m^2;

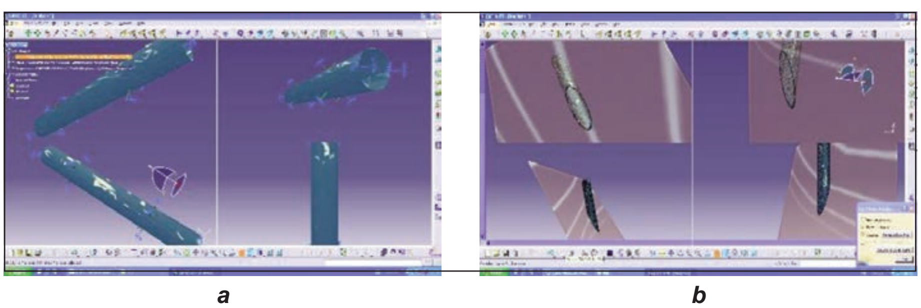

Fig. 4. Structural simulation- Deformation of floating structures:
a – multi-view visualisation; *b* – sectional view (Cut Plane Analysis)

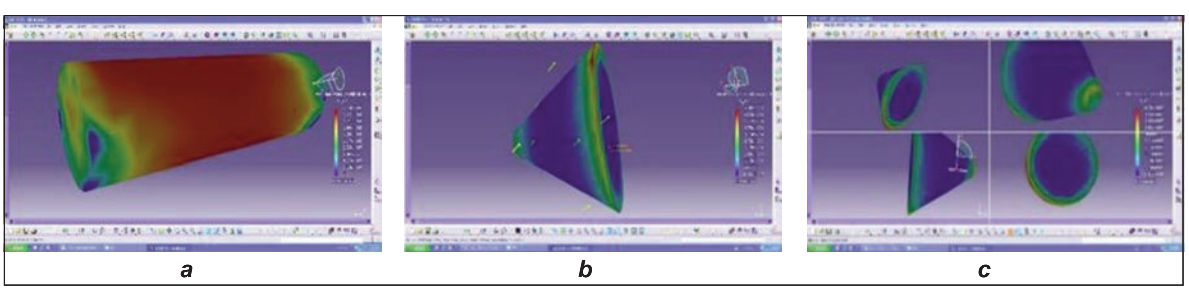

Fig. 5. Von Mises stress distribution during operational displacement: *a* – central unit; *b* – fine prow; *c* – stern

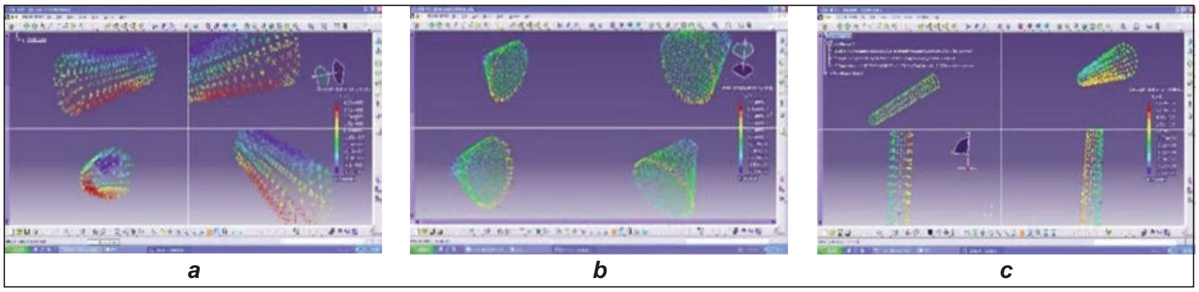

Fig. 6. Principal stress (main stress tensor) distributions: *a* – central unit; *b* – stern; *c* – floating structures

Stern: -0.25×10^7 to 7.75×10^7 N/m^2;
Both remain under the value of the admissible resistance of CM1.

- Floating structures: range of -1.13×10^7 to 8.62×10^6 N/m^2, within CM1's admissible limits (figure 6).

The results validate the structural resilience of the composite materials under simulated marine stresses, confirming the suitability of both CM1 and CM2 for use in the naval emergency shuttle.

Material testing and experimental validation

The developed composite materials were also subjected to physical-mechanical testing to characterise their performance. The test results are presented in table 2, and a demonstration model was tested in real operation conditions (figure 7), in order to validate the Iterative development of the flexible composite materials with textile matrix.

Finally, a demonstration model of the shuttle was tested under realistic conditions to validate the integrated system's design and material performance (figure 7).

Fig. 7. Demonstration model of the naval emergency shuttle

CONCLUSIONS

The conducted research demonstrates that the design and development of a rapid intervention naval unit for oil spill recovery necessitate the use of high-performance flexible composite materials capable of withstanding dynamic mechanical loads and harsh open-sea conditions.

The incremental development of the two composite material variants was supported by advanced Computer-Aided Design and Engineering *(CAD-CAE) tools*. Structural modelling and analysis were carried out using the Generative Structural Analysis module, with internal deformations assessed using Cut Plane Analysis. These enabled the precise simulation of operational stress conditions.

The simulation results showed that the deformations ranged from 0.0 to 10.5 mm for most subassemblies, confirming the structural integrity of the shuttle even under sea states up to Beaufort 6. For the central unit, the maximum deformation recovered was 25.3 mm – still within safe operational limits, ensuring no risk of structural collapse under severe agitation.

In conclusion, the composite materials developed through this research meet the functional, mechanical, and environmental requirements for a rapid-deployment naval shuttle intended for oil spill concentration and recovery. Their performance has been validated through both numerical simulations and field testing, confirming their suitability for high-risk marine intervention scenarios.

ACKNOWLEDGMENT

This scientific paper is funded by the Ministry of Research, Innovation and Digitalisation, UEFISCDI, project number PN-III-P2-2.1-PED-2021-1378, within PNCDI III.

Table 2

PHYSICAL-MECHANICAL CHARACTERISTICS OF THE COMPOSITE MATERIALS		
Characteristics	**CM1 (floating structures and central unit)**	**CM2 (fine prow and stern)**
Fibre composition (%)	PVC-coated 100% PES	PVC-coated 100% PES
Mass (g/m^2)	850	1800
Breaking strength (N, warp/weft)	2100/2100	4400/3300
Elongation at break (%, warp/weft)	28/30	16/24
Tear resistance (trouser) (N)	230/132	450/300
Tear resistance (wing) (N)	140/105	350/250

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Balancing of the national clothing production line based on the genetic taboo mixing algorithm

DOI: 10.35530/IT.076.05.2024105

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ABSTRACT – REZUMAT

Balancing of the national clothing production line based on the genetic taboo mixing algorithm

In order to solve the problems of complicated process types, long production process arrangement time and low production efficiency of national clothing production, a national clothing production line is constructed based on a hanging assembly line. Firstly, the national clothing production line is thoroughly explored. Considering the constraints of the production line and the multi-objective optimisation, a mathematical model of balance optimisation is constructed. Secondly, the adaptive improvement of the genetic algorithm (GA) in coding and genetic operation is explored. On this basis, the tabu search algorithm is embedded into the GA framework, and the genetic tabu hybrid algorithm is proposed to realise the production balance of national clothing. MATLAB software is used to solve the problem of balancing the production line process arrangement. Finally, the Flexsim simulation software is used to simulate the actual production process to verify the intelligent arrangement results, and an application analysis is carried out with a Mongolian clothing with a national clothing characteristic manufacturing process as an example. The results show that the genetic tabu hybrid algorithm is suitable for solving the problem of process arrangement balance in the national clothing production line. The assembly line equilibrium index after intelligent automatic arrangement of the genetic tabu hybrid algorithm was 6.6, the maximum beat and the minimum beat difference Fmin was 19. The simulation model verifies that the stable operation time of each station accounts for more than 95%, and the simulation results show that the arrangement scheme is feasible.

Keywords: *national clothing, clothing production line, genetic taboo hybrid algorithm, Flexsim, simulation optimisation*

Echilibrarea liniei de producție a îmbrăcămintei cu specific național pe baza algoritmului de amestecare a tabuurilor genetice

Pentru a rezolva problemele legate de tipurile complicate de procese, timpul îndelungat de organizare a procesului de producție și eficiența scăzută a producției de îmbrăcăminte cu specific național, se construiește o linie de producție de îmbrăcăminte cu specific național bazată pe o linie de asamblare suspendată. În primul rând, linia de producție de îmbrăcăminte cu specific național este explorată în profunzime, luând în considerare constrângerile liniei de producție și optimizarea multi-obiectiv, se construiește modelul matematic de optimizare a echilibrului. În al doilea rând, este explorată îmbunătățirea adaptivă a algoritmului genetic (GA) în codare și operare genetică, pe această bază, algoritmul de căutare tabu este încorporat în cadrul GA și este propus algoritmul hibrid tabu genetic pentru a realiza echilibrul producției de îmbrăcăminte națională, utilizând software-ul MATLAB pentru a rezolva problema echilibrului aranjamentului procesului liniei de producție. În cele din urmă, software-ul de simulare Flexsim este utilizat pentru a simula procesul de producție real pentru a verifica rezultatele aranjamentului inteligent și este efectuată o analiză a aplicației cu un exemplu de îmbrăcăminte mongolă cu un proces de fabricație caracteristic îmbrăcămintei naționale. Rezultatele arată că algoritmul hibrid tabu genetic este potrivit pentru rezolvarea problemei echilibrului aranjamentului procesului în linia de producție a îmbrăcămintei cu specific național. Indicele de echilibru al liniei de asamblare după aranjarea automată inteligentă a algoritmului hibrid tabu genetic a fost de 6,6, diferența de bătăi maximă și minimă Fmin a fost de 19. Modelul de simulare verifică faptul că timpul de funcționare stabil al fiecărei stații reprezintă mai mult de 95%, iar rezultatele simulării arată că schema de aranjare este fezabilă.

Cuvinte-cheie*: îmbrăcăminte națională, linie de producție de îmbrăcăminte, algoritm hibrid tabu genetic, Flexsim, optimizare prin simulare*

INTRODUCTION

The deep integration of information technology and the manufacturing industry, promoting new industrialisation, and promoting the high-end and intelligent development of the manufacturing industry, is triggering far-reaching industrial changes. National clothing sewing has always been based on customisation. Under the direction of intelligent and efficient production, it has gradually formed a market demand situation with multiple varieties, small batches, high quality and short delivery time, which requires the production of national clothing enterprises to be more flexible and rapid. In enterprise clothing production, the most important thing is production efficiency; the production efficiency of clothing mainly depends on the balance of the process arrangement on the production line. In the research of clothing production, scholars have carried out theoretical, methodological and

case application research on clothing production, but the study of clothing production mainly focuses on the clothing production lines construction based on the daily mass production of trousers, shirts and other relatively simple changes in style, it can not meet the production orders of national clothing manufacturing enterprises have the characteristics of small single quantity, changeable style and fast replacement, due to the complexity and variety of the production process of national clothing, the traditional manual arrangement method has the problems of long manual arrangement time and low arrangement efficiency, therefore, the balance problem of national clothing production line needs to be solved urgently.
Thus, the objective of our research focuses on solving the problem of intelligent process arrangement balance of the national costume production line through intelligent algorithm and virtual simulation technology, improving the work efficiency of the national costume production line, adapting to the changes of production tasks and product structure, promoting the high-end, intelligent and green development of the national clothing manufacturing industry.
In this paper, the national clothing production line is constructed based on the hanging line. Firstly, the national clothing production line is deeply explored, and the mathematical model of the new national clothing production line is constructed by comprehensive consideration of the constraints of the production line and multiple optimisation objectives. Secondly, the genetic algorithm itself is designed to ensure the optimisation efficiency and the accuracy of the results. Although the genetic algorithm (GA) has invisible parallelism and global solution space search ability, it also has some problems, such as poor local search ability, premature convergence or slow convergence speed in practical applications. In this paper, in terms of gene coding and genetic operation, adaptive improvement is explored according to the characteristics of the process arrangement balance problem of the national clothing production line, so that it can be dynamically adjusted with the number of iterations to avoid premature convergence in the process. In the aspect of algorithm design, the tabu search algorithm is embedded into the GA framework, and the genetic tabu hybrid algorithm is proposed to improve the search ability of the feasible solution. The MATLAB software is used to realise the programming and operation of the algorithm, and the intelligent optimisation arrangement of the national clothing production line is realised. The arrangement results are verified by Flexsim virtual simulation technology, and a national costume is taken as an example to analyse and verify.

LITERATURE REVIEW

At present, scholars' research on the balance optimisation of garment production lines mainly adopts the application research of intelligent algorithms and virtual simulation technology. In the application research of intelligent algorithm, after giving the optimization goal of garment production line and the constraint condition of production line balance, scholars adopt [1] ranked positional weight technique [2], grouping genetic algorithm (GGA) [3], particle swarm algorithm [4, 5], improved ant colony algorithm [6], genetic algorithm [7], NSGA-II algorithm [8], quadratic-selection genetic algorithm [9] and other intelligent algorithms to build the balance optimization model of clothing production line. Through the comparison and application of different intelligent algorithms such as exhaustive search, simulated annealing and simulated annealing with greedy [10], greedy algorithm, tabu search algorithm and simulated annealing algorithm [11], the balance optimization of garment production line is studied [12], taking trousers, shirts and other daily wear as an example to solve the balance of production line process arrangement, through computer automatic process scheduling, the processing tasks are evenly distributed to each workstation [13] to achieve the purpose of improving the production efficiency of the garment assembly line and lean production[14]. In the application research of virtual simulation technology, scholars applied Em-plant [15], Arena [16], Flexsim [17], Plant Simulation [18], Anylogic [19] and other simulation software build simulation optimization models through virtual simulation technology, the simulation design of the garment production line is carried out to realize the production visualization and the re-optimization of the pipeline balance [20].
In addition, in the latest research, in the mixed production line research, Zheng [21] proposed garment intelligent production scheduling algorithm based on modularization, and the target tracking genetic algorithm was designed to set up the model, realized mixed assembly line rapid production of a variety of clothing; Sheng [22] proposed using fuzzy clustering of equivalence relation, the method of building module group of shirt processing components was achieved; Sheng [23] proposed a method for predicting module the man-hours based on BP neural network and optimizing and application of mixed-mode component module production scheduling; Tong [24] designed the non-dominate sorting genetic (NSGA-II), and applied to solve the production lines of multi-style clothing. In terms of flexible job scheduling, Liu [25] proposed a dynamic scheduling method for the garment sewing process based on deep reinforcement learning to realise real-time response to order dynamic problems; Ju [26] proposed a method of using machine learning to predict the clothing production line staff efficiency, which can provide a reference for the future national clothing production process arrangement.

MATHEMATICAL MODELLING OF A NATIONAL CLOTHING PRODUCTION LINE

The key to the production efficiency of the clothing production line lies in the processing load balance of each workstation in the clothing production line. As far as possible, to achieve the production synchronisation and production equalisation of each workstation in the assembly line, to ensure the continuity of production, and to improve the production efficiency of clothing.

Problem posing

In the process of working procedure arrangement, it is necessary to determine the operators of each process, that is, the operation process arranged by each workstation, and there are 2 situations in which each process works on the workstation: a certain process works on the workstation or does not work on the workstation. The decision variable in the model is "whether a process is working in a workstation", and the purpose is to obtain the process scheduling scheme of the production line balance. The goal of assembly line balance in the garment production process mainly includes: (i) given the production line beat, minimise the number of workstations; (ii) given the number of workstations, minimise the production line beat; (iii) given the minimum number of workstations and the average beat, the workload of each workstation is balanced. In order to balance the load of each workstation, each process should be evenly distributed to each workstation as far as possible, so that the beat of each workstation tends to be synchronised. After the process arrangement is determined, the appropriate workers can be selected according to the actual situation.

Model decision variables

Assume that a certain garment has a total of I processes (divided into minimum processes), and the process number is recorded as i, then i = 1, 2,..., I. The number of clothing workstations is set to J (one workstation represents one operator), which is arranged according to the order of garment processing and transmission in the production line, and the numbers are j = 1, 2,..., J respectively. X_{ij} indicates that the j-th workstation processes the i-th process; if "processing", X_{ij} takes the value of 1, and if "not processing", X_{ij} is 0. The definition of decision variables is shown in formula 1. Based on the value of X_{ij} in the obtained optimal solution, the membership relationship between process i and station j can be clarified, and the job scheduling scheme can be obtained.

$$X_{ij} = \begin{cases} 1, \ i \text{ works in } J \text{ place} \\ 0, \text{ opposite} \end{cases} \begin{pmatrix} i = 1,2,\ldots,I \\ j = 1,2,\ldots,J \end{pmatrix} \quad (1)$$

Constraint condition

The order batch of clothing products, the working time and processing equipment of each process and the production process flow are known. In the assembly line scheduling, it is necessary to consider or meet certain constraints, so that the final optimisation scheme is a balance of various factors. The following is a detailed description.

(1) Considering that the production workers' operation proficiency and process quality requirements, classifying the non-separable process, and no longer splitting it, indicates that the process i is completed at a workstation.

(2) Considering the operation sequence of the process on the assembly line, setting the constraints of the preceding process, assuming that there are m tight preceding processes in the i-th process, which are denoted as $i_1,i_2,\ldots,i_m$, respectively, if there is no tight preceding process, then m is 0. It indicates that the preceding process of process i cannot be operated on the workstation behind process i, as shown in formula 2.

$$m = \begin{cases} i_1,i_2,\ldots,i_m, & i\text{-th preceding processes} \\ 0, & \text{no preceding processes} \end{cases} \quad (2)$$

(3) Considering the increase in floating time caused by changing equipment in the production process, a workstation is configured with up to 2 kinds of equipment, in which manual operation can be combined with any equipment.

(4) Supposing that the processing time of the i-th process is t_i, and the total operation time of the j-th workstation is T_j, see formula 3. SPT [5] refers to the theoretical average beat of the production line, the time it takes to produce a garment on a production line, see formula 4.

$$T_j = \sum_{i=1}^{I} t_i X_{ij}, \ j = 1,2,\ldots,J \quad (3)$$

$$\text{SPT} = \frac{\sum_{i=1}^{I} t_i}{J}, \ j = 1,2,\ldots,J \quad (4)$$

The working time of each workstation is set within the beat limit [LPT, UPT] (LPT=2SPT–UPT, UPT=SPT/η) [27], where η is the arrangement efficiency, which indicates the coefficient of the degree of process balance. The closer η is to 1, the better the degree of production line synchronisation. In this paper, the arrangement efficiency (η) is set to 90%, and the arrangement efficiency formula 5.

$$\eta = \frac{\text{SPT}}{\text{SPT}_{max}} \times 100\% \quad (5)$$

For the process that the beat is too large or too small, multiple processes can be combined in a workstation, or the process can be split, and it is assigned to 2~3 workstations to work together, so that the working time of each workstation is within the beat limit.

Objective function

The equilibrium index SI and workstation maximum beat and minimum beat difference F_{min} are set as the objective function of the production line. The model solves the minimum value of SI and the minimum value of Fmin, see formulas 6 and 7.

$$SI = \frac{1}{J}\sqrt{\sum_{j=1}^{J}(T_j - \text{SPT})^2} \quad (6)$$

$$F_{min} = \text{SPT}_{max} - \text{SPT}_{min} \quad (7)$$

PRODUCTION LINE BALANCE GENETIC TABU HYBRID ALGORITHM DESIGN

In this paper, the genetic tabu hybrid optimisation algorithm is used to establish a mathematical model

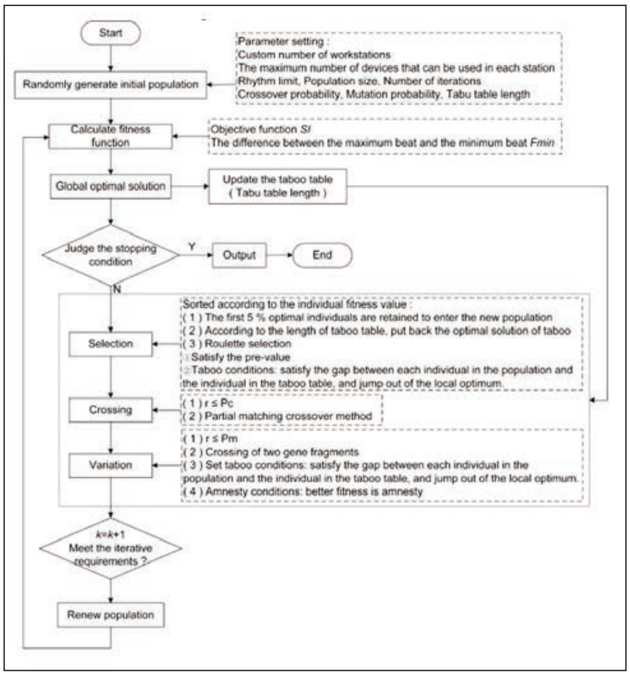

Fig. 1. Genetic tabu hybrid algorithm program flow chart

to intelligently optimise the national clothing production line. Because the genetic algorithm has strong global search ability through selection, crossover and mutation genetic operations, it is used as the main part of the algorithm, and the tabu search algorithm has strong local search ability through the tabu table and the amnesty criterion, which is used as an auxiliary algorithm. The flow chart of the genetic tabu hybrid algorithm is shown in figure 1. Finally, the MATLAB software is used to program and calculate the algorithm.

Step 1: Coding. In this paper, we select the real number coding method based on the process priority sequence.

Step 2: Formation the initial group and decoding. In this paper, the initial population is generated randomly, so that the initial population is evenly distributed throughout the solution space as much as possible, and a given number of individuals is selected to form the initial population $P(k)$, $k = 0$.

(1) According to the process operation sequence, calculate the branch of the process table according to the previous process of the production process.

(2) According to the constraint conditions, the value range of the theoretical average beat SPT and the beat limit is calculated.

(3) Gene segments were generated according to the average beat SPT and job priority order, that is, the process sequences, and the I processes are assigned to J workstations in order, where the processing time of each workstation is $T_1, T_2, \ldots, T_J$.

(4) If the processing time of the J-th workstation is less than the beat lower limit LPT, the (i+1)-th process is added to this workstation, and then it is judged whether the processing time of the J-th workstation is within the beat limit [LPT, UPT] after adding the (i+1)-th process.

(4.1) If the (i+1)-th process is added and the processing time of the J-th workstation is within the beat limit [LPT, UPT], the (i+1)-th process is assigned to the J-th workstation.

(4.2) If the (i+1)-th procedure is added, and the processing time of the J-th workstation is less than the beat lower limit LPT, the (i+2)-th procedure is assigned to the J-th workstation until the constraint is satisfied.

(5) If the processing time of the J-th workstation is greater than the rhythm upper limit UPT, the process on this workplace is assigned to the (J+1)-th workstation, and then it is judged whether the processing time meets the beat limit [LPT, UPT] range, and then go back to Step (3).

(6) Repeat the above allocation process until all processes in the chromosome are allocated.

Step 3: Evaluation of adaptation degree. The fitness function is the objective function. According to the fitness function, the adaptation degree of each individual in the current generation is calculated, and sorted in order of fitness values from smallest to largest, the smaller the better. The first individual after sorting is the optimal individual of the current generation.

Step 4: Update the global optimal solution. Find the optimal solution in the non-taboo neighbourhood, compare the optimal individual of the current generation with the global optimal solution, and update the global optimal solution.

Step 5: Determine whether to meet the termination condition. If satisfied, the output results; otherwise, turn to step 7.

Step 6: Update the taboo list. Update the optimal individual of the current generation to the taboo table.

Step 7: Selecting operation. Using the roulette wheel selection method to select chromosomes, the selection probability of the individual can be expressed as shown in formula 8, where i represents the individual, f_i represents the fitness value, and POP represents the population size.

$$p_i = \frac{f_i}{\sum_{i=1}^{pop} f_i} \tag{8}$$

Step 8: Crossover operation. For each individual, if the random number $r \leq P_c$ (P_c is the crossover probability), the chromosome is crossed. For the balance problem of the sewing production line, the crossover operation adopts a partially matched crossover method. The partially matched crossover method ensures that the genes of each chromosome appear only once, avoiding gene duplication. The schematic diagram of crossover operation is shown in figure 2.

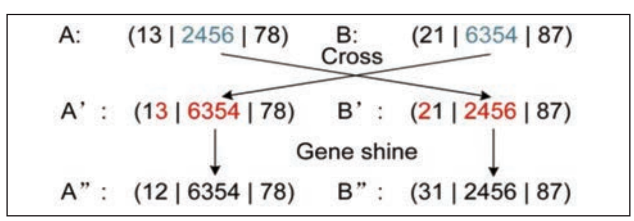

Fig. 2. Crossover operation diagram

A” : (12 | 6354 | 78)

Change process position

A* : (12 | 4356 | 78)

Fig. 3. Mutation operation diagram

Step 9: Variation operation. The mutation operation is based on the new individual obtained by the crossover operation. For each individual, if the random number $r \le P_m$ (P_m is the mutation probability), the chromosome is mutated; otherwise, consider the next chromosome. The mutation operation diagram is shown in figure 3.

Step 10: Update the population, go to step 3, and perform a round of iterations on the population $P(k)$. This time, the maximum number of iterations is used as the stopping condition.

EXAMPLE ANALYSIS OF PRODUCTION LINE BALANCE

Data preparation

In this paper, Mongolian clothing is used as an example to verify, and the clothing production data collected by field research is used as the original experimental data. The national clothing style is the Mongolian basic clothing, and the style diagram is shown in figure 4.

The national costume consists of 58 processes, of which the 58th process is the most time-consuming, 3945*s*, the 28th process is the most time-saving, 25*s*,

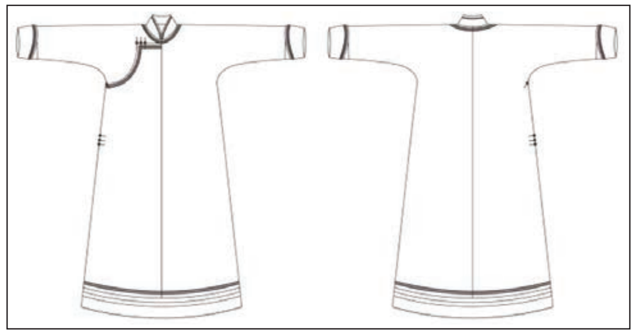

Fig. 4. Mongolian clothing style drawing

and the standard total processing time is 10807*s*. The national costume process flow chart is shown in figure 5.

It can be seen from figure 5 that the production sequence of each processing procedure of the national costume.

Application of a multi-objective national clothing production line balance algorithm

Assuming that the target daily output Q of the national clothing production line is 20 pieces per day, and the working time T is 8 hours per day, the theoretical average beat of the production line is calculated as follows:

$$SPT(t) = T/Q = 8 \times 60 \times 60/20 = 1440s \quad (9)$$

The total processing time T' of the national costume is 10807*s*, and the minimum number of workstations is as follows:

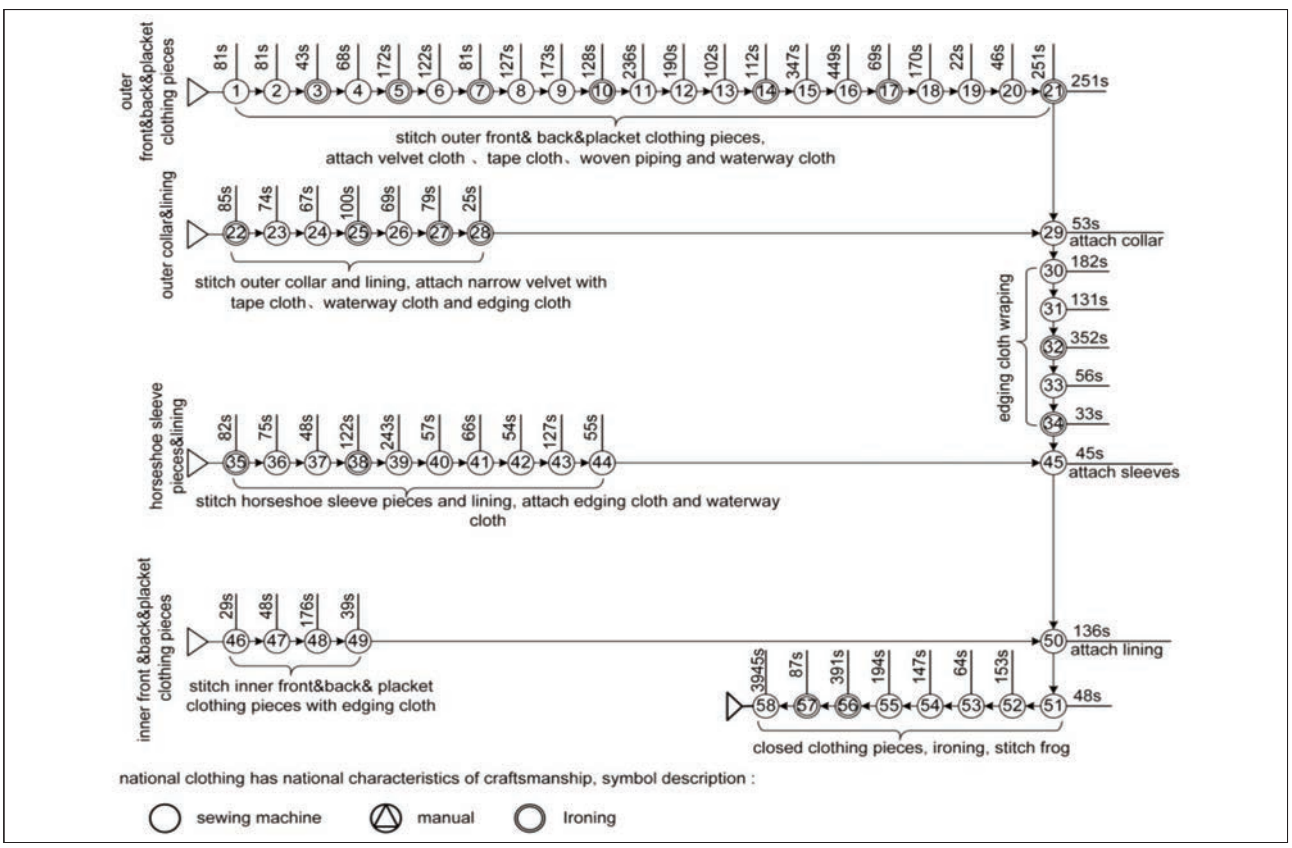

Fig. 5. The national costume process flow chart

$$W_{min} = T'/\mathrm{SPT}(t) + 1 = 10807/1440 + 1 = 8 \quad (10)$$

when the number of stations is 8, the average beat SPT can be obtained from formula 4, which is 1350*s*, the process arrangement efficiency η is 90%, and the rhythm boundary is:

$$\mathrm{UPT} = \mathrm{SPT}/90\% = 1500s$$

$$\mathrm{LPT} = 2\mathrm{SPT} - \mathrm{UPT} = 1200s$$

In this national clothing process arrangement operation parameters, the user-defined station numbers are set to 8, the population size is 100, the iteration times are 500, the crossover probability P_c is 0.9, the mutation probability P_m is 0.9, the tabu table length is 20, and the algorithm termination condition is that the number of iterations reaches the set value 500 times. Finally, the process arrangement scheme of the national clothing production line is output. The process arrangement result of the genetic tabu hybrid algorithm is shown in table 1.

Table 1

PIPELINING OF GENETIC TABU HYBRID ALGORITHM

Station	Process number	Beat (s)	Job nature
1	1-8, 35-39	1345	P, T
2	9-14, 22-23, 46-48	1353	P, T
3	15-21	1354	P, T
4	24-34, 40-42, 49	1363	P, T
5	43-45, 50-56	1360	P, T
6	57, 58	1344	S, T
7	57, 58	1344	S, T
8	57, 58	1344	S, T
Total	-	10807	-

Result analysis

By analysing the different algorithms used by scholars to arrange the process of garment production line, it can be seen that ranked positional weight technique [2] took trousers as an example, when the constraints weren't considered, it had better production balance efficiency, the smoothness index was 5.71, when the constraints were considered, the production efficiency was low, which confirmed the invalidity of the ranked positional weight technique for the balance of complex production lines. The particle swarm algorithm [4] took trousers as an example; the equilibrium index was 16.5, and the compilation efficiency was 96.1%. The improved ant colony algorithm [6] took a shirt as an example, and focuses on the two factors of work-in-process transfer time and transfer path; the compilation efficiency was improved to 88.96% compared with the manual compilation efficiency. Exhaustive search, simulated annealing algorithm and simulated annealing algorithm with greed [10] took a polo-shirt production as an example, computational results affirmed that the simulated annealing algorithm performed well in terms of accuracy and running time, the balance efficiency was between 60% – 80%.

In this paper, combined with the actual production constraints of the factory, the constraints and objective functions are set, and the balance problem of the national clothing production line is solved by the genetic tabu hybrid algorithm. According to the output results of the genetic tabu hybrid algorithm program, combined with table 1, it can be seen that the operation time of each station is within the beat boundary (1200, 1500). The equilibrium index *SI* can be obtained from formula 6 is 6.6, and the compilation efficiency η can be obtained from formula 5 is 98%, and the maximum beat and minimum beat difference F_{min} can be obtained from formula 7 is 19, which meets the requirement that the compilation efficiency η is greater than 85% and can be put into production [21]. However, in order to predict the actual production situation of the national clothing production line in advance and predict the possible problems in the actual production, this paper uses Flexsim simulation software to further simulate the production.

VIRTUAL SIMULATION

Simulation modeling

Flexsim garment production line simulation mainly includes model layout, model logic and parameter setting. Flexsim software structure modelling is shown in figure 6. Parameter setting needs to set the parameters such as station production time, transmission quantity, processing quantity, transmission time, preheating time, running time and arrival time interval.

Example verification

Supposing the number of orders is 100, the daily working time is 8 h, and the number of production line transfers is set to 10, the number of processing is set to constant 1, the transfer time is set to 0, and the preheating time is set to 10807s according to the processing time of a garment, it shows that the time of taking clothes is included in the working hours. Analysing the production factors, such as the operation status of each station and the daily production of orders.

According to the data in table 1, the model layout is set according to the actual station layout of the production line, and the direction of the transportation system is the transfer path of the work-in-process. The processing time of each station is mainly to set the processing time of the processor and run the garment production line model. The simulation results show that (figures 7 and 8 are the comparison diagrams of the optimal solution of the genetic tabu hybrid algorithm and the optimal solution of the genetic algorithm):

(1) The comparison of the operation and idle status of each station in the genetic tabu hybrid algorithm is shown in figure 7. The stable operation time of each station accounts for more than 95%, and there is no bottleneck station. The highest operating time accounted for 99.90%, and the lowest operating time accounted for 98.60%.

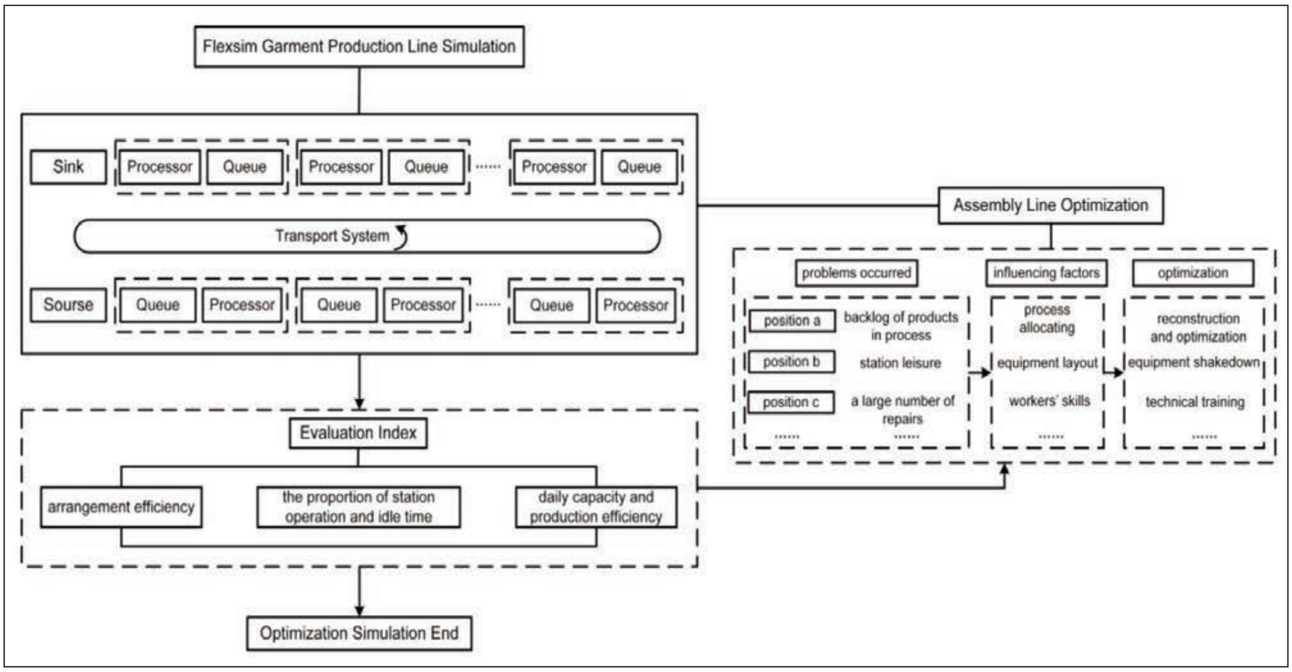

Fig. 6. Design diagram of clothing production simulation optimisation based on Flexsim software

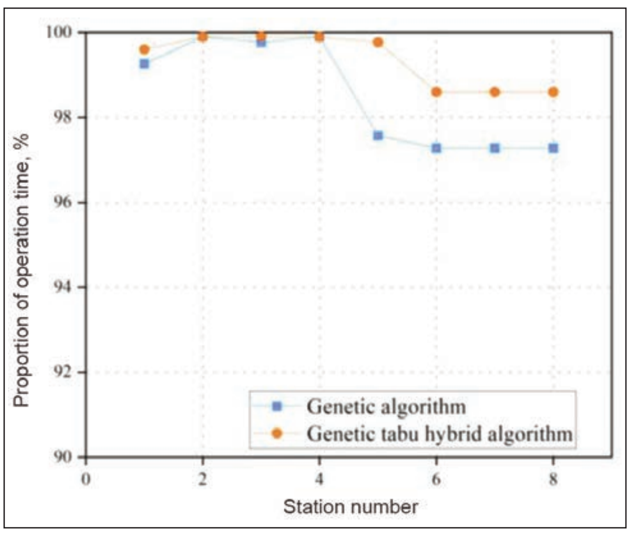

Fig. 7. Operation status table

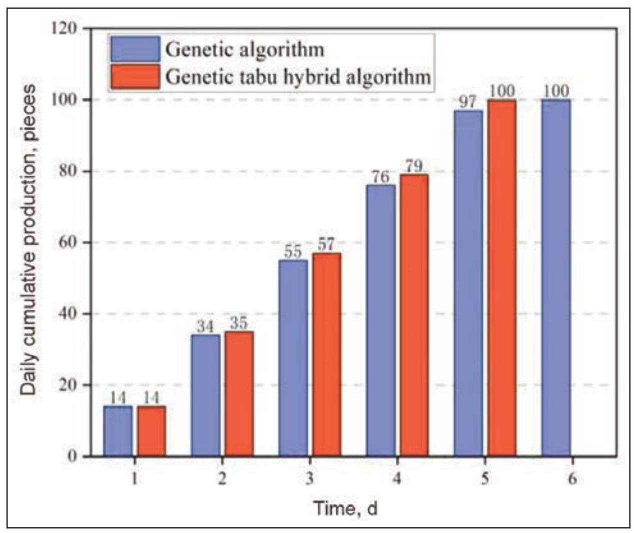

Fig. 8. Daily cumulation production table

(2) The cumulative production per order day of the genetic tabu hybrid algorithm is shown in figure 8, which takes 5 days to complete the order.

In summary, the simulation model of the national costume production line can observe the operation of the production line intuitively and clearly, and verify the feasibility of the production line arrangement scheme and the effectiveness of the algorithm.

RESULTS AND DISCUSSION

In this paper, aiming at the process arrangement problem of the national clothing production line, the intelligent arrangement of the national clothing production line is carried out by an intelligent algorithm and virtual simulation technology. Compared with the traditional manual arrangement method, the process arrangement speed is improved, and the compilation efficiency is high. The Flexsim software verifies the arrangement results in advance, which provides a theoretical reference for the promotion of intelligent manufacturing of national clothing.

In this paper, the genetic tabu hybrid algorithm is used to solve the balance problem of the national clothing production line. Theoretical calculation is carried out by evaluation index, the equilibrium index *SI* is 6.6, and the maximum beat and minimum beat difference F_{min} is 19. The computer is used instead of the manual to optimise the balance of the production line, which improves the speed of the process arrangement and efficiency. It meets the production orders of national clothing manufacturing enterprises with the characteristics of complex process, small single volume, changeable style and fast change.

In this paper, Flexsim software is used to simulate the operation of the production line of the intelligent scheduling scheme of the genetic tabu hybrid algorithm. It is assumed that the batch is 100 pieces, the daily working time is 8 hours, and the order needs 5 days to complete. This scheduling scheme has no bottleneck station, and the stable operation time of each station accounts for more than 95%. The feasibility of the production line scheduling scheme and the effectiveness of the algorithm are verified, which provides a reference for enterprises to arrange production.

CONCLUSION AND FUTURE RECOMMENDATIONS

In this paper, the national clothing production line is constructed based on the hanging assembly line. The national clothing production line is deeply explored, and the mathematical model of the new national clothing production line is constructed by considering the production line constraints and multi-optimisation objectives. The multi-objective genetic tabu hybrid algorithm is designed to minimise the equilibrium index and minimise the difference between the maximum beat and the minimum beat. The model is not only suitable for national clothing production, but also for other clothing production. It has good compatibility and meets the requirements of lean production. In the future:

- This mathematical model and virtual simulation technology are applied to mixed-style modular production layout optimisation. Combined with automatic equipment such as a template machine, production gestures are optimised to further improve the efficiency of multi-variety and small-batch production of national clothing.
- The production information management system (such as the MES system) and the hanging assembly line are connected. Through the production information management system, the production rhythm and rhythm trend map of each station in the production process are monitored in real time, and the production factors such as process, personnel, equipment, material transmission path and time on the hanging assembly line are timely and comprehensively guided to optimise the production. Through the digital twin, the virtual production line is constructed, and the real-time simulation optimisation strategy is deployed, so as to improve the national clothing production efficiency.
- At present, the process scheduling of garment production has shifted from traditional large-scale production to a flexible, dynamic scheduling mode driven by lean and digitisation. In the future, it is necessary for national clothing to further integrate intelligent technologies, such as recurrent neural network models, deep reinforcement learning, etc, combined with green technology, to achieve green production with energy saving and efficiency improvement.

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The influence of weft density in fabric on the mechanical characteristics of sewn seams

DOI: 10.35530/IT.076.05.2024145

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ABSTRACT – REZUMAT

The influence of weft density in fabric on the mechanical characteristics of sewn seams

The goal of this paper was to examine the influence of three different densities of fabric threads per weft (10, 17 and 25 m^{-1}) as well as three different yarn counts of weft yarn (20, 30 and 50 Tex) on the mechanical characteristics of sewn seams. To test the strength of seams, fabric samples were prepared according to the regulations of the ISO 13935-1 standard. The patterns were then sewn in the direction of the weft with the selected type of sewing seam, mark 1.01.01/301 according to the ISO 4916 standard. Using a video camera, it was determined that at one point the value of the force drops sharply, but then again it begins to grow to the point of breaking the seam, in all samples. This more precisely determines the point where the seam structure is significantly damaged. This phenomenon is analysed in detail in this paper, because in the available literature, only the end point of the break is taken as the strength of the seams. The obtained results show that the stitch strength values, for all samples, increase with the increase of: stitch density, thread density per weft and yarn per weft. The precise determination of these parameters, which affect the strength of the sewn seams, is a significant contribution for manufacturers of quality clothing because it gives them the opportunity to project the necessary production parameters in advance.

Keywords: *mechanical characteristics of seams, damage to sewn seams, structure and density of fabrics, yield point of the seam, breaking point of the seam*

Influența desimii firelor de bătătură din țesătură asupra caracteristicilor mecanice ale cusăturilor realizate

Scopul acestei lucrări a fost de a examina influența a trei desimi diferite ale firelor de bătătură (10, 17 și 25 cm^{-1}), precum și a trei tipuri diferite de finețe a firelor de bătătură (20, 30 și 50 Tex) asupra caracteristicilor mecanice ale cusăturilor. Pentru a testa rezistența cusăturilor, au fost pregătite probe de țesătură conform reglementărilor standardului ISO 13935-1. Modelele au fost apoi cusute în direcția bătăturii cu tipul de cusătură selectat, marca 1.01.01/301 conform standardului ISO 4916. Folosind o cameră video, s-a stabilit că la un moment dat valoarea forței scade brusc, dar apoi începe din nou să crească până la punctul de rupere a cusăturii, pentru toate probele. Acest lucru determină mai precis punctul în care structura cusăturii este deteriorată semnificativ. Acest fenomen este analizat în detaliu în această lucrare, deoarece în literatura disponibilă doar punctul final de rupere este considerat ca limita de rezistență a cusăturilor. Rezultatele obținute arată că valorile rezistenței cusăturilor, pentru toate probele, cresc odată cu creșterea: desimii cusăturii, desimii firelor de bătătură și finețea firului de bătătură. Determinarea precisă a acestor parametri, care afectează rezistența cusăturilor, reprezintă o contribuție semnificativă pentru producătorii de îmbrăcăminte de calitate, deoarece le oferă posibilitatea de a proiecta în avans parametrii de producție necesari.

Cuvinte-cheie: *caracteristicile mecanice ale cusăturilor, deteriorarea cusăturilor, structura și densitatea țesăturilor, limita de elasticitate a cusăturii, limita de rupere a cusăturii*

INTRODUCTION

When designing new high-quality clothing products, it is especially important to know the properties of textile materials and production conditions in order to obtain high-quality products in industrial conditions. The seam is one of the most important parameters of garments, because it joins pieces of fabric and gives the garment its final shape. The correct selection of fabric, sewing thread, and the type of seams greatly affects the comfort of the user and the aesthetic and functional requirements of the garment [1]. This area is extensively researched, providing a new approach for predicting weld quality and strength [2].

If the clothes are made of fabrics, it must be taken into account that each fabric is a complex material and that its structure affects its own properties. Therefore, many researchers are engaged in the analysis of fabric structure, which is considered one of the basic parameters that contribute to the dominant physical and qualitative properties of woven material [3]. In research, methods of evaluating the structure of woven material are given, weaving factors and factors of the integrated structure of fabrics are presented, and the differences and advantages of the mentioned factors are analysed [4]. Before fabric production, it is necessary to know how the structure of the fabric affects the quality of the seam, i.e. the yielding of the threads in the seam [5].

The performance of seams and the quality of textile materials are critical factors that affect the end product and the end user. Therefore, it is of great importance to examine the effect of seam types, seam density and sewing direction on the quality of seams in terms of seam strength and seam yielding, as this determines the optimal sewing conditions [6]. Thus, this area attracts a lot of attention from researchers. For example, the influence of fabric thread density and seam structure on linen fabrics on seam yielding characteristics and seam strength is investigated [7, 8]; influence of seam properties by evaluating seam characteristics such as seam compression, seam thickness, seam bending behavior and seam surface friction [1]; complex dynamic interactions between fabric performance, sewing process parameters and seam puckering [9]; efficiency, strength and elongation of seams on cotton fabrics [10]; the influence of different sewing parameters, such as: type of sewing thread, type of seam, direction of the seam as well as stitch density on the strength of the seams [11]; influence of stitch density and seam class on moisture management properties in seams [12]; the influence of the yarn count of the sewing thread on the performance of different types of stitches, the strength of the stitches, etc. [13]; durability of clothing depending on the strength of seams, density of stitches, aesthetic appearance and puckering of seams on different fabric structures [14]; the influence of different stitch densities on achieving proper and adequate seam quality, which ultimately determines the overall quality of any garment [15]; the influence of the relationship between the types of fabrics, the fineness of the sewing thread, and the parameters of the sewing needle on the strength, efficiency and puckering of seams [16]; the influence of seam parameters, such as: seam strength, seam yielding, seam puckering and sewing thread breakage on the life of clothing [17]; the influence of deformation method, sample elongation, type of fabrics, direction of warp and weft of fabric and position of seams on yielding of seams [18]; resistance to yarn yielding in the seam in fabrics as an important factor for designing fabrics before their industrial production [19]; the influence of the raw material composition of fabrics, the fineness of the sewing thread and the parameters of the sewing needle on the characteristics of the clothing seam, i.e. seam strength, seam strength efficiency, seam puckering, seam stiffness, etc. [20]; reasons that lead to poor seam quality such as sewing thread breakage, fabric tearing, excessive seam yielding, or their combinations [21]; yield resistance of seams of unbalanced fabrics [22]; the appearance of the seam depending on the types used: sewing threads, fabrics and stitches [23].

From the available literature, it can be seen that the problems of sewing damage do not have a single solution that could eliminate all the damage on the seams found on the fabric. All established parameters affecting fibres, yarns, fabric construction, sewing thread, stitch types and sewing machines must be tested [24].

In all these studies, a large number of parameters affecting the quality of seams were examined. In all tests, breaking strength is taken as one of the key indicators of seam quality. The research in this paper led to the knowledge that the quality of seams is impaired even before their tearing, which is shown on the device for testing breaking strength.

MATERIAL AND METHODS

The paper examined the influence of different weft densities and yarn count on the mechanical characteristics of sewn seams. For the purposes of researching the mechanical characteristics of seams, which are used to join woven textile materials, different samples of cotton fabrics were made in industrial conditions on a “Vamatex” loom with a weft feeding system with grippers and an electronic threading machine. Loom specifications are stated in table 1.

Table 1

LOOM SPECIFICATIONS	
Characteristic	**Value**
Manufacturer	VAMATEX
Category	Vamatex Rapier Looms
Type	P1001ES
Nominal width (mm)	2100
Weaving speed (wefts/min)	330
Serial number	27664
Year of manufacture	1997

The samples were made on the same loom to avoid the influence of different machines on the production of the samples. From the company’s production program, an article with a raw material composition of 100% cotton in a 1/1 plain weave was selected for the production of samples for research, on which the existing fineness of the yarn for the warp of Tt 30 Tex and the density of the yarn for the warp of 23.3 cm^{-1} were kept for all samples. The yarn density per warp and weft was determined according to the EN 14971 standard. The yarn density per weft was changed in three values: 10, 17 and 25 cm^{-1}. For each of these weft densities, three finenesses of weft yarn were used: Tt 20 Tex, Tt 30 Tex and Tt 50 Tex. The fineness of the warp and weft yarn is determined according to SRPS ISO 7211-5 and SRPS F.S2.511 standards. The surface mass of the fabrics was determined according to the SRPS EN 12127:2014 standard for nine different samples of woven fabrics for testing.

To test the strength of seams, fabric samples were prepared according to the regulations of the ISO 13935-1 standard. In the direction of the warp, laboratory samples for all nine fabrics with dimensions of 350 x 700 mm were cut. Then, each of the samples is individually folded in half so that the longer side is parallel to the folded part. The patterns were then

Table 2

STITCH MACHINE PARAMETERS	
Parameter	**Value**
Manufacturer	Juki
Type	DDL-5550
Stitch type	301
Stitch density (stitches/cm)	2, 3, 3.5, 4 and 5
Sewing speed (stitches/min)	3,000
Needle fineness	Nm 90
Presser foot pressure (N)	2.8
Thread tension (N)	0.50

stitched in the direction of the weft with the selected type of sewing stitch mark 1.01.01/301 according to the international standard ISO 4916. The patterns were sewn on a universal sewing machine manufactured by Juki mark DDL-5550 with stitch type 301. Parameters that were set on the stitch machine are shown in table 2.

The same type of thread was used for sewing the tested samples with fineness od Tt 47.7 Tex, strength of 23.37N and breaking elongation of 19.17%. The thread is made of 100% polyester fibre, and the composition is specified by the manufacturer. The measurement of seam strength was performed on a dynamometer Tenso Lab 3, series 2512A of the Italian manufacturer Mesdan S.p.A. The dynamometer gives numerous values and draws the curve F-Ɛ (force-elongation). These measurement results were further analysed using appropriate software for data processing. In this way, at each point of the diagram, changes in the force values depending on the stretching were determined. Table 3 shows different samples of tested fabrics that were sewn with the type of sewing seam marked 1.01.01/301. In table 3, marking d_{wa} indicates the density of threads in the warp direction per 1 longitudinal centimetre, while d_{we} indicates the same but in the weft direction.

RESULTS AND DISCUSSION

The strength of fabric samples was measured in the warp direction. The seams are sewn parallel to the direction of the weft. This was done to determine the effect of different weft thread thicknesses on the yielding of those weft threads in the seam. The seams are sewn with different stitch densities. This was done to determine the effect of seam density on its strength. Based on the measurements and research on the influence of different fabric densities on the mechanical characteristics of seams, the obtained results are presented. Tables 4, 5 and 6 show the results of measuring fabric samples with weft densities of 25 cm^{-1}, 17 cm^{-1} and 10 cm^{-1}.

Figures 1 to 3 show force-elongation curves, which represent the comparative results of seam strength measurements of all samples sewn with stitch densities of 2 cm^{-1} and 5 cm^{-1}. The curves show the force values at the yielding points of the seam.

Figure 4 shows the correlation between the force at the yield point of the seam and the total breaking force of the seam for samples with thread density per weft of 25 cm^{-1}, 17 cm^{-1} and 10 cm^{-1}.

Difficulties in seam strength testing arise from various seam tear failures that can be classified as: fabric break, fabric break at clamp, fabric break at seam, sewing thread break, thread pull, or any combination of the above. The relevant test results are only those samples where a break occurred at the seam itself. Breaks in other places were not considered for analysis in this research. For an easier analysis of the test results, a video camera that recorded the sample during the test was used. By analysing the videos, it can be seen that at one point the value of the force drops sharply, but then starts to increase again to the point of breaking the seam. This phenomenon is registered by the sample testing instrument and plotted on the force-elongation diagram. This phenomenon is analysed in detail in this paper, because in the available literature, only the end point of the break is taken as the strength of the seams. However, when assessing the quality of a seam on a garment, it is

Table 3

DIFFERENT SAMPLES OF FABRICS SEWN WITH THE TYPE OF SEWING SEAM MARKED 1.01.01/301

Sample code	Weave structure	Yarn count, T_t (Tex)		Yarn type		Density		Mass ($g \times m^{-2}$)
		warp	weft	warp	weft	warp d_{wa} (cm^{-1})	weft d_{we} (cm^{-1})	
A	Plain 1/1	30	50	100 Co		23.3	25	207.36
B			30					165.16
C			20					128.24
D			50				17	150.61
E			30					129.29
F			20					107.14
G			50				10	128.24
H			30					111.36
I			20					96.59

Table 4

MEASUREMENT RESULTS OF FABRIC SAMPLES WITH A WEFT DENSITY OF 25 cm^{-1}					
Sample marking	Stitch density (cm^{-1})	Seam yielding		Breaking point	
		Elongation (%)	Force (N)	Elongation (%)	Force (N)
A	2	5.973	119	8.96	205
	3	7.284	168	8.622	221
	3.5	7.753	175	9.245	230
	4	7.604	188	8.201	239
	5	7.719	197	8.313	248
B	2	6.551	116	8.337	180
	3	6.392	121	7.879	197
	3.5	6.68	132	8.906	208
	4	6.838	156	8.176	215
	5	6.828	164	7.422	222
C	2	7.571	100	9.797	168
	3	6.113	100	8.052	175
	3.5	5.509	102	6.7	180
	4	5.658	132	6.998	187
	5	5.789	146	6.531	195

Table 5

MEASUREMENT RESULTS OF FABRIC SAMPLES WITH A WEFT DENSITY OF 17 cm^{-1}					
Sample marking	Stitch density (cm^{-1})	Seam yielding		Breaking point	
		Elongation (%)	Force (N)	Elongation (%)	Force (N)
D	2	6.522	124	8.152	182
	3	5.525	150	7.317	190
	3.5	6.67	160	7.856	202
	4	6.17	172	6.905	210
	5	7.136	197	8.474	220
E	2	5.352	88	8.028	165
	3	5.781	105	7.411	168
	3.5	6.392	123	7.73	172
	4	5.211	156	6.253	183
	5	6.551	157	7.146	191
F	2	5.525	80	6.869	138
	3	4.786	89	7.178	142
	3.5	6.65	102	8.867	150
	4	6.838	116	9.812	164
	5	6.7	121	7.891	171

important to determine that the seam is damaged to the extent that its appearance impairs the quality of the garment. This is exactly what happens at the point where the value of the forces drops sharply. Therefore, values of the F-Ɛ curve were followed in this paper. A uniform increase in force was observed in all samples up to a point where the force suddenly starts to decrease, and then the force increases again. That part of the curve, in this paper, for all samples, is defined as seam yielding. By reviewing the video footage, it can be seen that there is a significant disruption of the seam structure, but the tearing device continues to tear until the seam is completely torn. At the place of a sudden drop in the force value, seam damage occurs, which is mainly caused by the yielding of the fabric threads on the warp or on the weft in the seam itself, where these threads are held by the sewing thread.

The obtained results show that the values of the force at the point of yielding of the seam and the breaking force of the seam are affected by the stitch density. Namely, if we look at the values shown in table 4, for sample A, it can be seen that the force values increase during the yielding of the seam with an increase in stitch density. This happens because denser stitches strengthen the seam structure itself. This makes the seam more resistant to external forces. The values of the force at the point of yielding of the seam increase in samples B and C as well.

Also, in all samples, the breaking forces of the stitches increase with increasing stitch density. This happens because denser stitches, despite the damage to the seam at the point of seam yielding, still retain, to a certain extent, the remaining strength of the seam structure.

Table 6

MEASUREMENT RESULTS OF FABRIC SAMPLES WITH A WEFT DENSITY OF 10 cm^{-1}					
Sample marking	Stitch density (cm^{-1})	Seam yielding		Breaking point	
		Elongation (%)	Force (N)	Elongation (%)	Force (N)
G	2	5.352	98	8.028	169
	3	5.946	112	8.474	177
	3.5	5.658	117	7.891	185
	4	5.815	145	7.604	191
	5	6.59	161	7.938	196
H	2	4.906	67	8.176	142
	3	5.047	84	7.422	146
	3.5	5.955	114	7.742	152
	4	5.781	129	7.263	160
	5	6.104	132	7.295	168
I	2	4.473	69	6.859	117
	3	5.368	99	6.71	122
	3.5	5.674	96	7.765	131
	4	5.824	103	6.869	137
	5	5.195	119	6.828	147

In tables 5 and 6, the values for samples D, E, F, G, H and I are shown. For all these samples, the values of the force at the yield point of the seam and the values of the breaking force of the seam can be explained in the same way as for samples A, B and C. The obtained results show that the values of the force at the yield point of the seam and the breaking force of the seam are affected by the thread density per weft. Namely, for the same yarn count of the weft, which amounts to Tt = 50 Tex, sample A has a

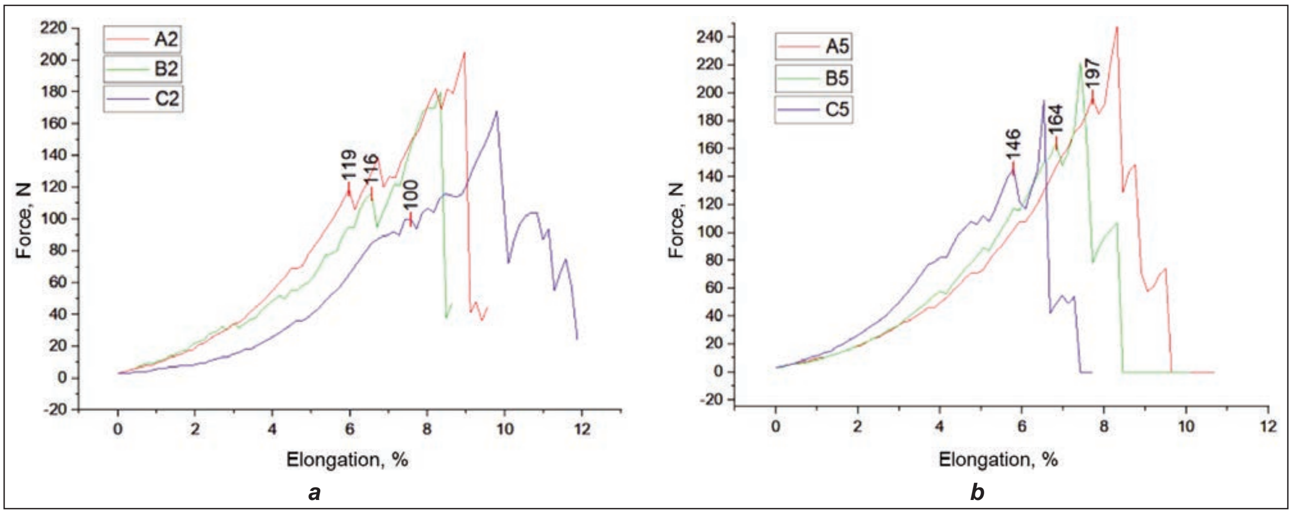

Fig. 1. Comparative results of the influence of different yarn counts of weft yarns at densities of 25 cm^{-1} and the number of stitches: *a* – 2 cm^{-1}; *b* – 5 cm^{-1} on the strength of the seam

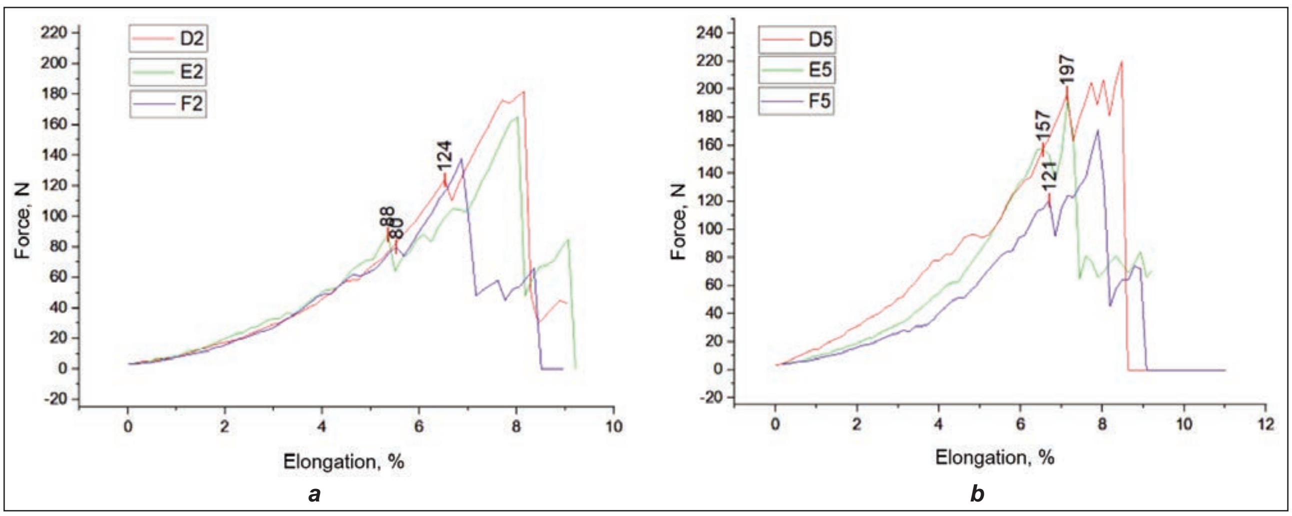

Fig. 2. Comparative results of the influence of different yarn counts of weft yarns at densities of 17 cm^{-1} and the number of stitches: *a* – 2 cm^{-1}; *b* – 5 cm^{-1} on the strength of the seam

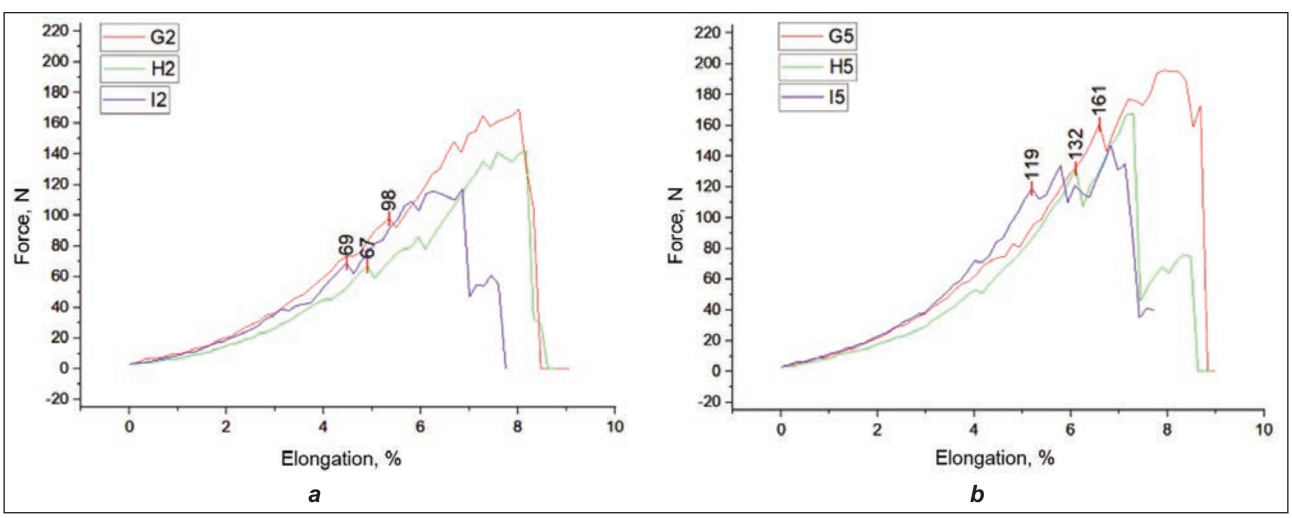

Fig. 3. Comparative results of the influence of different yarn counts of weft yarns at densities of 10 cm^{-1} and the number of stitches: *a* – 2 cm^{-1}; *b* – 5 cm^{-1} on the strength of the seam

density per weft of 25 cm^{-1}, sample D has a density per weft of 17 cm$^{-1,}$ and sample G has a density per weft of 10 cm^{-1}. In terms of seam yielding and seam breaking force, it can be seen that the force values are the highest for all stitches in sample A. Then they decrease in sample D and are the least in sample G.

Deviation, in seam yielding, is seen only in sample A for stitch density of 2 cm^{-1}, where the force value is lower than the value for sample D. Also, for 5 cm^{-1}, the seam yield force values are the same for these two samples.

For a yarn count of Tt = 30 Tex, sample B has a weft density of 25 cm^{-1}, sample E has a weft density of 17 cm^{-1}, and sample H has a weft density of 10 cm^{-1}. In terms of seam yielding and seam breaking force, it can be seen that the force values are the highest for all stitches in sample B. Then they decrease in sample E and are the least in sample H. The deviation in seam yielding is seen only in sample B for a stitch density of 4 cm^{-1}, where the force value is the same as for sample E.

For yarn count of Tt = 20 Tex, sample C has a weft density of 25 cm^{-1}, sample F has a weft density of 17 cm^{-1} and sample I has a weft density of 10 cm^{-1}. In terms of seam yielding and seam breaking force, it can be seen that the force values are the highest for all stitches in sample C. Then they decrease in sample F and are the least in sample I. The deviation in seam yielding is seen only in sample C for a stitch density of 3.5 cm^{-1}, where the force value is the same as for sample F.

The obtained results show that the values of the seam yielding force and the breaking force are affected by the yarn count of the threads per weft. Namely, the yarn count of threads per weft is Tt = 50 Tex for sample A, Tt = 30 Tex for sample B and Tt = 20 Tex for sample C. In the case of seam yielding and seam breaking force, it can be seen that the force values are the highest for all stitches of sample A. Then they decrease in sample B, and they are the least in sample C. The same is true for samples D, E and F, as well as for samples G, H and I. From the obtained results, it can be seen that the weft with a larger cross-section more intensively resists thread yielding in the seam.

Figure 4 shows the correlation between the force at the yield point and the breaking force of the seam for samples with weft densities of 25 cm^{-1}, 17 cm^{-1} and 10 cm^{-1}. The results show that the correlation coefficient between the analysed parameters is the lowest for fabrics with the lowest weft thread density.

CONCLUSION

This research elucidates the influence of different weft yarn counts and different weft densities on the mechanical characteristics of seams in 100% cotton raw material fabrics woven in plain weave. This paper aimed to investigate the influence of three different fabric densities per weft (10, 17 and 25 cm^{-1}) as well as three different weft yarn counts (20, 30 and 50 Tex) on the mechanical characteristics of sewn seams.

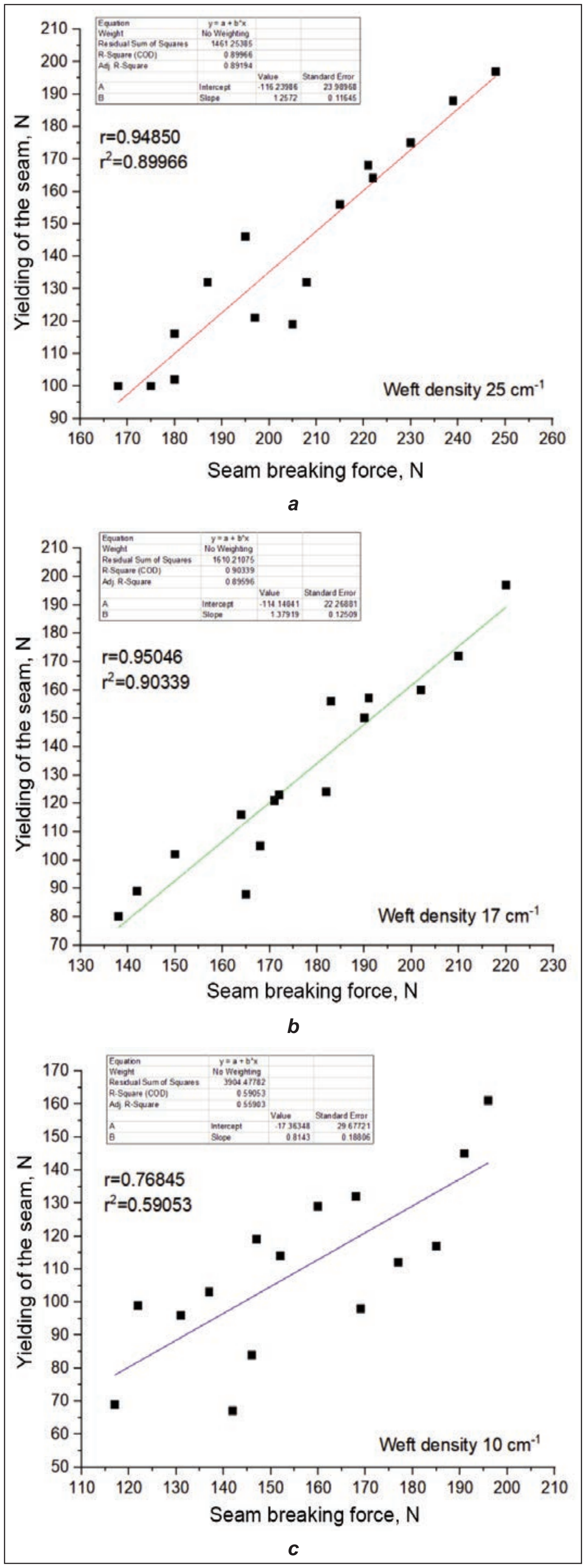

Fig. 4. Representation of the correlation between the strength at the yield point and the breaking force of the seam in fabrics with the density of weft wires: *a* – 25 cm^{-1}; *b* – 17 cm^{-1}; *c* – 10 cm^{-1}

Using a video camera, it was determined that, in all samples, at one point, the force value drops sharply, but then starts to rise again to the point of breaking the seam. This more precisely determines the point where the seam structure is significantly damaged. With further seam loading, after this point of uniform increase in force, the force values decrease, and in most cases then increase. In this part, damage to the seams most often occurs in the form of dislocation of the warp and weft threads in the fabric in the area of the seams. This phenomenon is analysed in detail in this paper because, in the available literature, only the end point of the break is taken as the strength of the seams.

The obtained results show that the seam strength values, for all samples, increase with the increase of: stitch density, thread density per weft and yarn count of threads per weft. The precise determination of these parameters, which affect the strength of the sewn seams, is a significant contribution for manufacturers of quality clothing because it gives them the opportunity to project the necessary production parameters in advance. By knowing this data, it is possible to project in advance the intensity of the forces to which the seams can be subjected in clothing without impairing their quality.

ACKNOWLEDGMENT

Project BG16RFPR002-1.014-0005-Competence Centre „Smart Mechatronic, Eco and Energy-Saving Systems and Technologies", Technical University-Gabrovo, Bulgaria.

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Application of the TOPSIS optimisation method with different weight selections on selected criteria in basalt, aramid, and carbon layered composite structures

DOI: 10.35530/IT.076.05.2024184

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ABSTRACT – REZUMAT

Application of the TOPSIS optimisation method with different weight selections on selected criteria in basalt, aramid, and carbon layered composite structures

Composite materials have a wide range of applications today due to the advantages they offer, including durability and lightness, and are widely preferred as raw materials and products in industrial production. This study focuses on optimising certain performance criteria of these materials, which are critical in terms of engineering design. In the study, three different high-tech fabric materials (Basalt, Aramid, Carbon) were produced in 2 and 3 layers by the vacuum infusion method, and 6 composite plates were obtained. The TOPSIS optimisation technique was applied to determine the most suitable of these composites in terms of thermal and economic properties such as heat insulation, sound insulation, cost and lightness. Optimum alternatives were determined by giving weights according to the priority status of the criteria. As a result of the analysis in all three weight combinations, it was determined that the optimum composite material was the 3-layer structure with the Carbon/Aramid/Basalt combination.

Keywords: *hybrid composite, thermal insulation, sound insulation, cost, lightness*

Aplicarea metodei de optimizare TOPSIS cu diferite selecții de greutate pe baza unor criterii selectate în structuri compozite stratificate din bazalt, aramidă și carbon

Materialele compozite au astăzi o gamă largă de utilizări datorită avantajelor pe care le oferă, precum durabilitatea și greutatea redusă, și sunt preferate pe scară largă ca materii prime și produse în producția industrială. Acest studiu se concentrează pe procesul de optimizare a anumitor criterii de performanță ale acestor materiale, care sunt esențiale din punct de vedere al proiectării tehnice. În cadrul studiului, trei materiale textile diferite de înaltă tehnologie (bazalt, aramidă, carbon) au fost produse în 2 și 3 straturi prin metoda infuziei în vid și s-au obținut 6 plăci compozite. Tehnica de optimizare TOPSIS a fost aplicată pentru a determina cele mai potrivite dintre aceste compozite în ceea ce privește proprietățile termice și economice, cum ar fi izolația termică, izolația fonică, costul și greutatea redusă. Alternativele optime au fost determinate prin stabilirea de greutăți în funcție de statutul de prioritate al criteriilor. Ca rezultat al analizei în toate cele trei combinații de greutăți, s-a stabilit că materialul compozit optim este structura cu 3 straturi cu combinația carbon/aramidă/bazalt.

Cuvinte-cheie*: compozit hibrid, izolare termică, izolare fonică, cost, greutate redusă*

INTRODUCTION

Composite materials are widely used in many engineering fields such as aviation, automotive and marine due to their high strength and low weight properties. When different composite materials are brought together with a design framework where certain properties are prioritised, it is necessary to use multi-criteria decision-making techniques to make the most appropriate choice. These techniques guide engineering decisions in production processes and provide optimal solutions according to performance, cost and other critical parameters. TOPSIS, one of the frequently used optimisation methods, allows alternatives to be ranked as closest to the positive ideal solution and farthest from the negative ideal solution. This method is based on the principle that the most suitable alternative is the one with the least distance from the positive ideal solution and the most distance from the negative ideal solution, and is thus used as an effective selection tool in the decision-making process [1]. Various publications have been examined in the literature, especially in the textile field and in many other fields, where the TOPSIS method has been applied. Acar and Güner applied the TOPSIS method to solve the customer selection problem in a clothing company by using the selection criteria of customer return speed, high order variety, profit margin rate, sample approval speed and suitability of the order for the company [2]. Acar et al. [3] applied the TOPSIS method for sustainability performance measurement in the textile industry, Yükseloğlu et al. [4] in 2015 to determine the parameters of the Open-End spinning machine in yarn selection for the weaving process, Tekez [5] to analyse the type and effects of error using fuzzy TOPSIS in the knitting process, Öztürk [6] to select the most suitable fabric raw material supplier for a ready-made clothing company, Nazar et al. [7] to determine the most suitable supplier for this company from the raw materials used for the fabric weaving process in a woven fabric production factory.

Yilmazbilek et al. applied two different evaluation methods of composite waste. First, weighting was applied to the determined criteria, and ANP and TOP-IS methods were applied separately to the results obtained from each weighting method. In the ANP and TOPSIS results performed with all weighting methods used, the pyrolysis alternative was found to be the most suitable option [8]. Alp et al. comparatively examined the effects of rotation speed, feed rate and cutting tool type on cutting force, deformation factor and surface roughness of flax fibre reinforced polymer composites with a full factorial experimental design and TOPSIS method. At the end of the study, it was observed that the optimum cutting parameter WC cutting tool was obtained from high rotation speed and low feed rate. It was observed that the most important factor among the cutting parameters was rotation speed, then cutting tool type and feed rate, respectively [9].

Akhoundi and Modanloo used TOPSIS and MOORA techniques simultaneously to select the best printing condition [10]. A manufacturing device for continuous carbon fibre reinforced polycarbonate prepreg filament (CCFRPF) was designed by Chen et al., based on the resin fusion impregnation theory, and an optimisation method was proposed for the preparation process parameters according to the TOPSIS optimisation theory [11]. Xu et al. applied TOPSIS and PCA methods together for low-speed impact analysis and multi-objective optimisation of hybrid carbon/basalt fibre reinforced composite laminate [12]. TOPSIS evaluation analysis was used by Pei et al. to design a lightweight and cost-effective fire-resistant structure for steel bridges, and the structure proposed by the method was found to have the highest integrated performance [13].

Fabrics produced from basalt, aramid and carbon fibres are widely preferred in the production of composite materials due to their superior properties. These materials are used as reinforcement elements to increase performance in various sectors and significantly improve the properties of composites, such as design flexibility. In literature, studies on the mechanical and physical properties of composites formed by these fibres with different matrix materials are widely available. Deng et al. examined basalt continuous fibre composites with polypropylene (PP) and polycarbonate (PC) matrices. The processing of the composites was optimised. In BF-PC composites, optimising the material preparation and processing steps enabled the polymer to better impregnate the fibres and improved the mechanical properties [14]. Liu et al. discussed the chemical composition and production technology of BF and discussed its application potential in the field of electrical materials, creating a source for future applications [15]. Xiao et al. increased the interface bond strength with DGEBA resin by modifying the aramid fibre fabric (PPTA) surface with phthalic anhydride and anhydrous aluminium chloride ($AlCl_3$) catalysis. As a result of the modification, the tensile, flexural and interlayer shear strengths of the composite increased significantly, and the mechanical properties reached maximum values. This improvement made aramid fibre composites more suitable for structural applications [16]. Baltacı et al. produced aramid and carbon fibre reinforced thermoplastic composites with different angle orientations by the hot pressing method and investigated their vibration behaviour under impact loads [17]. Novotna et al. investigated the effect of surface layer material on impact strength, dielectric properties, electromagnetic interference (EMI) shielding and sound absorption performance in sandwich composites [18].

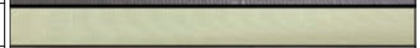
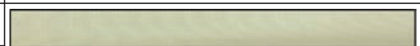
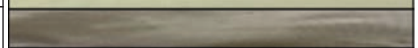
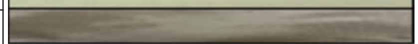
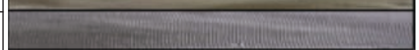
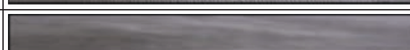
In this study, the use of the TOPSIS optimisation technique was investigated in determining the most suitable one according to the selected parameters of 6 different composite plates produced with the vacuum infusion method, where 3 different high-tech fabrics (Basalt, Aramid, Carbon) were used as reinforcement in 2 and 3 layers. In the study, the TOPSIS method was used to give the importance of the weights of selected features of composites obtained from basalt, aramid and carbon fabric, to rank the most suitable alternatives according to the determined criteria (selected parameters) and to determine the alternative that will rank first. The selected parameters are thermal properties in the form of heat and sound insulation, and cost and lightness properties. An optimum alternative was tried to be determined by applying different weights to the thermal properties.

MATERIAL AND METHODS

Material

In the experimental study, Basalt, Aramid and Carbon fabrics were used as composite reinforcement components. The fabric texture structures were selected as plain weave, with an areal density of 200 g/m². Basalt, Aramid and Carbon fabrics selected in the study have various superior properties. For example, Basalt fabric shows excellent mechanical properties, while Aramid fabric is a high-tech material that stands out with its high strength, excellent thermal stability and superior impact resistance. Although carbon fabric is much lighter than steel with its high mechanical strength and low density, it offers high tensile and compressive strength, providing significant advantages in structural applications. These fabrics were chosen to monitor the effects of the different advantages that will be obtained by different placements of these features in the layers of the layered composite design. The experimental plan is given in table 1. Six different layered composite plates were produced. For the matrix component of the composite, MGS Lamination Epoxy Resin L160 was used in combination with MGS Lamination Epoxy Hardener H160. The resin-to-hardener ratio was 100:25, and the gelation time was 40 minutes at room temperature. The reinforcement-to-resin ratio in the composites was maintained at 70% to 30%.

Table 1

EXPERIMENTAL PLAN			
No.	**Sample code***	**Arrangement of layers**	
1	CAB	1st: Carbon	
		2nd: Aramid	
		3rd: Basalt	
2	ACB	1st: Aramid	
		2nd: Carbon	
		3rd: Basalt	
3	ABC	1st: Aramid	
		2nd: Basalt	
		3rd: Carbon	
4	AB	1st: Aramid	
		2nd: Basalt	
5	BC	1st: Basalt	
		2nd: Carbon	
6	CA	1st: Carbon	
		2nd: Aramid	

Note: * C – Carbon fabric, A – Aramid fabric, B – Basalt fabric

Method

In this study, the TOPSIS optimisation method was applied to selected properties of composite plates produced using a combination of the hand lay-up method and the vacuum infusion method, in accordance with the test plan. Among the selected parameters for thermal properties, thermal insulation and sound insulation were evaluated, alongside other parameters such as cost and lightness. These parameters were given weights according to the selection priority, and the optimum alternative was evaluated by giving high weights to the most important properties, respectively. The heat transfer coefficient test for thermal insulation was carried out in accordance with TS EN 12667 standard, and the sound transmission loss test for sound insulation was carried out in accordance with ASTM E-2611:2009 standard. Cost and lightness parameters were calculated for a 1 m^2 composite plate produced, considering the reinforcement and resin ratio (70:30). Cost data were made according to November 2024 data and calculated in TL/m^2 [19, 20].

TOPSIS optimisation method

The TOPSIS optimisation technique, positive ideal solution maximises the benefit criterion or attributes and minimises the cost criterion or attributes; negative ideal solution maximises the cost criterion or attributes and minimises the benefit criterion or attributes. The selected criterion is expected to have the minimum distance from the positive ideal solution and the maximum distance from the negative ideal solution. The steps used for the TOPSIS method are summarised in figure 1, and table 2 shows the equations used in these steps [3, 6, 7, 13].

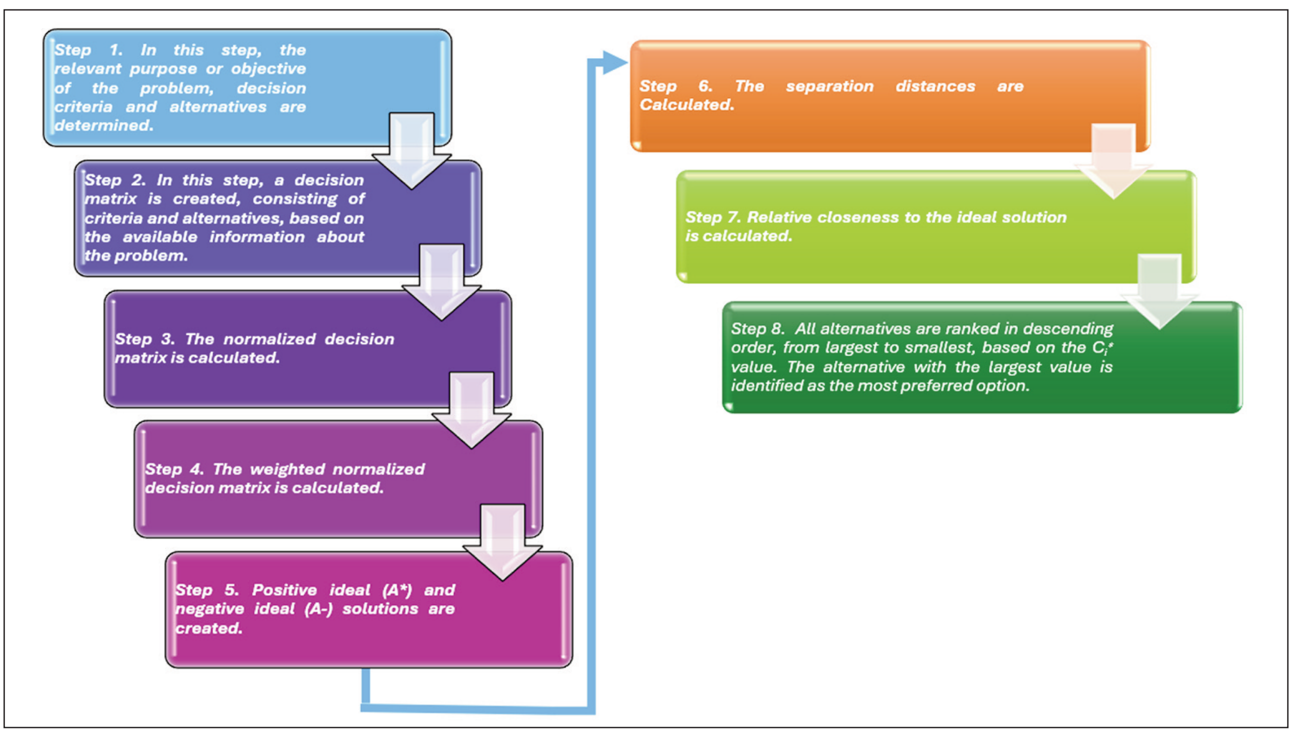


Fig. 1. TOPSIS application steps

Table 2

EQUATIONS USED IN TOPSIS APPLICATION STEPS		
Steps	**Equations**	**Equation No**
Step 1	Decision criteria and alternatives are determined.	
Step 2	$D_{MN} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1N} \\ a_{21} & a_{22} & \dots & a_{2N} \\ \dots & \dots & \dots & \dots \\ a_{M1} & a_{M2} & \dots & a_{MN} \end{bmatrix}$	(1)
Step 3	$r_{ij} = x_{ij} / \sqrt{\sum_{i=1}^{m} x_{ij}^2} \quad i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n$	(2)
Step 4	$V_{ij} = r_{ij} \times W_j \quad i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n$	(3)
Step 5	$A^* = \{(\max_i v_{ij} \mid j \in J), (\min_i v_{ij} \mid j \in J')\}$	(4)
	$A^- = \{(\min_i v_{ij} \mid j \in J), (\max_i v_{ij} \mid j \in J')\}$	(5)
Step 6	$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}$	(6)
	$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}$	(7)
Step 7	$C_i^* = \dfrac{S_i^-}{S_i^- + S_i^*}$	(8)
Step 8	All alternatives are ranked in descending order from largest to smallest according to the C_i^* value.	

RESULTS AND DISCUSSION

The TOPSIS optimisation method was applied step by step, as shown in the tables below (tables 3–7). First, the criteria were weighted according to their importance, the decision matrix was created, and the normalised matrix was calculated. Finally, the alternatives were ranked from 1 to 6. In table 7, steps 6–8, the ranking is presented based on the weights assigned to the first group.

Step 1. Criteria, alternatives and selected weights used in the study.

Table 3

THE CRITERIA DETERMINED FOR THE TOPSIS METHOD AND THE WEIGHTS SELECTED ACCORDING TO THE IMPORTANCE PRIORITY OF THE CRITERIA					
Criteria	4	Thermal Conductivity Coefficient Test (W/mK)	Sound Transmission Loss Test (dB)	Cost ($/m^2)	Lightness (g/m^2)
Weights	Weight of the 1st group (W1)	0.4	0.4	0.1	0.1
	Weight of the 2nd group (W2)	0.5	0.1	0.3	0.1
	Weight of the 3rd group (W3)	0.1	0.5	0.3	0.1

Step 2. Creating the decision matrix.

Table 4

DECISION MATRIX CREATED FOR TOPSIS OPTIMIZATION TECHNIQUE				
Alternatives	**Criteria**			
	Thermal Conductivity Coefficient Test (W/mK)	**Sound Transmission Loss Test (dB)**	**Cost ($/m^2)***	**Lightness (g/m^2)**
CAB	33.31	16	108.96	857.2
ACB	17.69	12	108.96	857.2
ABC	19	11	108.96	857.2
AB	12.63	9	73.09	571.4
BC	16.81	11	49.54	571.4
CA	22.38	8	95.20	571.4

** 1$ = 34,6 TL in November 2024.*

Step 3. Normalise the decision matrix.

Table 5

THE REINFORCEMENT MATERIAL TYPES USED IN HAND LAY-UP AND RTM SAMPLES												
Alternatives	**Criteria**											
	Thermal Conductivity Coefficient Test (W/mK)			**Sound Transmission Loss Test (dB)**			**Cost ($/m^2)**			**Lightness (g/m^2)**		
	Weights			**Weights**			**Weights**			**Weights**		
	0.4	**0.5**	**0.1**	**0.4**	**0.1**	**0.5**	**0.1**	**0.3**	**0.3**	**0.1**	**0.1**	**0.1**
CAB	0.64	0.64	0.64	0.57	0.57	0.57	0.48	0.48	0.48	0.48	0.48	0.48
ACB	0.34	0.34	0.34	0.43	0.43	0.43	0.48	0.48	0.48	0.48	0.48	0.48
ABC	0.36	0.36	0.36	0.39	0.39	0.39	0.48	0.48	0.48	0.48	0.48	0.48
AB	0.24	0.24	0.24	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
BC	0.32	0.32	0.32	0.39	0.39	0.39	0.22	0.22	0.22	0.32	0.32	0.32
CA	0.43	0.43	0.43	0.29	0.29	0.29	0.42	0.42	0.42	0.32	0.32	0.32

Step 4 and Step 5. Weighting and finding positive and negative ideal values.

Table 6

WEIGHTED DECISION MATRIX AND POSITIVE IDEAL (A^*) AND NEGATIVE IDEAL (A^-) VALUES												
Alternatives	**Criteria**											
	Thermal Conductivity Coefficient Test (W/mK)			**Sound Transmission Loss Test (dB)**			**Cost ($/m^2)**			**Lightness (g/m^2)**		
	Weights			**Weights**			**Weights**			**Weights**		
	0.4	**0.5**	**0.1**	**0.4**	**0.1**	**0.5**	**0.1**	**0.3**	**0.3**	**0.1**	**0.1**	**0.1**
CAB	0.255	0.319	0.064	0.228	0.057	0.285	0.048	0.143	0.143	0.048	0.048	0.048
ACB	0.136	0.169	0.034	0.171	0.043	0.214	0.048	0.143	0.143	0.048	0.048	0.048
ABC	0.146	0.182	0.036	0.157	0.039	0.196	0.048	0.143	0.143	0.048	0.048	0.048
AB	0.097	0.121	0.024	0.128	0.032	0.160	0.032	0.096	0.096	0.032	0.032	0.032
BC	0.129	0.161	0.032	0.157	0.039	0.196	0.022	0.065	0.065	0.032	0.032	0.032
CA	0.171	0.214	0.043	0.114	0.029	0.143	0.042	0.125	0.125	0.032	0.032	0.032
A^*	0.255	0.319	0.064	0.228	0.057	0.285	0.048	0.143	0.143	0.048	0.048	0.048
A^-	0.097	0.121	0.024	0.114	0.029	0.143	0.022	0.065	0.065	0.032	0.032	0.032

Step 6-8. Discrimination from the positive ideal solution, discrimination from the negative ideal solution and ranking.

Table 7

THE VALUES OF SEPARATION FROM THE POSITIVE IDEAL SOLUTION (S_i^*) AND SEPARATION FROM THE NEGATIVE IDEAL SOLUTION (S_i^-), C_i AND RANKING												
Alternatives	**S_i^***			**S_i^-**			**C_i**			**Ranking**		
	Weights			**Weights**			**Weights**			**Weights**		
	W1	**W2**	**W3**	**W1**	**W2**	**W3**	**W1**	**W2**	**W3**	**W1**	**W2**	**W3**
CAB	0.0005	0.0003	0.0004	0.1974	0.2151	0.1676	1.00	1.00	1.00	**1**	**1**	**1**
BC	0.0533	0.0413	0.0537	0.2066	0.1808	0.2114	0.79	0.81	0.80	2	2	2
CA	0.2125	0.2516	0.1968	0.2125	0.2516	0.1968	0.50	0.50	0.50	3	3	5
ACB	0.1325	0.1502	0.0772	0.0752	0.0939	0.1068	0.36	0.38	0.58	4	5	3
ABC	0.1307	0.1382	0.0931	0.0714	0.1006	0.0962	0.35	0.42	0.51	5	4	4
AB	0.1885	0.2057	0.1399	0.0174	0.0309	0.0353	0.08	0.13	0.20	6	6	6

According to table 7, it is seen that the Carbon/Aramid/Basalt alternative, which ranks 1st in all weighting options, has the highest CC_i value. Accordingly, the most suitable layer layout sequence will be alternative 1. In all weight combinations, the alternative with the lowest CC_i value is the Aramid/Basalt composite plate. Other rankings vary according to weighting choices.

CONCLUSION

In composite materials, determining the properties suitable for the area of use is of great importance. In the design process of the composite, the selection parameters that determine these properties play a decisive role. In this study, thermal insulation, sound insulation, cost and lightness parameters were determined as selection criteria in layered fabric reinforced epoxy composite plates. A total of 6 composite plates were produced: three with three layers and three with two layers, with three different weighting combinations applied to the criteria. Accordingly, in the 1st combination, the thermal and sound insulation criteria are of equal importance, in the 2nd combination, the thermal insulation and cost criteria are more important than the other criteria, and in the 3rd combination, the sound insulation and cost criteria are more important than the other criteria. The application of optimisation techniques not only identified the most suitable solution but also ranked the alternatives according to their suitability. In this study, the TOPSIS method was applied as the optimisation technique.

According to the 3 different combination weights selected, it was seen that the most suitable composite plate for each combination was the Carbon/Aramid/Basalt layered composite (1st Alternative, CAB, 3-layered). For each weighting combination, the appropriate alternatives are varied 3rd, 4th and 5th in ranking. Ranking the most suitable option in the 6th was found to be Aramid/Basalt layered composite in all weightings. In this study, unlike other studies, determining the first alternative with the TOPSIS method by giving importance weights to the selected properties of composites obtained from basalt, aramid, and carbon fabric is an innovative approach for its use in the textile industry.

ACKNOLEDGEMENTS

This study was supported by Karabük University Scientific Research Projects unit. Project ID: KBÜBAP-23-ABP-136.

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Maintaining the antibacterial durability of chitosan-added cotton fabric to *E-coli* bacteria after many washing cycles

DOI: 10.35530/IT.076.05.2024141

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ABSTRACT – REZUMAT

Maintaining the antibacterial durability of chitosan-added cotton fabric to *E-coli* bacteria after many washing cycles

In countries with hot and humid climates like Vietnam, textile products made from natural fibres will have limitations in resisting the attack and destruction of bacteria, microorganisms and mould. However, this is an opportunity to develop textile products with antibacterial properties to protect consumers under certain conditions. Furthermore, polluted air combined with Vietnam's hot and humid climate are causes of increased epidemics. These are the reasons why antibacterial textile products will increase in type, quantity, and quality to satisfy consumer needs. Antibacterial treatment of textile materials using chitosan is ecologically significant and has many advantages. Chitosan is a natural biopolymer with many chemical characteristics including its ability to convert to natural cations. This article develops a technological process for antibacterial finishing treatment for cotton fabrics with antibacterial durability maintaining after 20 washing cycles with chitosan produced in Vietnam. This study combines three methods, microbial method, infrared spectroscopy (FTIR) analysis method, and scanning electron microscope (SEM) method to evaluate the antibacterial ability and antibacterial durability of cotton fabric after complete treatment with chitosan. The results showed that after washing up to 20 cycles, chitosan bonded to cellulose stably and the antibacterial performance reached 56.62%. This indicated that chitosan-treated cotton fabric exhibits notable antibacterial properties, enhancing its suitability for antimicrobial products.

Keywords: *chitosan, cotton fabric, antibacterial treatment, fibre surface, textile product*

Menținerea proprietăților antibacteriene ale țesăturii din bumbac cu adaos de chitosan față de bacteria *E. coli* după numeroase cicluri de spălare

În țările cu climă caldă și umedă, precum Vietnamul, produsele textile fabricate din fibre naturale vor avea limitări în ceea ce privește rezistența la atacul și distrugerea bacteriilor, microorganismelor și mucegaiului. Cu toate acestea, există oportunitatea de a dezvolta produse textile cu proprietăți antibacteriene pentru a proteja consumatorii în anumite condiții. În plus, aerul poluat, combinat cu clima caldă și umedă din Vietnam, sunt cauze ale dezvoltării epidemiilor. Acestea sunt motivele pentru care produsele textile antibacteriene vor crește ca tip, cantitate și calitate pentru a satisface nevoile consumatorilor. Tratamentul antibacterian al materialelor textile cu ajutorul chitosanului este important din punct de vedere ecologic și prezintă multe avantaje. Chitosanul este un biopolimer natural cu multe caracteristici chimice, inclusiv prin capacitatea sa de a se transforma în cationi naturali. Acest articol dezvoltă un proces tehnologic pentru tratamentul antibacterian de finisare a țesăturilor din bumbac, cu menținerea durabilității antibacteriene după 20 de cicluri de spălare cu chitosan produs în Vietnam. Acest studiu combină trei metode: metoda microbiană, metoda de analiză prin spectroscopie în infraroșu (FTIR) și metoda microscopului electronic de baleiaj (SEM) pentru a evalua capacitatea antibacteriană și durabilitatea antibacteriană a țesăturii din bumbac după tratamentul complet cu chitosan. Rezultatele au arătat că, după 20 de cicluri de spălare, chitosanul s-a legat stabil de celuloză, iar performanța antibacteriană a atins 56,62%. Acest lucru indică faptul că țesătura din bumbac tratată cu chitosan prezintă proprietăți antibacteriene remarcabile, sporind utilizarea acesteia pentru fabricarea produselor antimicrobiene.

Cuvinte-cheie*: chitosan, țesătură din bumbac, tratament antibacterian, suprafața fibrelor, produs textil*

INTRODUCTION

Owing to the increase in industrialization in the 20th century, protective clothing made of natural, environmentally friendly synthetic fibres was researched and developed, and is considered promising in the future because of its comparative advantages in terms of technology, environment, economics, and legality [1]. Other research on low-profile, wearable textile antennas for Wireless Body Area Network applications in the 5.8 GHz ISM band was designed to protect the body from back radiation [2]. However, clothes of natural fibres are a very favourable environment for bacteria to grow because the surface area of the textile is large and has the ability to retain moisture. In recent years, consumer demand for antibacterial textile products has been increasing because, as living standards improve, people's need for protection is becoming increasingly important. Research on antibacterial treatment of fabrics with chitosan is increasing because of the many advantages of this product. Evaluating the quality of fabrics after many washing cycles is an effective measure in the textile industry. The chemical resistance of the fabric after different washing periods was evaluated according to the ISO 6530:2005 test method [3]. Colour fastness and antibacterial ability after adding chitosan were also evaluated after many washing cycles [4–8]. Chitosan treatment reduces *Staphylococcus aureus* (*S. aureus*) bacteria by 99% and improves washing durability through ionic bonding with wool keratin, particularly with chitosan of molecular weights (MW) 100,000–400,000. In another study, hinokitiol-grafted-chitosan (HTCS) was synthesized and applied to cotton fabric as an antibacterial agent. Compared with chitosan (CS) and hinokitiol (HT), HTCS showed a lower minimum inhibitory concentration (MIC) and significantly improved antibacterial efficacy against *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*S. aureus*). After 25 wash cycles, the HTCS-treated fabric maintained its antibacterial properties, hydrophilicity, and strength, indicating its potential for textile applications [9]. Chitosan was added to jute-cotton-blended denim to enhance its antimicrobial properties. The presence of chitosan in the blended fabric was verified by Fourier transform infrared spectroscopy [10]. The skin-dyed cotton fabric treated with chitosan exhibited a significant reduction in *E. coli* and *S. aureus* bacterial growth by 97.20% and 98.03%, respectively. Additionally, the chitosan-treated fabric displayed a higher Ultraviolet Protection Factor (UPF) value of 84.80% compared to the alum-treated fabric 66.70%), indicating superior ultraviolet protection [11]. A novel antibacterial agent (AgNPs@HTCS) was synthesized by grafting hinokitiol (HT) onto chitosan (CS) and incorporating nanosilver (AgNPs). When applied to fabrics, AgNPs@HTCS exhibited low minimum inhibitory concentrations against *S. aureus* and *E. coli*, maintaining high antibacterial efficacy after 25 wash cycles [12]. The melamine salt of chitosan phosphate (MCHP) was synthesized and combined with polyvinyl alcohol (PVA) to coat the cotton fabric. Coatings of PVA/nCH/MP and PVA/MCHP significantly elevated the Limiting Oxygen Index (LOI) of cotton fabric, from 17.2% to 57.9% and 58.2%, respectively. Moreover, the treated samples exhibited substantial antibacterial efficacy against both gram-positive (*S. aureus*) and gram-negative (*E. coli*) bacteria, as evidenced by the larger inhibition zone diameters (IZD) compared to the control sample [13].

A simple and eco-friendly method was employed to create superhydrophobic cotton fabrics using chitosan-based composite coatings. The treated fabric exhibited outstanding super hydrophobicity with a water contact angle of 154.4° and demonstrated excellent antibacterial activity against both Gram-positive and Gram-negative bacteria, with inhibition zones of 16 and 22 mm, respectively, in disk diffusion tests. Additionally, chitosan-PAni-ZnO-STA-coated cotton effectively inhibited bacterial growth in shake-flask tests. Moreover, tests on self-cleaning, blood repellency, and oil-water separation performance confirmed the potential of modified cotton for environmental and clinical applications [14].

In general, antibacterial treatment of fabric using chitosan and chitosan derivatives has been mentioned a lot in research [9, 15–17]. The antibacterial properties of fabrics treated with chitosan, especially with its derivatives, provide high antibacterial ability and wash durability up to 20 cycles [18, 19]. A review paper has shown chitosan fibres and the synthesis of chitosan nanofibers, which have antibacterial properties [20]. Studies using chitosan have shown that the antibacterial ability of the fabric is quite high; however, its antibacterial durability is limited. If a chemical bond is not created between chitosan and the fabric, antibacterial durability will only be maintained after 1–2 washing cycles. When creating a chemical bond between chitosan and fabric, the antibacterial durability of the treated fabric is improved, and the antibacterial properties can be maintained after 10 washes. However, no author has clearly stated the mechanism of the connection between cellulose and chitosan or demonstrated this connection. Some points to note when treating emergency resistance using chitosan are as follows:

- The antibacterial ability of fabrics treated with chitosan depends on three factors: degree deacetylation (DD), MW, and concentration of chitosan used. When DD increases from 0.65 to 0.95, the antibacterial ability gradually increases and, in most studies, it has been shown that the DD must be above 0.85, to ensure the antibacterial ability of the fabric after treatment. The MW of chitosan in the studies is also very rich from 1,800 to 480,000. Studies show that as MW increases, the antibacterial ability of the fabric also increases when the chitosan concentration used is low. However, the antibacterial ability decreases for certain high MW. When using high chitosan concentrations (about 1%), the effect of MW on antibacterial ability is not clear.
- To put chitosan on fabric, researchers often use the pad-dry-cure method. To dissolve chitosan, most studies use a weak acid, acetic acid, and, as a result, the treated fabric does not have antibacterial durability after washing.
- To ensure antibacterial durability of the fabric after washing, a chemical bond was created between chitosan and cellulose. Substances such as 1,3-dimethyllol-4,5-dihydrocyethylenne urea (DMDHEU), citric acid (CA), (2-hydroxy)propyl-3trimethylamommnium)propyl)chitosan chloride) (HTCC), and cyanuric chloride (CNC) have been used as cross-linking agents between chitosan and cellulose in many studies.
- The method of evaluating antibacterial properties in most studies used the shaking method according to the ASTM E2149-01 standard, and a few studies used the AATCC100 standard.

MATERIALS AND METHODS

Material

- Fabric: The 100% cotton fabric was supplied by Nam Dinh Textile Garment J.S. CORP (Natexco), Viet Nam. The fabrics were then desized, scoured, bleached, and mercerized. The technical characteristics of the fabric are presented in table 1.

- Chitosan with the MW of 200,000 Dalton, DD of 90% was supplied by Institute of Chemistry-Vietnam Academy of Science and Technology
- Citric acid – CA ($C_6H_8O_7$) and Sodium Hypophosphite – SHP (NaH_2PO_2) supplied by Johnson Matthey Co., Ltd

Table 1

TECHNICAL CHARACTERISTICS OF THE FABRIC					
Construction	**Yarn count (Ne)**		**Fabric density (yarn/100 mm)**		**Weight of fabric (g/m^2)**
	warp	**weft**	**warp**	**weft**	
Plain weave	24	24	268	237	140

Methods

Preparation for a chitosan solution

Through general research and laboratory experiments, it was found that for treated cotton fabric to have good antibacterial properties, the chitosan concentration must be between 0.8 and 1%. Therefore, to ensure the best amount of chitosan on cotton fabric after treatment, the study will use a chitosan concentration of 1% relative to the fabric (o.w.f). The CA concentration used also ranges from 3–7%. However, through research and surveys, it has been found that with a CA concentration of 3–5%, chitosan is difficult to dissolve completely and takes more time to prepare the solution. If the CA concentration is greater than 7%, the durability of cotton fabric will be greatly reduced. Therefore, the study chose a CA concentration of 7% in solution (o.w.b). SHP and CA were mixed in a 1:1 mol ratio.

Fabric treatment

The fabric was prepared using distilled water, CA concentration 7%, chitosan 1%, SHP and CA in a mole ratio of 1:1, Erkatel NR impregnation agent: 0.1%, following the pad-dry-cure technique.

Subsequent experiments compared the untreated fabrics with the treated fabrics.

This study employed a one-bath, pad-dry-cure technique for fabric treatment. First, the fabric was impregnated with the finishing solution, then padded, dried, and cured. The antibacterial treatment of cotton fabric with the antibacterial agent was carried out in nine steps, as shown in figure 1. The fabric samples, containing dissolved chitosan, were soaked in the solution (previously mixed with the soaking agent). The soaking process ensured that the solution was evenly and thoroughly absorbed by the fabric sample. The sample was then padded, dried at the selected temperature and time, washed with distilled water, and allowed to air dry at room temperature. Finally, the sample was transferred to a standard conditioning chamber for 24 hours. The device for standard conditions: Climatest, Model M250-RH from Mesdan-Italy.

This experimental process was carried out at the Textile Chemistry Laboratory, School of Materials Science and Engineering, Hanoi University of Science and Technology (HUST).

Washing process

To determine the antibacterial durability of the fabric after treatment, the treated samples were washed in accordance with ISO 6330 standard clause 6A, using ECE non phosphate reference detergent (A). An Electrolux EW 1290 W (Italy) front-load washing machine was used. The washed samples were stored after 15 and 20 wash cycles to test their antibacterial ability. The experiments were performed at the Textile Materials Laboratory, School of Materials Science and Engineering of Hanoi University of Science and Technology (HUST).

The washing parameters were as follows: temperature of 25°C, spin speed 900 rpm with extra rinse and extra dry. Greige knitted interlock fabric with mass per unit area of 300 g/m^2 and size of 200 x 200 mm was used as ballasts.

Assessment of treated fabric's properties

• Antibacterial ability

The antibacterial ability of the samples was tested with *Escherichia coli* (*E. coli*), according to the AATCC 11303 standards after antibacterial treatment and after 15 and 20 washing cycles according to the ASTM E 2149-01 standard. Prepare all the equipment needed for the process were sterilized at 121°C for 20 minutes. The bacterial strain was activated and examined with LB medium. Measuring OD density and determining CFU/ml to analyse the antibacterial ability. The results were obtained after 3 repetitions of the experiment at 0 h, 1 h. The entire experimental process was carried out at the Proteomics laboratory – Centre for Biotechnology Research and Development, School of Chemistry and Life Sciences, Hanoi University of Science and Technology (HUST).

• Breaking force and elongation at break

The standard ISO 13934-1 was used to determine the breaking force and elongation before and after treatment. The experimental was conducted using AND multi-purpose testing equipment (Japan) at the Textile Materials Laboratory, School of Materials Science and Engineering, Hanoi University of Science and Technology (HUST).

Tensile equipment: Universal Testing machine 5000N from AND Japan, Model RTC 1250A.

• Comfort characteristic

Comfort characteristics of fabric were investigated through the air-permeability and water vapor permeability.

Air-permeability: The standard ISO 9237:1995 was used to determine the breathability of fabric before and after treatment. The experiment was carried out using M021A, Air permeability Tester (SDL-Atlas, England).

Water vapor permeability (WVP): The water vapor permeability of the fabric allows sweat to drain easily for the user in hot weather conditions, bringing comfort to the wearer. The greater the WVP of the fabric, the better the vapor exchange capacity of the fabric, which means that the higher the WVP capacity of the fabric, the better the comfort of the fabric. On the contrary, the smaller the water vapor permeability speed of the fabric, the less comfortable the fabric. This experiment was followed by the standard UNI 4818-26. The experiment was carried out using Water vapor permeability Tester code 3122 of Mesdan – Italy.

These experiments were conducted at the Textile Materials Laboratory, School of Materials Science and Engineering of Hanoi University of Science and Technology (HUST).

• Kawabata characteristic

Examine the Kawabata properties to assess the effects of the Chitosan treatment process on cotton fabrics, focusing on the treated fabrics surface characteristics (friction and roughness), tensile deformation, slip deformation (form stability and the tendency for wrinkles); and compression deformation (fullness, softness, smoothness, anti-drape stiffness). Test samples, prepared with a size of 200 x 200 mm before and after treatment with chitosan, were tested using the Kawabata equipment system in the following order of modules:

KES-FB4-A (Surface friction and roughness): Surface friction and roughness characteristic data is useful for determining fullness and softness, smoothness, crispness

KES-FB3-A: (Compression tester): Data is useful for determining fullness and softness, smoothness, anti-drape stiffness

KES-FB1-A: (Tensile & Shear tester): Data is useful for determining stiffness and anti-drape stiffness. These properties often influence stability and the tendency for wrinkles.

These experiments were conducted at the Textile Materials Laboratory of School of Materials Science and Engineering of Hanoi University of Science and Technology (HUST).

• FTIR analysis

Infrared spectra of the fabric samples before, after antibacterial treatment, and after washing were obtained using a Nicolet 6700 FT-IR Spectrometer (Nicolet, Japan), at Petrochemical Research Institute, School of Chemistry and Life Sciences, of Hanoi University of Science and Technology (HUST).

• SEM analysis

SEM images of the samples were taken using the device JEOL 6360 (Japan), at Polymer Composite Key Laboratory, School of Materials Science and Engineering of Hanoi University of Science and Technology (HUST).

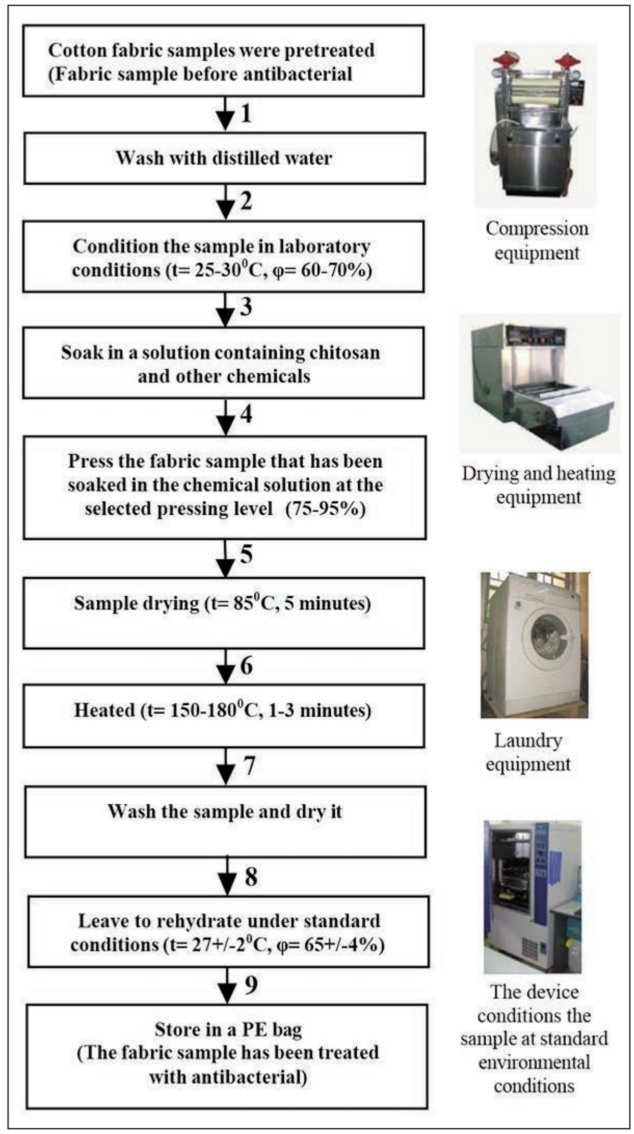

Fig. 1. Process of attaching chitosan to cotton fabric

RESULTS AND DISCUSSION

Table 2 shows the antibacterial ability of cotton fabric samples treated with chitosan after 15 and 20 washing cycles. Cotton fabric treated with chitosan still retained its antibacterial properties, although the antibacterial ability has decreased significantly, with the corresponding decrease in bacteria rate being 63.63% and 56.52%.

The properties of untreated and chitosan-treated fabrics are shown in tables 3–5, showing that after chitosan- treatment, the technical properties are better.

The analysis using FTIR infrared spectroscopy also proves that fabric samples after 20 washing cycles retain their antibacterial properties through the appearance of new peaks at wavelengths of 1730 cm^{-1} and 1582 cm^{-1} (figures 2 and 3).

The influence of 20 washing cycles on the antibacterial properties of the cotton fabric was evaluated through image analysis of the cotton fibre surface of fabric samples treated with chitosan using scanning electron microscopy (SEM) (figure 4).

Table 2

RESULTS OF RESEARCH ON ANTIBACTERIAL PROPERTIES OF FABRICS WITH CHITOSAN AFTER 15 AND 20 WASHING CYCLES								
Fabric samples	**Curing temperature (°C)**	**Curing time (minutes)**	**Pick-up level (%)**	**Initial number of *E. coli* bacteria ($x10^5$)**	**Number of *E. coli* bacteria remaining after contact with fabric ($x10^5$)**		**The rate of bacteria decreases after time of contact with the fabric R (%)**	
					2 minutes	**60 minutes**	**2 minutes**	**60 minutes**
Control	-	-	-	41	51	51	-	-
Treated sample (TS) after 15 washings cycles	170	2	80	55	34	20	38.18	63.63
Control	-	-	-	59	61	64	-	-
Treated sample (TS) after 20 washings cycles	170	2	80	46	31	20	48.33	56.52

Table 3

STRENGTH AND ELONGATION OF UNTREATED AND TREATED COTTON FABRIC								
Fabric samples	**Tensile strength (N) ISO 13934-1**		**The ratio decreases in the warp yarn direction (%)**	**The ratio decreases in the weft yarn direction (%)**	**Breaking elongation (mm) ISO 13934-1**		**The ratio decreases in the warp yarn direction (%)**	**The ratio decreases in the weft yarn direction (%)**
	warp yarn direction	**weft yarn direction**			**warp yarn direction**	**weft yarn direction**		
Untreated	537.09	477.84	-	-	32.50	53.62	-	-
Chitosan treated	336.18	289.07	37.40	39.50	23.43	41.59	27.90	22.43

Table 4

COMFORT CHARACTERISTICS OF UNTREATED AND TREATED COTTON FABRIC				
Fabric samples	**Air permeability ($l/m^2 \cdot s$) ISO 9237**	**Water vapor permeability ($g/dm^2.24h$) UNI 4818-26**	**Drape (%) NF G07-109**	**Wrinkle recovery angle (WRA) (Degree) ISO 2313**
Untreated	141	1.2776	43.26	58
Chitosan treated	161	1.3837	67.26	126

As shown in figure 4, *e*, after 20 washing cycles, the cotton fibre surface was significantly damaged quite a lot, showing that the cotton fibres were loose, and the fibre surface was no longer flat and smooth before washing. It is assumed that the chitosan membrane surrounding the cotton fibre was broken, and the amount of chitosan was lost, as shown by the rate of decreased bacteria after contact with the fabric declined after 20 washings cycles (table 5). However, some chitosan may form a strong bond with cellulose, which still exists on the fabric after 20 washing cycles. Therefore, the fabric still exhibited antibacterial resistance even after 20 washing cycles, as shown in table 5. From the results of this study can conclude that:

- The antibacterial treatment conditions for cotton fabric with chitosan allow the treated fabric to have very high antibacterial ability, Cheng et al. [15] also found that chitosan-modified cotton fabrics have similar antimicrobial performance and antibacterial durability even up to 20 washing cycles.
- Antibacterial treatment of the cotton fabric with chitosan bonded a certain amount of chitosan to the cotton fabric. The amount of chitosan in cotton gives the fabric its antibacterial ability and durability after many washing cycles.

After many washing cycles, some bonds between chitosan and cellulose gradually broke, leading to a gradual decrease in the antibacterial ability of the fabric (table 2). After 20 washing cycles, the cotton fabric treated with chitosan retained its antibacterial properties, proving that a certain amount of chitosan was firmly bonded to cellulose and was not lost. Thus, the fabric still exhibited antibacterial properties.

Table 5

KAWABATA CHARACTERISTICS AND TEARING STRENGTH OF UNTREATED AND TREATED COTTON FABRIC			
Characteristics		**Untreated fabrics**	**Chitosan treated fabrics**
Surface properties	MIU	0.179	0.155
	MMD	0.019	0.016
	SMD	6.237	4.615
Tensile properties	LT	0.612	0.585
	WT	15.00	11.78
	RT	31.07	43.52
Shear properties	G	1.27	5.79
	2HG	2.92	5.99
	2HG5	5.73	6.34
Compression properties	LC	0.224	0.288
	WC	0.230	0.282
	RC	27.39	42.91
Tearing strength	Warp (N)	14.95	9.72
	Weft (N)	9.21	6.13

Note: MIU, mean frictional coefficient; MMD: Fluctuation of mean frictional coefficient; SMD: Surface mean roughness (μm); LT: Tensile rigidity; WT: Tensile energy (cN/cm^2); RT: Tensile recoverability (%); G: Shear rigidity (gl/cm. degree); 2HG: elasticity for minute shear (gl/cm); 2HG5: elasticity for large shear (gl/cm); LC: compressive linearity; WC: compressive energy (cN/cm^2); RC: compressive recoverability (%).

On the other hand, the appearance of NH groups on cotton fabric is shown by the appearance of a new peak at 1582 cm^{-1} in the FTIR infrared spectrum of fabric samples treated with chitosan after 20 washing cycles (figure 2). The image results of the FTIR spectrum (figure 3) show that, compared to the untreated sample, the cotton fabric sample treated only with CA also appeared at a wavelength of 1730 cm^{-1}, proving that there was a CA molecule esterifying the cellulose molecule. The cotton fabric sample treated with chitosan in the presence of CA, in addition to the new peak at 1730 cm^{-1} corresponding to the carbonyl group of the ester, also has a new peak at 1588 cm^{-1} (corresponding to the imine group NH), proving that the CA molecule not only esterifies the cellulose molecule (peak at 1733 cm^{-1}), but also esterifies the chitosan molecule (peak at 1588 cm^{-1}) to create a new NH bond. Ultimately, the FTIR (Fourier-transform infrared spectroscopy) results of figures 2 and 3 both showed a peak at 1588 cm^{-1} which corresponds to NH group (secondary amine group), which explains for the antibacterial ability of fabric after treatment with chitosan solution.

To clarify the assertion that there is a chitosan film on the surface of the cotton fibres, SEM images of the fabric samples were compared. The figure 4 are SEM images of untreated cotton fabric, fabric treated with chitosan, fabric treated with chitosan after 10 washing cycles, 15 washing cycles, and 20 washing cycles Observation of SEM image results shows that with untreated cotton fabric sample, fabric treated with chitosan and fabric treated with chitosan after 10 washing cycles, the fibre surface has changed little, however, after 20 washing cycles, the fibre surface has been damaged, the microfibrils are separated,

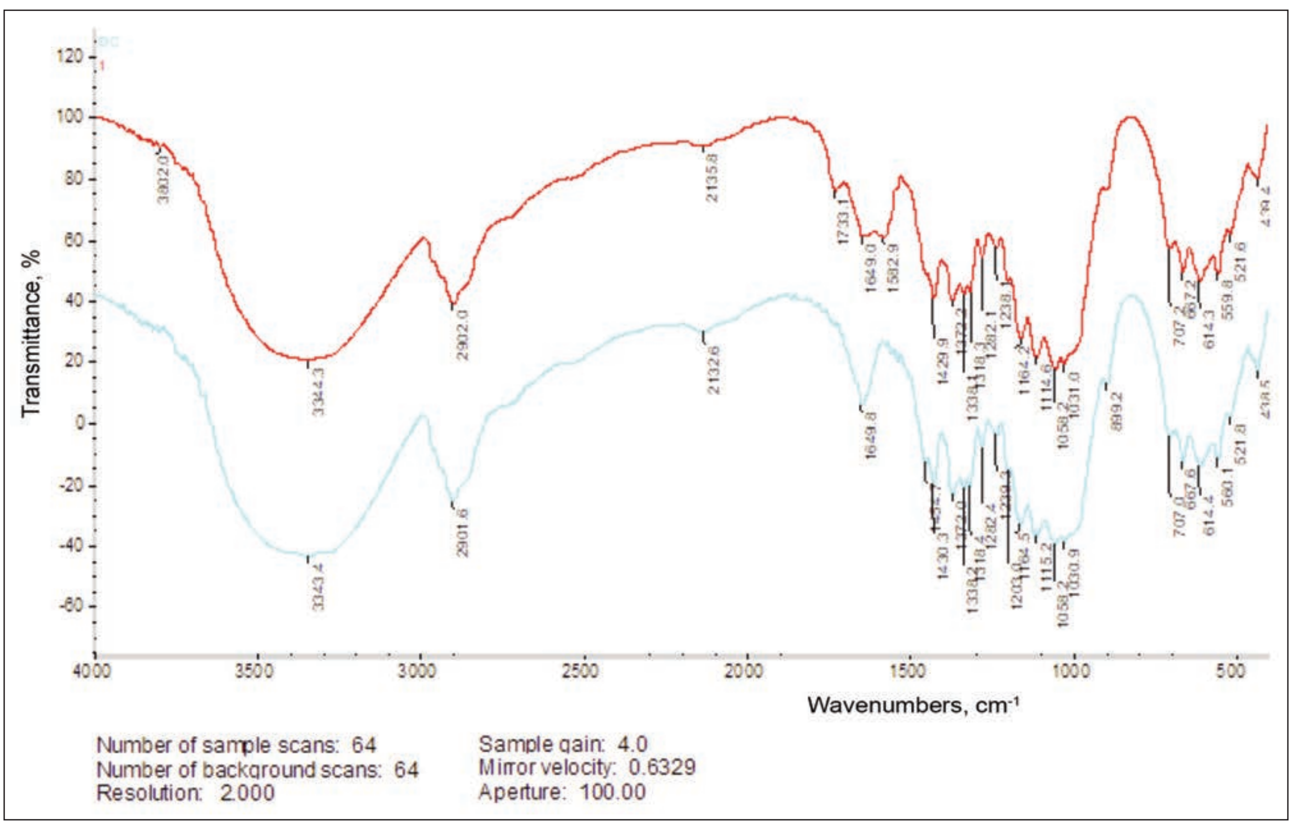

Fig. 2. FTIR of fabric treated with chitosan (red line) and fabric without treatment (green line) after 20 washing cycles

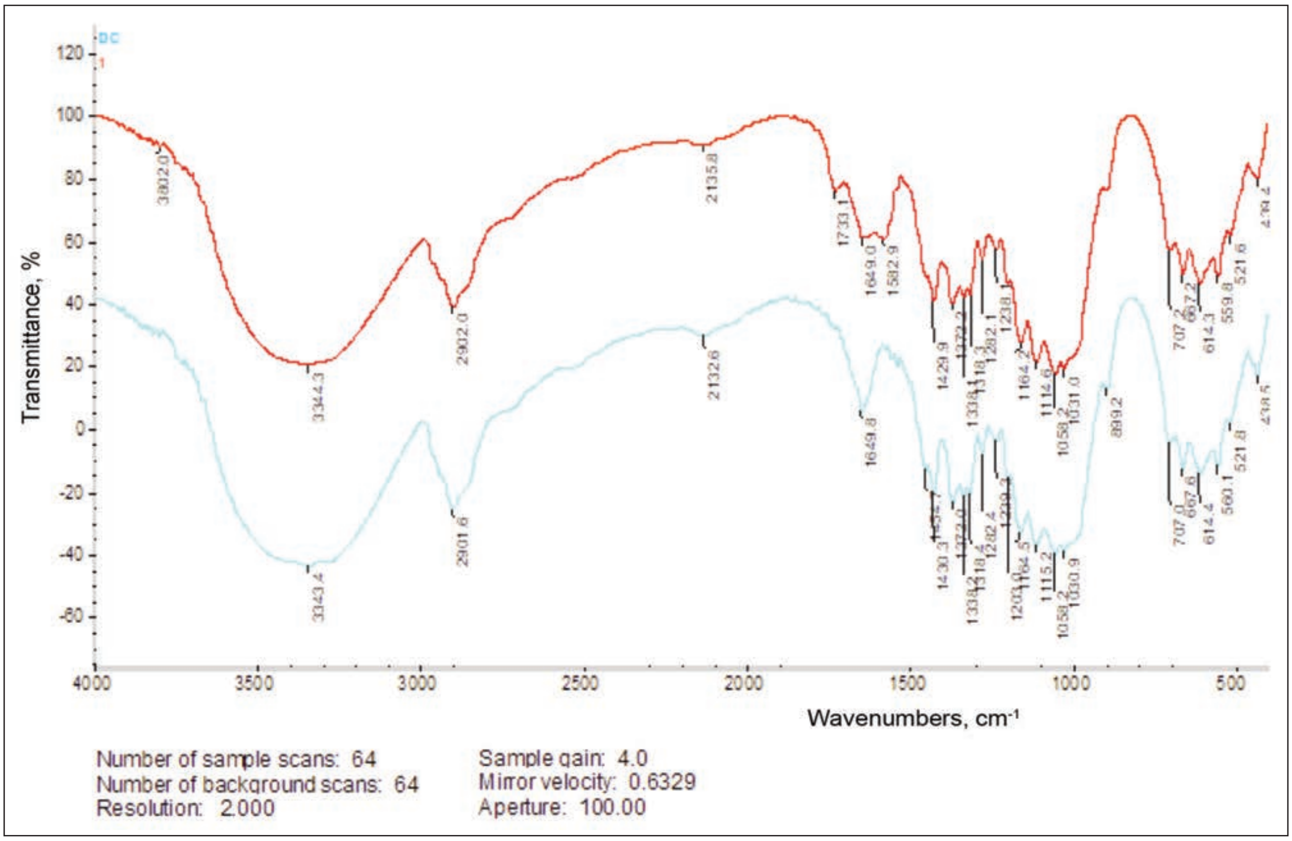

Fig. 3. FTIR of fabric without treatment (red line), fabric treated with CA (blue line), and fabric treated with chitosan (green line)

forming small frays. For fabric samples treated with chitosan, after washing cycles, there are more changes. The chitosan film on the fibre surface seems to be damaged with increasing level after washing cycles and peels off to form very thin films, most clearly in the sample treated after 20 washing cycles (figure 4, *e*).

From the analysis of the FTIR spectrum results, SEM images, and chemical reactions mentioned above, combined with the results of testing the antibacterial properties of fabrics after treatment with chitosan, the antibacterial properties of treated fabrics after control washing cycles. This shows that an ester reaction occurred during the process of fixing chitosan attached to the cotton fabric, and the bond created between chitosan and cotton fabric was quite stable. Therefore, this study proposes the following bonding mechanisms between chitosan and cotton fabric:

- If the ester reaction only occurs between chitosan and CA or between cellulose and CA, then the bond between chitosan and cellulose on the cotton fabric will give the cotton fabric treated with chitosan antibacterial durability after 20 washing cycles is just a physical and chemical bond. The physicochemical bond here is understood to be a hydrogen bond and Van der Waals bonds between chitosan molecules and cellulose molecules in the macromolecules of chitosan and cellulose. In other words, the existence of chitosan on cotton fabric after treatment and washing to give cotton fabric antibacterial properties is due to intramolecular and extra-molecular bonds between cellulose macromolecules and macromolecules created by chitosan molecules; however, these bonds are all weak and unstable. It is very difficult to maintain bond strength after 20 washing cycles, so the ability to bond chitosan and cellulose is purely a physical and chemical bond, which is unlikely.
- If the esterification reaction occurs simultaneously between chitosan and CA, and between CA and cellulose, the bond between chitosan and cellulose on the cotton fabric will make the cotton fabric treated with chitosan-resistant bacteria and antibacterial durability after washing cycles is a combination of both physicochemical bonds and chemical bonds. Therefore, the hypothesis that chitosan is bound to cotton fabric by both physical and chemical bonding mechanisms is the most scientifically based approach. The chemical bond was stable so that the fabric treated with chitosan retained its antibacterial properties after washing cycles.
- The pad-dry-cure treatment technique of fixing chitosan attached to the cotton fabric in this study may have created a chitosan film on the fibre surface. This chitosan film created covalent bonds, Van der Waals bonds, and hydrogen bonds with the cotton fabric. However, after washing cycles, a certain amount of chitosan can only create Van der Waals bonds, and the hydrogen bond with the fabric is gradually lost. Only chitosan molecules chemically bonded to cotton fabric were stable after 20 washing cycles, demonstrating that the antibacterial

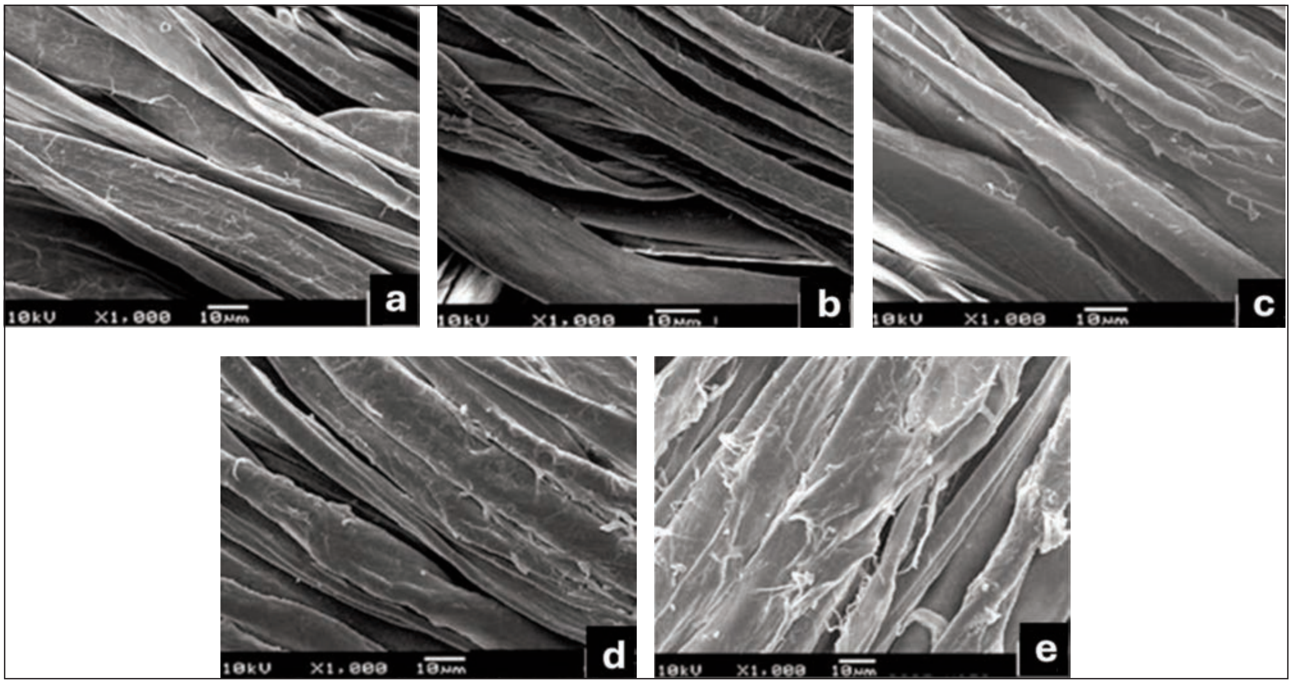

Fig. 4. SEM images of: *a* – untreated cotton fabric; *b* – fabric treated with chitosan; *c* – fabric treated with chitosan after 10 washing cycles; *d* – 15 washing cycles; *e* – 20 washing cycles

properties of cotton fabric treated with chitosan after 20 washing cycles reached 56.62%. The FTIR infrared spectrum (figures 2 and 3) still shows that picks containing imine group NH at wavelength 1588 cm^{-1} are also consistent with this proposal.

CONCLUSIONS

Research results with chitosan have shown that:

- Technological factors such as curing heating temperature, curing heating time, and pick-up level clearly affect the antibacterial properties and durability of cotton fabric treated with chitosan. The optimal technological parameters for treating antibacterial cotton fabric with chitosan has been found to ensure the antibacterial durability of the fabric after 20 washing cycles: curing temperature 170°C, curing time 2 min, pick-up level 80%.
- Combining SEM images of the fibre surfaces, the results of studying fibre surface characteristics on the Kawabata device, and the results of measuring the air permeability of fabric samples after treatment allowed us to determine that chitosan was present on the cotton fibre surface.
- After washing up to 20 washing cycles, chitosan was bonded to cellulose quite stably. From this, the antibacterial nature of the fabric after treatment, as well as after washing, is the presence of chitosan on the cotton fabric with the antibacterial bactericidal mechanism clarified.
- The mechanical strength and drape of the fabric after treatment with chitosan were reduced, but the comfort properties were improved. After treatment, the air permeability of the fabric increased, the ability to recover from creases increased, the friction coefficient decreased, and the fabric surface became smoother.
- Antibacterial cotton fabric with chitosan is suitable for use as a garment fabric because of its high antibacterial durability, good thermo-physiological comfort, high wrinkle resistance, and smooth fabric surface. Although the mechanical strength of the fabric is reduced, it still satisfies the requirements for garment fabrics. Furthermore, in terms of the ecological environment and user safety, cotton fabric treated with chitosan is even more suitable.

Our research investigated the durability of cotton fabric treated with chitosan as an antibacterial agent, specifically targeting the gram-negative bacterium Escherichia coli, and showed promising results. In future studies, we will further explore the antibacterial properties of this treated fabric after multiple washing cycles, focusing on gram-positive bacteria, such as *Staphylococcus aureus* (*S. aureus*) to assess the fabric's overall antibacterial performance after washing.

ACKNOWLEDGMENTS

This research was funded by Hanoi University of Science and Technology for University Projects T2009-105.

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Sustainable biomedical waste management in healthcare: exploring composting through Fuzzy DEMATEL-ANP analysis

DOI: 10.35530/IT.076.05.202520

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ABSTRACT – REZUMAT

Sustainable biomedical waste management in healthcare: exploring composting through Fuzzy DEMATEL-ANP analysis

Effective biomedical waste management is critical for ensuring health safety, environmental sustainability, and regulatory compliance in healthcare settings. This study introduces an integrated decision-making framework that combines the Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) with the Analytic Network Process (ANP) to evaluate and prioritise sustainable waste management practices, with a focus on composting and recycling. The framework incorporates fuzzy logic to handle uncertainties in expert-driven evaluations, ensuring robust and adaptive assessments. Using criteria such as environmental impact, health safety, cost-efficiency, social equity, and regulatory adherence, the DEMATEL analysis highlights key causal relationships, providing targeted prioritisation of strategies. Results indicate that composting achieves superior performance, with higher scores in environmental sustainability (0.85) and health impact (0.88), making it the preferred approach for fostering circular economy practices. The objective of this study is to support data-driven decision-making by integrating expert opinions and system interdependencies. This study underscores the importance of multi-criteria, data-driven methods like Fuzzy DEMATEL-ANP in advancing sustainable biomedical waste management systems, promoting resource optimisation and sustainable development within healthcare facilities.

Keywords: *biomedical waste management, Fuzzy DEMATEL-ANP, healthcare waste optimisation, multi-criteria decision-making, sustainable development*

Gestionarea durabilă a deșeurilor biomedicale în domeniul sănătății: explorarea compostării prin analiza Fuzzy DEMATEL-ANP

Gestionarea eficientă a deșeurilor biomedicale este esențială pentru asigurarea siguranței sănătății, a durabilității mediului și a conformității cu reglementările în unitățile medicale. Acest studiu introduce un cadru integrat de luare a deciziilor care combină Laboratorul de evaluare și testare a luării deciziilor de tip fuzzy (DEMATEL) cu Procesul analitic de rețea (ANP) pentru a evalua și prioritiza practicile durabile de gestionare a deșeurilor, concentrându-se pe compostare și reciclare. Cadrul încorporează logica de tip fuzzy pentru a gestiona incertitudinile din evaluările efectuate de experți, asigurând evaluări robuste și adaptabile. Folosind criterii precum impactul asupra mediului, siguranța sănătății, eficiența costurilor, echitatea socială și respectarea reglementărilor, analiza DEMATEL evidențiază relațiile cauzale cheie, oferind o prioritizare țintită a strategiilor. Rezultatele indică faptul că performanțele compostării sunt superioare, cu scoruri mai mari în ceea ce privește durabilitatea mediului (0,85) și impactul asupra sănătății (0,88), ceea ce o face abordarea preferată pentru promovarea practicilor economiei circulare. Obiectivul acestui studiu este de a sprijini luarea deciziilor bazate pe date prin integrarea opiniilor experților și a interdependențelor sistemului. Acest studiu subliniază importanța metodelor multicriteriale, bazate pe date, precum Fuzzy DEMATEL-ANP, în promovarea sistemelor durabile de gestionare a deșeurilor biomedicale, promovând optimizarea resurselor și dezvoltarea durabilă în cadrul unităților medicale.

Cuvinte-cheie*: gestionarea deșeurilor biomedicale, Fuzzy DEMATEL-ANP, optimizarea deșeurilor din domeniul sănătății, luarea deciziilor pe baza mai multor criterii, dezvoltare durabilă*

INTRODUCTION

A Smart Biomedical Management System (SBMS) utilises cutting-edge technologies, including cloud computing, big data analytics, artificial intelligence (AI), and the Internet of Things (IoT), to optimise patient care, medical equipment, and device management. This system enables the easy monitoring of biomedical equipment in labs, clinics, and hospitals in real-time. Continuous data on the condition usage and operational effectiveness of medical equipment is provided by IoT sensors integrated into the device. By preventing device malfunctions or downtime, which could otherwise impair vital operations and patient outcomes, this empowers healthcare providers to employ predictive maintenance strategies. AI algorithms also examine sensor data to find trends that point to equipment wear or malfunctions, assisting hospital administration in making prompt decisions about equipment replacements or repairs. Using barcoding and radio-frequency identification

(RFID) technologies, SBMS also makes it easier to track assets accurately, reducing losses and guaranteeing that vital equipment is available in an emergency.

A cutting-edge strategy for managing sustainable biomedical waste is represented by this study. Management through the evaluation and integration of fuzzy DEMATEL and ANP methods gives priority to eco-friendly activities, especially composting. It makes use of fuzzy logic as well and offers a solid, flexible and data-driven approach to expert judgment uncertainties construction through examining how various criteria, like environmental, are interdependent. The model finds that composting has the greatest impact on health safety, cost-effectiveness, and a sustainable approach that successfully advances the objectives of the circular economy. This new hybrid methodology for making decisions improves the accuracy and applicability of sustainability evaluations for the management of medical waste.

Furthermore, SBMS ensures compliance with regulatory standards by maintaining digital records of calibration, testing, and maintenance, reducing the burden of manual documentation. In patient care, wearable devices connected to SBMS platforms monitor vital signs, sending alerts to healthcare providers if abnormalities are detected, enabling proactive interventions. Such systems are pivotal in enhancing patient safety, operational efficiency, and cost management, making healthcare delivery more responsive and sustainable (figure 1). As healthcare becomes increasingly data-driven, the adoption of smart biomedical management systems is expected to grow, leading to more resilient and adaptive healthcare infrastructures in the future.

Both medical waste (MW) and biomedical waste (BMW) management have become important worldwide concerns that are inextricably linked to environmental preservation, public health and socioeconomic prosperity. The increasing production of these wastes, especially in light of recent COVID-19 pandemic events, has increased the need for efficient and long-term management plans. Using a variety of recent studies that emphasise definitions, sources classification, potential hazards management procedures, the impact of global health crises, the critical role of disposal method and site selection and the use of advanced decision-making tools to address the complexities inherent in this field, this literature survey seeks to provide a thorough overview of the key aspects of BMW and MW management. Waste produced in healthcare facilities and associated industries is generally referred to by the terms BMW and MW. This covers waste from medical labs, blood banks, mortuaries, research and training facilities, biotechnology establishments, clinics, nursing homes, hospitals and animal shelters, among other healthcare-related operations.

The division of waste into hazardous and non-hazardous categories is a basic component of BMW management. Radiologically active and infectious waste are included in hazardous BMW, which necessitates strict management procedures to reduce risks. Whereas the remainder is usually hazardous, including both infectious and non-infectious hazardous waste, ordinary medical waste, which makes up a sizable portion in some contexts, such as Vietnam, consists of general waste from everyday activities within healthcare facilities. The first and most important stage in efficient management is the correct separation of waste at the source, which is frequently accomplished with standard colour-coded disposal bags. Collection and storage come next, followed by appropriate treatment, transportation in vehicles with biohazard symbols and disposal at the end.

Thorough training in these protocols is required for healthcare personnel with a focus on safety precautions and the appropriate language or medium of instruction. The ultimate objective of good BMW/MW management is to avoid detrimental effects on the environment and human health. Resources such as water, air and land can become contaminated as a result of poor management. Regulations like the Biomedical Waste Management Rules of 2016 highlight that healthcare providers have a legal and social responsibility to manage in a responsible and sustainable manner. In order to supervise these procedures, reduce waste production and communicate with the appropriate municipal and pollution control authorities, every healthcare facility should ideally set up a special waste management committee.

The difficulties with medical waste management have been brought to light by the recent COVID-19 pandemic. A record amount of infectious medical waste was produced worldwide as a result of the increase in healthcare activities and preventive measures. This put tremendous strain on treatment facilities already in place and increased the risk of contact infection if improperly managed. In developing nations with possibly weaker waste management systems, this situation has been especially problematic, underscoring the urgent need for efficient methods to manage large volumes of medical waste quickly to avert environmental and public health emergencies.

The pandemic has therefore increased attention to finding and putting into practice efficient methods for disposing of medical waste. Studies are assessing techniques like pyrolysis, microwave incineration, autoclave, chemical techniques, dry heat, ozone, ultraviolet light and vaporised hydrogen peroxide. Interestingly, ozone is a potentially appropriate method that fits with the circular economy's tenets for medical waste. Choosing suitable disposal techniques and sites for BMW/MW is a difficult decision-making process with many competing factors and options. When assessing these options, local governments and healthcare organisations must apply strong methodologies because they face a great deal of uncertainty.

Techniques known as Multi-Criteria Decision Making (MCDM) have grown in popularity as a means of tackling these issues because they provide organised frameworks for taking into account a variety of elements such as technical, economic, social and environmental considerations. In recent studies, different MCDM techniques have been used to address particular BMW/MW management issues. Hospital medical waste management effectiveness, for example, has been assessed using intuitionistic fuzzy multi-criteria decision-making techniques, taking into account factors like waste control infrastructure and qualified staff. Autoclaving was found to be a promising option in one study.

Similar to this, hesitant fuzzy MCDM methods have been proposed for choosing the best BMW disposal treatment method, evaluating alternatives based on social acceptance technology, operation environmental protection cost, noise and health risk. Additionally, to account for the inherent uncertainty in decision-making processes, fuzzy MCDM methodologies have been developed in single and interval-valued spherical fuzzy environments. These methodologies include the Weighted Aggregated Sum Product Assessment for ranking alternatives and the Criteria Importance Through Intercriteria Correlation for objective criterion weighting. The best healthcare waste recycling technologies that adhere to the circular economy's tenets have also been investigated through the integration of the Analytical Hierarchy Process with Weighted Aggregated Sum Product Assessment in a fuzzy environment. The practical implementation of these integrated approaches is demonstrated by case studies such as the Red2Green technology's selection as Tripura, India's top healthcare waste recycling option.

As evidenced by a study conducted for Istanbul, studies have used interval-valued neutrosophic fuzzy EDAS methods to assess possible sites based on hierarchical criteria when choosing locations for waste disposal facilities. These factors include infrastructure disaster risks, costs, social acceptance, environmental impacts and distance to settlement areas. As demonstrated in a case study conducted in Thailand, the fuzzy analytical hierarchy process in conjunction with goal programming has also been used to identify appropriate sites for infectious waste disposal centres, taking into account infrastructure, geological, social and environmental factors.

Additionally, models based on analysis network processes have been created to create risk assessment techniques for medical waste treatment facilities with the goal of determining the best treatment sites. This is especially important during infectious disease outbreaks like the one that occurred in Wuhan during COVID-19.

As demonstrated in a study conducted in Bilaspur, India, quality function deployment-based models coupled with geographic information systems have also been used to assess possible BMW disposal locations, taking into account both subjective and objective criteria. The shift to a circular economy is having a greater impact on healthcare waste management since it highlights the necessity of lowering waste production and encouraging material and product reuse and recycling. Choosing and implementing suitable healthcare waste recycling technologies is necessary due to this paradigm shift. Multi-Criteria Decision Making techniques have been used to address this issue in fuzzy environments, taking into account different recycling options and selection criteria based on expert opinions. In order to support resource efficiency and environmental sustainability, the objective is to identify practical methods for reusing disposable medical waste.

Effective medical waste management is still hampered by a number of issues, especially in developing nations, despite improvements in techniques and technology. Progress is still hampered by problems with insufficient infrastructure, limited funding, a lack of knowledge and training and ineffective shipping and disposal methods. Specific challenges in the third-party logistics management of biomedical waste have been brought to light by studies that concentrate on nations like Vietnam and India, highlighting the necessity of addressing limitations related to disposal and transportation. Additionally, some hospitals' selection of infectious medical waste contractors relies heavily on subjective evaluations and experience, which emphasises the need for more accurate and objective evaluation techniques like fuzzy Multi-Criteria Decision Making models.

Biomedical and medical waste effectively is a complex task that calls for an all-encompassing and coordinated strategy. Strong classification, safe handling practices, suitable treatment and disposal techniques and thoughtful site selection for waste management facilities are all vitally needed according to the literature. The growing use of advanced multi-criteria decision-making techniques, which enable the methodical evaluation of various and frequently incompatible criteria, shows an increasing understanding of the complexity involved in these decisions. The need for robust and flexible waste management systems has been underlined by the effects of international health emergencies like the COVID-19 pandemic. Going forward, the safe and sustainable management of biomedical and medical waste will be essential to protecting human health and the environment. This will be achieved through sustained research and development efforts, the adoption of circular economy principles and focused interventions to address the unique challenges in various contexts, especially in developing countries.

This study sets itself apart by combining Fuzzy DEMATEL and ANP, especially for biomedical waste management, which is frequently dominated by conventional single-criterion or crisp MCDM approaches to prioritise recycling and composting. This hybrid model provides a dynamic and realistic assessment by capturing interdependencies and causal relationships among criteria, in contrast to traditional approaches that treat criteria as independent. Additionally, using fuzzy logic improves how ambiguity in expert input is handled, leading to more complex and trustworthy decision-making, especially in complex healthcare settings.

Its main goal is to create a fuzzy logic-based multi-criteria decision-making framework for assessing sustainable biomedical waste disposal practices. This study offers a comparative advantage in evaluating interdependent sustainability parameters like environmental and health impacts, cost-efficiency, and compliance because it holistically integrates fuzzy DEMATEL and ANP in contrast to earlier research that concentrated on single-criteria evaluation or isolated technologies. The suggested Fuzzy DEMATEL-ANP model has drawbacks despite having a strong analytical basis. The calibre and objectivity of expert opinions, which can introduce bias, are crucial to the reliability of the results' dependability.

Additionally, its applicability in low-resource settings where computational capabilities are limited may be limited by the complexity of matrix computations and fuzzy logic conversions. The model's long-term validity and responsiveness in changing healthcare environments may be impacted by its failure to take into consideration dynamic temporal changes in waste generation or technology adoption.

MATERIALS AND METHODS

Biomedical waste management systems are evaluated using the Analytic Network Process (ANP) method in the study. It acknowledges important evaluation factors like cost-effectiveness, sustainability initiatives, technological viability, environmental impact, segregation practices, regulatory compliance, health and safety concerns and stakeholder involvement. The following options are evaluated: chemical treatment, landfilling, recycling, autoclaving, incineration and microwaves. Subjective evaluations are quantified using the fuzzy ANP method according to predetermined standards. Each alternative's distance from an ideal solution is measured by the proximity coefficients. A sensitivity analysis ensures reproducibility and reliability. Peer review and case studies are used to validate the findings. This approach provides helpful viewpoints for developing sustainable biomedical waste management procedures.

Selection of parameters

A systematic literature review and expert interviews were used to determine the parameters chosen for this study, which include environmental impact, segregation practices, regulatory compliance, health and safety, technological feasibility, cost-effectiveness, sustainability practices and stakeholder engagement. These metrics, which are in line with international guidelines suggested by the WHO, EPA and CPCB, are widely acknowledged as essential elements in assessing biomedical waste management systems. Their incorporation guarantees a comprehensive and contextually appropriate assessment of the available options. Because they offer a reliable way to measure subjective evaluations in situations involving multiple criteria for decision-making, fuzzy linguistic scales and triangular fuzzy numbers were employed to represent the degree of uncertainty in expert opinions.

Effect criteria analysis

A methodical framework for assessing and ranking composting techniques in biomedical waste management is the fuzzy DEMATEL-based Analytic Network Process (ANP). This method deals with subjectivity and ambiguity in expert opinions on factors like cost-effectiveness, environmental impact and regulatory compliance. Through the identification of causal relationships between these criteria, the DEMATEL

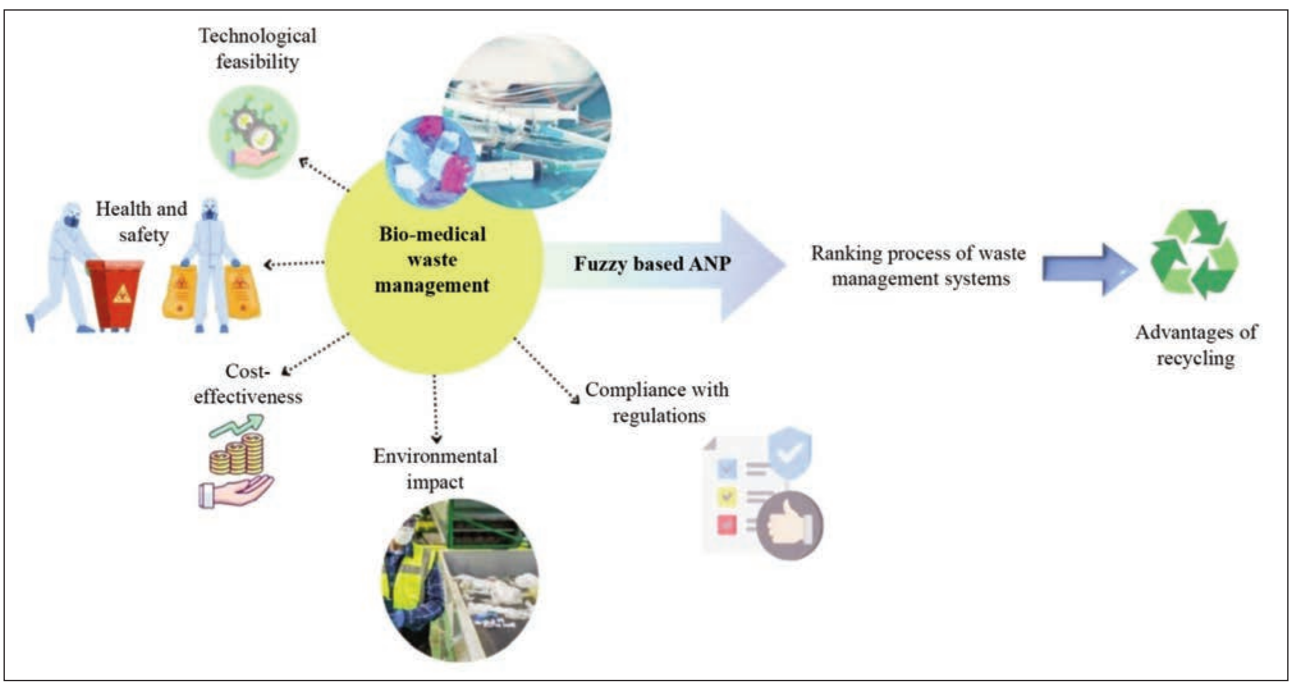

Fig. 1. Bio-medical waste management using Fuzzy-based ANP

method assists stakeholders in making well-informed decisions regarding effective and sustainable composting techniques. Through the creation of nutrient-rich compost and the safe disposal of biomedical waste, this strategy promotes the circular economy concepts in healthcare environments. The DEMATEL method addresses decision-making uncertainties in recycling by integrating the assessment of multiple factors influencing waste recycling processes.

Figure 1 illustrates how the DEMATEL approach ranks attributes that have a major impact on waste management outcomes by establishing links between criteria and determining cause-and-effect relationships.

The Fuzzy DEMATEL-Based ANP (Analytic Network Process) approach used in this study incorporates multiple iterative matrix calculations, pairwise comparisons, normalisation steps, and weight derivations involving Triangular Fuzzy Numbers (TFNs). The computational complexity primarily depends on the number of criteria (n) and alternatives (m). The DEMATEL portion involves $O(n^2)$ operations for generating and normalising direct-relation matrices, while the ANP supermatrix formation and limit matrix calculations typically exhibit $O(n^3)$ complexity. Considering the fuzzification process, each linguistic input requires three separate values (L, M, U), tripling the input size and slightly increasing computation. However, the structured methodology supports parallel processing and matrix-based optimisation, making it suitable for real-time decision support in moderate-scale real-world biomedical waste scenarios where criteria and alternative numbers are reasonably bounded.

Proposed Fuzzy DEMATEL-based ANP approach

The Fuzzy Decision-Making Trial and Evaluation Laboratory (Fuzzy DEMATEL) combined with the Analytic Network Process (ANP) is a robust analytic network process-making (ANPM) approach designed to tackle the complexity of biomedical waste (BMW) management in healthcare. This method integrates the strengths of both DEMATEL, which identifies the cause-and-effect relationships among criteria, and ANP, which handles the interdependence among them. Below is an elaboration of the technique, incorporating essential equations to support the methodology.

In the Fuzzy DEMATEL method, experts assess the direct influence of one criterion over another using linguistic variables, which are then converted into triangular fuzzy numbers. $\tilde{a}_{ij} = (a_{ij}^L, a_{ij}^M, a_{ij}^U)$, representing the lowest, most likely, and highest impact values. The fuzzy influence matrix $\tilde{A} = [\bar{a}_{ij}]$ for all criteria can be computed, where a_{ij} represents the influence of the criterion i on criterion j. The initial step is to normalise the matrix using equation 1:

$$\bar{Z} = \frac{\bar{A}}{\max\left(\sum_{j=1}^{n} a_{ij}^M\right)} \quad i, j = 1,2, \ldots, n \qquad (1)$$

where n is the total number of criteria. The normalised matrix ensures that all fuzzy values lie between 0 and 1.

The total influence matrix is derived as equation 2:

$$\tilde{T} = \tilde{Z} \cdot (I - \tilde{Z})^{-1} \qquad (2)$$

where I is the identity matrix, and $\bar{T} = [\tilde{t}_{ij}]$ provides the aggregated influence of the criterion i on criterion j. The sums of rows D_i and columns R_j are used to determine the degree to which each factor acts as a cause or effect in equation 3:

$$D_i = \textstyle\sum_{j=1}^{n} \tilde{t}_{ij},\; R_j = \sum_{i=1}^{n} \tilde{t}_{ij} \qquad (3)$$

This equation pertains to the total influence matrix. $\bar{T}$ generated from the fuzzy DEMATEL method. Here's what the components mean: $\tilde{t}_{ij}$ represents the degree of influence (expressed as a fuzzy value) that criterion i has on criterion j. D_i is the sum of the i^{th} row of the matrix $\bar{T}$, which quantifies how much influence criterion i exerts on all other criteria. This is referred to as the "dispatching" or "causal" power. R_j is the sum of the j^{th} column, representing how much criterion j is influenced by all other criteria, known as the "receiving" or "effect" power.

The net effect of a criterion i is given by $D_i - R_i$, where a positive value indicates a causal criterion, and a negative value suggests an effect criterion. If $D_i - R_i > 0$: the criterion is causal (it influences others more than it is influenced). If $D_i - R_i < 0$: the criterion is an effect (it is more influenced by others). This step is crucial because it reveals interdependencies and directionality of influence among criteria, helping identify driving factors (causal) and resultant factors (effects).

In the next stage, the ANP framework accounts for the interdependencies between the criteria. The supermatrix W is constructed based on the weights and influences derived from the DEMATEL analysis. To ensure convergence, the supermatrix is raised to a limiting power in equation 4.

$$W_\infty = \lim_{k\to\infty} W^k \qquad (4)$$

This equation is a key step in the Analytic Network Process (ANP): W is the weighted supermatrix, constructed based on influence weights derived from the DEMATEL phase. The supermatrix W contains all possible interrelations between elements (criteria and sub-criteria) across clusters in the network. Raising W to the power k repeatedly (i.e., W^k) allows the weights to propagate through the network of dependencies. When k tends to infinity, the result converges to a limiting supermatrix W_∞, which represents a stable distribution of weights, showing the global priorities of all elements. This ensures that the feedback loops and interdependencies in the system are fully accounted for, producing a robust prioritisation of decision alternatives.

RESULTS

A total of 150 biological waste management decision-makers, including legislators, hospital administrators

Table 1

CRITERIA CHARACTERISTICS						
Criteria	**Environmental Impact (EI)**	**Compliance with regulations (CR)**	**Health Safety (HS)**	**Time Flexibility (TF)**	**Cost-Effectiveness (CE)**	**Social Equity (SE)**
Weight	(0.250, 0.300, 0.350)	(0.150, 0.200, 0.250)	(0.200, 0.250, 0.300)	(0.100, 0.150, 0.200)	(0.100, 0.120, 0.150)	(0.080, 0.100, 0.120)
Type	Positively oriented	Positively oriented	Positively oriented	Positively oriented	Positively oriented	Positively oriented

and practitioners, participated in the study. They assessed various options for biomedical waste management using the Fuzzy DEMATEL-Based ANP method. This diverse input enhanced the validity of the findings and the evaluation procedure. The evaluation took into account real-world concerns in biomedical waste management thanks to the collective expertise of these decision-makers, which enhanced the validity and applicability of the findings for the waste management community.

Quantitative assessment findings

The study's findings, a thorough evaluation methodology and the outcomes of using the Fuzzy DEMATEL-based ANP approach are all provided here. These findings provide valuable information about the effectiveness of different biomedical waste management techniques according to the predetermined standards.

Step 1: Create a decision matrix

In this study, the Fuzzy DEMATEL-Based Analytic Network Process (ANP) approach was used to evaluate the following criteria: Social Equity, Cost-Effectiveness, Health Safety, Environmental Impact and Compliance with Regulations. Each criterion has a different weight assigned to it based on how important it is. The environmental impact criterion has the highest weight (0.250, 0.300, 0.350) indicating its crucial role in the decision-making process. Every one of the six criteria – EI, CR, HS, TF, CE, and SE – is positive oriented, which is illustrated in table 1. Finally, the analysis of biomedical waste management options is influenced to a lesser extent by Social Equity and Cost-Effectiveness, but it is still significant when considering Compliance with Regulations, Health Safety and Time Flexibility.

Linguistic terms are given corresponding Triangular Fuzzy Numbers (TFNs) in this table, which are shown as the upper bound (*U*), middle value (*M*) and lower bound (*L*). The TFN (1,1,3), where 1 is the middle value and lower bound, and 3 is the upper bound, defines the Very Low term. The TFNs rise as the linguistic terms go from Low to Very High, indicating higher levels of the assessed criteria, which is illustrated in table 2. Utilising an organised fuzzy logic-based process, this technique enables decision-makers to translate subjective qualitative evaluations into quantitative values. The TFNs make it possible to handle variability and uncertainty while guaranteeing that expert opinions are recorded in a thorough, adaptable way for later examination.

Table 2

FUZZY SCALE FOR LINGUISTICS WITH TRIANGULAR FUZZY NUMBERS (TFNS)				
Code	**Linguistic term**	**Lower bound**	**Middle value**	**Upper bound**
1	Very low	1	1	3
2	Low	1	3	5
3	Medium	3	5	7
4	High	5	7	9
5	Very high	7	9	9

Key assumptions, such as the use of triangular fuzzy numbers, the assumption of expert consistency, and static criteria relevance, were adopted based on standard practices in fuzzy research. These assumptions are valid as they provide a balance between mathematical rigour and interpretability. The triangular fuzzy representation ensures computational simplicity while effectively modelling uncertainty.

Furthermore, the assumption of criteria stability during the assessment period is essential for meaningful comparison and is supported by expert consensus from multiple healthcare settings.

Six important criteria are compared between recycling and composting in the decision matrix: environmental impact, cost-effectiveness, health safety, compliance with regulations and social equity. In areas such as Environmental Impact (0.85), Compliance with Regulations (0.90), Health Safety (0.88), and Social Equity (0.80), composting outperforms other methods, suggesting a greater overall advantage for the environment and society. Recycling, on the other hand, is more cost-effective and time-efficient because it exhibits advantages in both areas (0.70 and Time Flexibility 0.60). The result was illustrated in the decision matrix (table 3). By taking into account numerous pertinent factors, this matrix assists decision-makers in balancing the advantages and disadvantages of each option, enabling them to make well-informed decisions regarding biomedical waste management (figure 2).

Step 2: Construct the Normalised Decision Matrix

To create the normalised decision matrix, you can use the following formulas:

1. For Positive Ideal Solution:

$$\bar{r}_{ij} = \frac{a_{ij}}{c_j^*}, \quad c_j^* = \max_i c_{ij} \tag{5}$$

Table 3

DECISION MATRIX FOR RECYCLING AND COMPOSTING						
Option	**Environmental Impact**	**Compliance with Regulations**	**Health Safety**	**Time Flexibility**	**Cost-Effectiveness**	**Social Equity**
Recycling	0.75	0.85	0.8	0.6	0.7	0.65
Composting	0.85	0.9	0.88	0.7	0.65	0.8

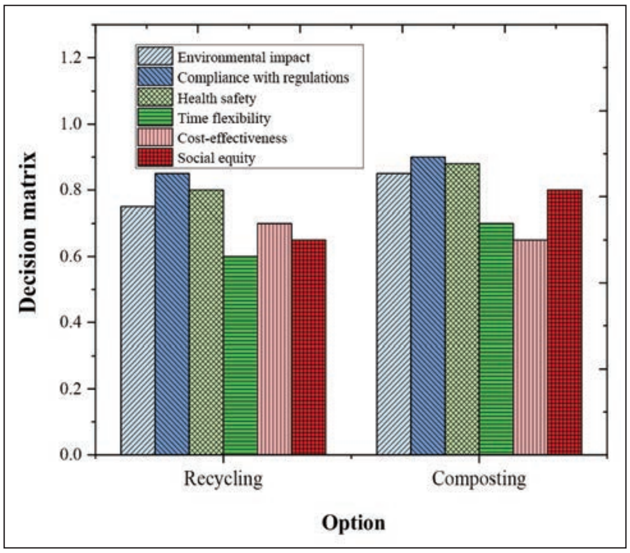

Fig. 2. Recycling and composting selection tool

This calculates the normalised value based on the maximum value for each criterion.

2. For Negative Ideal Solution:

$$\bar{r}_{ij} = \frac{a_j^-}{c_{ij}}, \quad a_j^- = \min_i a_{ij} \tag{6}$$

where, $\bar{r}_{ij}$ is the normalised value for the alternative i and criterion j, a_{ij} – original performance value for the alternative i under criterion j, c_j^* – positive ideal solution, defined as the maximum value of the criterion j, a_j^- – negative ideal solution, defined as the minimum value of the criterion j.

This computes the normalised value based on the minimum value for each criterion.

The triangle fuzzy numbers shown in table 4, bottom, middle, and upper boundaries are represented by a set of three normalised values (L M U) for each criterion. The information regarding recycling and composting is based on six criteria (health, safety, regulations, environmental impact, and compliance). This normalised decision matrix (Time Flexibility, Cost-Effectiveness, and Social Equity) is displayed above. A more uniform comparison over a range of criteria is made possible by this normalisation, which scales the criterion between 0 and 1. Composting performs better overall in terms of social fairness, health, safety, environmental effect, and regulatory compliance, as indicated by the majority of the criteria with higher values.

Recycling's cost and efficiency advantages are shown by its better performance in terms of time flexibility and cost-effectiveness. Parameter comparability is ensured by normalisation, which eliminates scale and unit disparities.

Step 3: Construct the Weighted Normalised Decision Matrix

To create the weighted normalised decision matrix, apply the following formula:

$$\bar{v}_{ij} = \bar{r}_{ij} \times w_j \tag{7}$$

where $\bar{v}_{ij}$ is a weighted, normalised value for the alternative i under criterion j, $\bar{r}_{ij}$ – normalised value for alternative i and criterion j, w_j – weight assigned to criterion j.

The normalised values of recycling and composting are weighted, allowing the weighted normalised decision matrix to account for the relative importance of each parameter, which is illustrated in table 5. Every parameter has a weight that corresponds to its importance in the decision-making process. The parameters with the highest weight (0.25) are environmental impact, and the lowest weight (0.05) is social equity. The weighted contributions of every option across the parameters are represented by the final values.

Table 4

NEGATIVE AND POSITIVE IDEAL SOLUTIONS OF RECYCLING AND COMPOSTING				
Parameter	**Recycling**		**Composting**	
	Positive ideal	**Negative ideal**	**Positive ideal**	**Negative ideal**
Environmental Impact	(0.9, 1.0, 1.0)	(0.0, 0.1, 0.2)	(0.95, 1.0, 1.0)	(0.0, 0.1, 0.2)
Compliance with regulations	(0.85, 0.9, 1.0)	(0.0, 0.1, 0.2)	(0.9, 1.0, 1.0)	(0.0, 0.1, 0.2)
Health Safety	(0.8, 0.85, 0.9)	(0.0, 0.1, 0.2)	(0.9, 0.95, 1.0)	(0.0, 0.1, 0.2)
Time Flexibility	(0.75, 0.8, 0.85)	(0.0, 0.1, 0.2)	(0.7, 0.75, 0.8)	(0.0, 0.1, 0.2)
Cost-Effectiveness	(0.85, 0.9, 1.0)	(0.0, 0.1, 0.2)	(0.75, 0.8, 0.85)	(0.0, 0.1, 0.2)
Social Equity	(0.7, 0.75, 0.8)	(0.0, 0.1, 0.2)	(0.8, 0.85, 0.9)	(0.0, 0.1, 0.2)

Table 5

DISTANCE FROM POSITIVE AND NEGATIVE IDEAL SOLUTIONS		
Method	**Distance from the positive ideal**	**Distance from the negative ideal**
Recycling	0.15	0.2
Composting	0.1	0.1

For example, composting performs better in these areas and makes stronger contributions to Environmental Impact and Health Safety. Recycling, meanwhile, excels in areas where efficiency and cost savings are valued, as evidenced by its noteworthy scores in time flexibility and cost-effectiveness.

Step 4: Identify the Fuzzy Positive Ideal Solution (FPIS, A) and Fuzzy Negative Ideal Solution (FNIS, A⁻)*

The FPIS and FNIS for the alternative can be defined as:

$$A^* - \{\bar{v}_1^*, \bar{v}_2^*, ..., \bar{v}_n^*\} - \left\{\max_{i\in B} \bar{v}_{ij}, \min_{i\in C} \bar{v}_{ij}\right\}$$
$$A^- - \{\bar{v}_1^-, \bar{v}_2^-, ..., \bar{v}_n^-\} - \left\{\min_{i\in B} \bar{v}_{ij}, \max_{i\in C} \bar{v}_{ij}\right\} \quad (8)$$

where A^* is a Fuzzy Positive Ideal Solution, A^- – Fuzzy Negative Ideal Solution, $\bar{v}_i^*$ – maximum value of the alternative i for all criteria in the set B, $\bar{v}_i^-$ – minimum value of the alternative i for all criteria in the set C, B – set of criteria where higher values are better (positive ideal); C – set of criteria where lower values are better (negative ideal).

The positive and negative ideal solutions are shown in table 6. The ideal solutions, both positive and negative, for recycling and composting are based on six important parameters.

Table 6

CLOSENESS COEFFICIENT	
Criteria	C_i
Composting	0.987
Recycling	0.965

The positive ideal values for recycling consistently represent the lowest acceptable outcomes, indicating ineffectiveness, while the negative ideal values consistently reflect strong performance, especially in Environmental Impact and Compliance with Regulations. Composting performs exceptionally well in these domains, as evidenced by even higher positive ideal values, particularly in Environmental Impact and Health Safety. It is clear from both approaches that shared negative ideal solutions, reaching minimal effectiveness, are undesirable across the board for optimal performance standards. The study presents quantitative assessments that underscore composting's superior performance with scores of 0.85 in environmental sustainability and 0.88 in health impact, derived from the weighted influence matrices and limiting supermatrix of the ANP. These values highlight composting's dual benefits in waste minimisation and public health enhancement.

Step 5: Calculate Distances to the Fuzzy Positive Ideal Solution (FPIS, A) and Fuzzy Negative Ideal Solution (FNIS, A⁻)*

The distances from each alternative to the FPIS and FNIS are calculated as follows:

1. Distance to FPIS (A^*):

$$S_i^* = \sum_{j=1}^{n} d(\bar{v}_{ij}, \bar{v}_j^*) \text{ for } i = 1, 2, \dots, m \quad (9)$$

2. Distance to FNIS (A^-):

$$S_i^- = \sum_{j=1}^{n} d(\bar{v}_{ij}, \bar{v}_i^-) \text{ for } i = 1, 2, \dots, m \quad (10)$$

Distance Calculation for Triangular Fuzzy Numbers

Given two triangular fuzzy numbers (a_1,b_1,c_1) and (a_2,b_2,c_2), the distance d between these fuzzy numbers can be computed using the formula:

$$d_v(\bar{M}_1,\bar{M}_2) = \sqrt{\frac{1}{3}\left[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2\right]} \quad (11)$$

where $d(\bar{v}_{ij}, \bar{v}_j^*)$ and $d(\bar{v}_{ij}, \bar{v}_i^-)$ are crisp numerical values representing the distances from each alternative to the ideal solutions.

The results below show the single values of the separations between the composting and recycling positive and negative ideal solutions (table 7). With recycling's distance from the positive ideal at 0.15, it is comparatively close to reaching optimal performance, but there is still room for improvement. The data indicate a significant deviation from the minimum acceptable standards, as indicated by the 0.2 distance from the negative ideal. Compared to other methods, composting exhibits a lower distance of 0.10 from the positive ideal, indicating its increased effectiveness in attaining the intended results. According to this comparison, composting performs better than recycling in both categories, suggesting that it might be the better choice for managing biomedical waste.

Step 6: Calculate Closeness Coefficient and Rank Alternatives

Table 7

COMPARATIVE ANALYSIS FINDINGS WITH AHP				
Rank order	1	2	3	4
DEMATEL	Recycling	Recycling	Recycling	Recycling
Fuzzy DEMATEL-Based ANP	Compositing	Compositing	Compositing	Recycling

Closeness Coefficient Calculation

To evaluate each alternative, use the following formula to compute the closeness coefficient (*CC*):

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{12}$$

where D_i^- is the distance of the alternative from the Worst Possible Ideal Solution (FNIS), D_i^+ – distance of the alternative *i* from the Best Possible Ideal Solution (FPIS).

The closeness coefficients for recycling and composting are shown in table 8 and show how closely each approach resembles the optimal waste management solution. Composting is a highly advantageous option due to its strong performance and effectiveness in achieving optimal outcomes, as evidenced by its closeness coefficient of 0.987. Recycling, on the other hand, has a closeness coefficient of 0.965, indicating that although it is also effective, it performs marginally less optimally than composting.

Comparative analysis

The results of the comparative study between DEMATEL and fuzzy-based Analytic Network Process (ANP), two distinct decision-making techniques, are presented in table 9. Recycling maintains a top ranking in the DEMATEL method after four evaluations, demonstrating its effectiveness and appropriateness for waste management. On the other hand, composting is ranked first in the first three rankings of the Fuzzy DEMATEL-Based ANP analysis, indicating that it is a good option when taking fuzzy logic into account. As a result of a somewhat less positive evaluation under fuzzy criteria, recycling comes in at number four in this method.

SOCIAL MANAGERIAL IMPLICATIONS

In healthcare settings where waste generation poses serious risks to the environment and public health, this study highlights the significance of sustainable waste management practices. The study emphasises how important it is for healthcare facilities to adopt recycling and composting procedures using a fuzzy DEMATEL-based Analytic Network Process (ANP) framework. By lowering the negative effects of inappropriate waste disposal and advancing long-term social benefits, these practices encourage environmental stewardship, regulatory compliance and public health improvement. Several environmental and infrastructure factors, including geographic location, policy regulations, climate variability and technological infrastructure, may have an impact on how effective the suggested framework is. The model is flexible and context-sensitive since it can be localised by modifying weights and linguistic scales in accordance with expert input specific to a given area. The study also emphasises how introducing recycling and composting procedures in healthcare facilities has positive social and environmental effects. These methods can comply with more stringent environmental regulations, increase social equity and reduce waste management expenses. The study suggests creating integrated waste management frameworks to promote a circular economy while reducing environmental damage and reliance on landfills. The entire medical community eventually gains from a more sustainable healthcare system as a result.

DISCUSSION

This study evaluated biomedical waste management practices with an emphasis on recycling and composting using the Fuzzy DEMATEL-Based ANP method. Through the conversion of qualitative expert opinions into quantifiable fuzzy values, the methodology methodically addressed the complexity of interdependent criteria of interest. 150 decision-makers with specialised knowledge contributed to the discussion of six main criteria: social equity, cost-effectiveness, time flexibility, health safety, environmental impact and regulatory compliance. To control subjectivity and uncertainty, the model used TFNs and incorporated these criteria into a structured decision matrix. The research precisely normalised and weighted the alternatives by calculating the positive and negative ideal solutions, producing a strong framework for comparative analysis. In four of the six major categories, such as Environmental Impact and Health Safety, the results showed that composting performed better than recycling, demonstrating its greater suitability from a societal and environmental perspective. On the other hand, recycling demonstrated better results in terms of cost-effectiveness and time flexibility, which reflected operational and financial efficiency. This study proposes a robust, data-driven framework using Fuzzy DEMATEL-ANP, which integrates expert opinions and systematically addresses uncertainty to support realistic and adaptive decision-making. The approach directly contributes to circular economy implementation in healthcare by offering prioritised strategies such as composting for sustainable biomedical waste management. It was confirmed by the analysis that the Fuzzy DEMATEL-Based ANP approach successfully reconciled competing criteria, giving decision makers a clear and trustworthy way to assess waste management options. This thorough framework made sure the chosen approach took into account the practical limitations that stakeholders face in real-world situations, in addition to complying with legal and environmental requirements.

LIMITATIONS OF THE STUDY

Despite its valuable insights, this study has several limitations. The reliance on expert opinions, while necessary for qualitative assessment, may introduce subjective bias, especially in the context of fuzzy logic interpretations. The model's applicability is constrained by the selection of criteria and alternatives, which may not comprehensively capture the diversity of biomedical waste management practices across different regions or facility types. Additionally, the study assumes static interdependencies among criteria, which may evolve due to policy changes, technological advancements, or emerging environmental concerns. The framework's performance is also limited by the availability and accuracy of expert data, which could affect the generalizability of the findings. Future research should consider dynamic modelling approaches, broader stakeholder inputs, and real-time data integration to enhance robustness and applicability across varied healthcare settings.

CONCLUSION

The application of a Fuzzy DEMATEL-based Analytic Network Process (ANP) has provided valuable insights into the management of biomedical waste, particularly regarding composting and recycling strategies. There are significant practical ramifications for healthcare organisations looking to optimise their biomedical waste management systems using the integrated fuzzy DEMATEL-ANP framework. In order to improve compliance, lower environmental risks, and advance circular economy principles, healthcare administrators can prioritise strategies such as recycling and composting according to a number of interconnected criteria. This model can be applied to healthcare facilities of different sizes and incorporated into policy frameworks to direct staff training, infrastructure investments, and treatment technology selection, guaranteeing sustainable waste management and regulatory compliance. Fuzzy logic is used in this study to handle expert evaluation uncertainties, allowing for a thorough evaluation of the main factors affecting biomedical waste management choices. The integration of Fuzzy DEMATEL and ANP provides methodological innovation by enabling precise evaluation of complex interdependencies in biomedical waste factors.

The model highlights composting as a top priority, offering clear practical implications for healthcare administrators.

Out of all the factors that were examined, the most important ones were environmental impact, compliance with regulations, health and safety, cost-effectiveness, time flexibility and social equity. By enabling experts to offer nuanced inputs, the fuzzy scale improved the reliability of the results' dependability. Weight assignments made the significance of the criteria clear, and a normalised decision matrix compared different approaches. The most successful approach was composting, which received a score of 0 points for compliance and 0 points for environmental benefit. In particular, the fuzzy DEMATEL-based ANP method ranked composting higher than recycling, outperforming conventional methods by providing deeper insights. The significance of using a variety of analytical tools to make well-informed and sustainable waste management decisions is highlighted by these findings.

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Development and application of a green degree evaluation framework for the environmental sustainability of clothing

DOI: 10.35530/IT.076.05.20254

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ABSTRACT – REZUMAT

Development and application of a green degree evaluation framework for the environmental sustainability of clothing

The production, use, and disposal of clothing contribute significantly to environmental pollution and resource depletion, necessitating robust methodologies to evaluate environmental sustainability. Nevertheless, a holistic framework for evaluating the environmental sustainability of clothing is still absent. To bridge this gap, this study introduces the concept of green degree to develop a holistic evaluation framework for clothing, which comprises an evaluation system and an evaluation model. The clothing green degree evaluation system is based on the principles of environmental friendliness, technological advancement, and economic rationality, and is composed of green material, green design, green production, green quality, and green packaging. TFN-AHP and grey clustering method were integrated to develop the evaluation model. Among the five evaluation dimensions, green production and green material received the highest weights, at 36.89% and 33.64% respectively. To validate the proposed model, a men's polo shirt was evaluated as a case study. With a score of 3.647, the shirt was evaluated as 'green' grade on the five-tier green degree scale, a result consistent with its actual environmental properties. Through this green degree evaluation framework, the environmental sustainability of clothing can be evaluated, thereby providing a scientific basis for product development and classification strategies.

Keywords: *environmental sustainability of clothing, clothing green degree, evaluation framework, TFN-AHP, grey clustering method*

Dezvoltarea și aplicarea unui cadru de evaluare a gradului de ecologie pentru sustenabilitatea de mediu a articolelor de îmbrăcăminte

Producerea, utilizarea și eliminarea articolelor de îmbrăcăminte contribuie semnificativ la poluarea mediului și la epuizarea resurselor, ceea ce impune dezvoltarea unor metodologii solide pentru evaluarea sustenabilității de mediu. Cu toate acestea, un cadru holistic pentru evaluarea sustenabilității de mediu a articolelor de îmbrăcăminte lipsește încă. Pentru a acoperi acest gol, studiul de față introduce conceptul de grad de ecologie, în vederea dezvoltării unui cadru de evaluare holistic pentru articolele de îmbrăcăminte, care cuprinde un sistem de evaluare și un model de evaluare. Sistemul de evaluare a gradului de ecologie al îmbrăcămintei se bazează pe principiile de protejare a mediului, progresului tehnologic și raționalității economice, și este compus din cinci parametri: materiale ecologice, design ecologic, producție ecologică, calitate ecologică și ambalaj ecologic. Metodele TFN-AHP și de grupare gri (grey clustering) au fost integrate pentru a dezvolta modelul de evaluare. Dintre cei cinci parametrii de evaluare, producția ecologică și materialele ecologice au primit cele mai mari ponderi, de 36,89%, respectiv 33,64%. Pentru validarea modelului propus, un tricou polo pentru bărbați a fost evaluat ca studiu de caz. Cu un scor de 3,647, tricoul a fost clasificat ca „ecologic" pe o scară cu cinci trepte a gradului de ecologie, rezultat care corespunde proprietăților sale reale de mediu. Prin intermediul acestui cadru de evaluare a gradului de ecologie, sustenabilitatea de mediu a articolelor de îmbrăcăminte poate fi evaluată riguros, oferind astfel o bază științifică pentru dezvoltarea produselor și strategiile de clasificare.

Cuvinte-cheie: *sustenabilitatea de mediu a articolelor de îmbrăcăminte, gradul de ecologie al îmbrăcămintei, cadru de evaluare, metoda TFN-AHP, metoda de grupare gri*

INTRODUCTION

A major contributor to global pollution, the textile and clothing industry generates significant greenhouse gas emissions and water pollution [1]. Escalating environmental challenges necessitate that the industry embrace responsibility for mitigating its impact. This entails a critical balance between economic growth, industrial innovation, and ecological conservation to ensure a sustainable future [2]. Nevertheless, despite this recognized urgency, the industry persists as a model of high input, consumption, and pollution, coupled with low yield – an operational pattern far removed from the goals of sustainable management [3].

Sustainable development requires responsible consumption and production by enterprises and consumers, and ensuring the environmental sustainability of products is an effective way to achieve this goal [4].

Nevertheless, most clothing products are not sustainable, either in the nature of the product or in the quantity of the product. First of all, it is a recognised fact that clothing products have a serious impact on the environment [5]. The environmental impact of clothing products during their life cycle is manifested by: i) High water consumption, water eutrophication and soil pollution due to extraction of raw materials from natural resources [6]; ii) Emissions of BTEX compounds, NO_X, SO_2 and other harmful compounds during the extraction of raw materials from petrochemical resources [7]; iii) Greenhouse gas emissions and water pollution from industrial production [8]; iv) High water consumption and water eutrophication due to consumer washing [9].

Secondly, there is an overproduction of clothing, which results in a huge amount of waste. In the clothing industry, fast-changing customer needs, seasonal product fluctuations, low high-tech content of products and a wide range of suppliers require enterprises to achieve fast, low-cost production of products [10]. Nevertheless, fast-changing fashion trends and fierce market competition have led to a growing oversupply of clothing, which results in a huge waste of resources. In addition, to maximise profits, the majority of clothing enterprises do not invest too much in selecting sustainable raw materials, introducing advanced equipment, improving working conditions and reducing production pollution [11]. In conclusion, for promoting the sustainable development of the textile and clothing industry, it is essential to improve the environmental sustainability of clothing. Nevertheless, a scientific and comprehensive evaluation system and methodology are required to improve the environmental sustainability of clothing.

At present, eco-label and carbon-labelling are the most common sustainability evaluation criteria for clothing, including OEKO-TEX, Global Organic Textile Standard [12], Carbon Reduction Label, Carbon Free TM Product Certification label, etc. [13]. Eco-label focuses on the safety of the clothing's material composition and the low toxicity of chemical additives, which regulates the pH level, formaldehyde content, extractable heavy metal content, organotin content, colour fastness of clothing, etc. [14]. Carbon-labelling focuses on the carbon footprint of the clothing at the production stage, which is presented in the form of a grade, a value, etc. [15]. Clothing eco-labels and carbon-labelling guide companies on regulated and green production, as well as facilitating consumers' choice of sustainable products. Nevertheless, with the enrichment of sustainable development concepts and the innovation of green products, sustainability evaluation criteria for clothing need to be enriched as well, which requires an evaluation system for a comprehensive evaluation of the environmental sustainability of clothing [16, 17]. To establish a comprehensive evaluation system, the first step is to select an evaluation method that can fully reflect the environmental sustainability of clothing. At present, the green degree evaluation is a commonly used method for product evaluation, which is derived from the Green Product [18]. Environmental friendliness, technological advancement, and economic rationality are the core dimensions of the green degree evaluation, which can fully quantify the environmental sustainability of a product [19]. In the field of building materials, machine parts, transportation, etc., the green degree evaluation has become a common evaluation method for evaluating the environmental sustainability of their products, and its comprehensive evaluation dimensions can theoretically provide new ideas for evaluating the environmental sustainability of clothing. Nevertheless, green degree evaluation has yet to be applied to the environmental sustainability evaluation of clothing, nor has it been leveraged to create an evaluation system grounded in the distinctive characteristics of clothing product. Therefore, we developed a green degree evaluation framework for the environmental sustainability of clothing, drawing on the concept of green degree and the distinctive characteristics of clothing. Our study contributes to the body of knowledge by providing a holistic evaluation framework for the environmental sustainability of clothing; it also offers a foundation for informing the development of sustainable products.

RELATED THEORY AND WORK

Review of related theories

To establish the clothing green degree evaluation system and model, research experience in the fields of engineering technology and art design is required. Firstly, the clothing green degree evaluation system is a sustainable evaluation system based on clothing product characteristics, which requires discussing the related works on the life cycle of clothing and the characteristics of sustainable clothing. Secondly, this evaluation system is based on the green degree theory, which requires discussing the related works on the product green degree evaluation.

Different types of clothing are produced and processed in different ways, which leads to different life cycles [20]. However, in general, the life cycle of a garment typically includes the stages of raw material extraction, clothing production, retailing, use and end of life [21]. At present, related works have provided a detailed explanation of the concept, the definition, and the stages of the life cycle of clothing, and although different researchers differ in how they define life cycle stages, there is no clear divergence in the basic opinions and findings of the researchers [22, 23]. By synthesizing related works, the life cycle stages of clothing can generally be divided into the raw material extraction and production stage (extraction and production of raw materials for clothing fibres and accessories.), the fabric weaving and clothing manufacturing stage (fabric production and clothing production.), the retailing stage (traditional retail and online retail.), the use and maintenance stage (washing, ironing, and drying of clothing), and the end-of-life stage (direct reuse, recycling, landfill, or incineration) [8, 21]. The clothing green degree evaluation is one of the methods of product sustainability evaluation, which requires discussing the related works on the characteristics of sustainable clothing. Generally, sustainable clothing is high-quality clothing that minimises pollution and waste of resources, and contributes to human health, based on the principle of environmental protection [24, 25]. Although there is no authoritative definition of sustainable clothing, research generally agrees that sustainable clothing should be sustainable in terms of materials, patterns, and production conditions [26]. Thereby, the characteristics of sustainable clothing generally include the use of environmentally friendly materials [27], the application of sustainable design strategy [28], and efficient and clean production conditions [29]. In addition, the use of environmentally friendly packaging has been recognised in recent years as an essential manifestation of the characteristics of sustainable clothing [30].

At present, there are many research fields that have applied the green degree evaluation to the sustainable evaluation of products [31, 32]; however, there is still a lack of related work on the clothing green degree evaluation. Related works on product green degree evaluation are based on their own research content to establish the evaluation system, which has no uniform requirement for the establishment of the system [33], and the selection of research methods also differs [34]. However, there is one thing in common, as all related works have established their evaluation systems around the environmental, economic, and technical attributes of products, which is consistent with the core dimensions of the green degree evaluation. Thereby, the establishment of the clothing green degree evaluation system should be based on the core dimensions of green degree evaluation, combined with the related works on the life cycle of clothing and the characteristics of sustainable clothing, to establish the evaluation system and select the appropriate evaluation method. In summary, by reviewing the related works on the life cycle of clothing, the characteristics of sustainable clothing, and the product green degree evaluation, we obtained the concept of the clothing green degree: the degree to which a garment is environmentally friendly, technologically advanced, and economically rational throughout its life cycle. The clothing green degree can fully reflect the sustainability of clothing, and the clothing green degree evaluation system is the specific evaluation dimension and content. Thereby, we introduced the green degree evaluation, based on the principles of environmental friendliness, technological advancement, and economic rationality. We established the clothing green evaluation system with five evaluation dimensions: green material, green design, green production, green quality, and green packaging, as shown in figure 1.

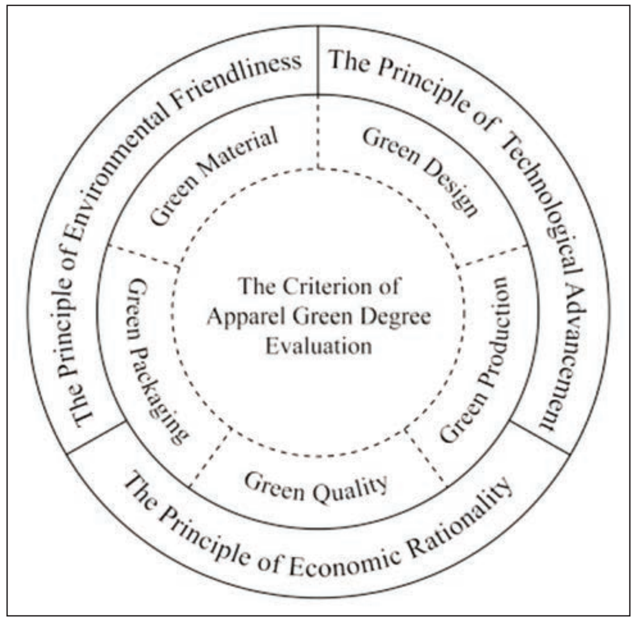


Fig. 1. Establishment principle of the clothing green degree evaluation system

The clothing green degree can be expressed by the equation, as shown in equation 1:

$$G_{clo} = f(M_{clo}, D_{clo}, P_{clo}, Q_{clo}, B_{clo}) \quad (1)$$

where G_{clo} is the clothing green degree. M_{clo} is the degree to which a garment is environmentally friendly, technologically advanced, and economically rational in terms of the green materials dimension. D_{clo} is the degree to which a garment is environmentally friendly, technologically advanced, and economically rational in terms of the green design dimension. P_{clo} is the degree to which a garment is environmentally friendly, technologically advanced, and economically rational in terms of the green production dimension. Q_{clo} is the degree to which a garment is environmentally friendly, technologically advanced, and economically rational in terms of the green quality dimension. B_{clo} is the degree to which a garment is environmentally friendly, technologically advanced, and economically rational in terms of the green packaging dimension.

In our research, the green material dimension focuses on the source of raw materials for clothing and the utilization of materials [26, 27], firstly, identifying the source of raw materials for clothing fibres and accessories (sewing thread, button, zip, fabric tape, filling material, etc.), secondly, assessing the utilization of materials at the end of the clothing life cycle. This dimension reflects the characteristics of sustainable clothing (the use of environmentally friendly materials) and refers to 2 life cycle stages: the raw material extraction and production stage, and the end-of-life stage. The green design dimension focuses on the degree to which the design of the clothing's structure, style and fabric is compatible with sustainable design strategy [35]. This dimension reflects the characteristics of sustainable clothing (the application of sustainable design strategy); it is also the dimension that best reflects the characteristics of the clothing product. The green production dimension focuses on the manufacturing capacity and processing level of clothing manufacturers [36, 37]. Firstly, assessing the manufacturing capacity, secondly, a large amount of waste material is generated during the clothing manufacturing process [37], which requires assessing the level of recycling and reuse of waste material. This dimension reflects the characteristics of sustainable clothing (efficient and clean production conditions) and refers to the life cycle stage of fabric weaving and clothing manufacturing. The green quality dimension focuses on the quality, functional, and economic attributes of clothing [38, 39], firstly, assessing the amount of product standard (E.g., OEKO-TEX, etc.) the clothing fulfils, secondly, assessing the comfort of clothing, and finally, assessing the production and maintenance cost of clothing. This dimension refers to the life cycle stage of use and maintenance. The green packaging dimension focuses on the attributes of clothing packaging materials and packaging body [30]. This dimension reflects the characteristics of sustainable clothing (the use of environmentally friendly packaging) and refers to the life cycle stage of the end-of-life.

Establishment of the evaluation system

The clothing green degree evaluation system (5 indexes at first class, 11 indexes at second class, 27 indexes at third class) is established by reviewing related works in the previous section, as shown in table 1.

Table 1

THE CLOTHING GREEN DEGREE EVALUATION SYSTEM

First-class index	Second-class index	Third-class index	Index interpretation and evaluation standards
Green material C_1	Material sources C_{11}	Usage rate of renewable raw materials C_{111}	Ratio of renewable materials to fibre and accessory raw materials, the higher this ratio, the higher the green degree.
		Usage rate of recycled raw materials C_{112}	Ratio of recycled materials to fibre and accessory raw materials, the higher this ratio, the higher the green degree.
		Usage rate of degradable raw materials C_{112}	Ratio of degradable materials to fibre and accessory raw materials, the higher this ratio, the higher the green degree.
	Utilisation of materials C_{12}	Quantity of material types C_{121}	The quantity of fibre and accessory raw materials, the lower this quantity, the higher the green degree.
		Recyclability of materials C_{122}	The proportion of resources that can be recycled and then processed for reuse after clothing is discarded. The higher this proportion, the higher the green degree.
		Reusability of materials C_{123}	The proportion of resources that can be disassembled and reused directly after the garment is discarded. The higher this proportion, the higher the green degree
Green design C_2	Structure and styling C_{21}	The classical degree of clothing style C_{211}	The style matches the classic design philosophy and avoids temporary fashions; the more classic the style, the higher the green degree.
		The degree of simplicity of the clothing pattern C_{212}	The pattern should be simple, balancing the proportions of clothing and aiming for zero-waste design. The simpler the clothing pattern, the higher the green degree.
		Replaceability of clothing components C_{213}	The degree of replaceability of clothing components, the higher this degree, the higher the green degree.
	Colour and texture C_{22}	The degree of the original colour of clothing C_{221}	Emphasis on the original colours of fabrics and accessories to reduce the hazards of dyes and auxiliaries, the higher the degree, the higher the green degree.
		The degree of the original texture of clothing C_{222}	Emphasis on the original texture of fabrics and accessories to reduce unnecessary decoration and craftsmanship, the higher this degree, the higher the green degree.
Green production C_3	Manufacturing capacity C_{31}	Usage rate of energy-saving equipment C_{311}	Ratio of energy-saving equipment used in manufacturing to total equipment; the higher this ratio, the higher the green degree.
		The level of green process technology C_{312}	Levels of control and processing of noise, waste gas and wastewater during manufacturing, the higher this level, the higher the green degree.
		The level of the efficient manufacturing process C_{313}	Levels of manufacturing workshop automation and manufacturing process simplification, the higher this level, the higher the green degree.
	Processing level C_{32}	Technical level of waste material recycling C_{321}	The technical level of recycling of trimmings, waste clothing patterns, leftover material, etc., for post-processing reuse, the higher this level, the higher the green degree.

Table 1 (continuation)

First-class index	Second-class index	Third-class index	Index interpretation and evaluation standards
		Technical level of waste material reuse C_{322}	The technical level of direct reuse of trimmings, waste clothing patterns, leftover material, etc., the higher this level, the higher the green degree.
Green quality C_4	Quality attributes C_{41}	Quality standard of clothing C_{411}	The level of product standards (E.g., OEKO-TEX, etc.) that the clothing can fulfil, the higher this level, the higher the green degree.
		Comfort of clothing C_{412}	Including thermal-wet comfort, fitness comfort, contact comfort, etc., the more conditions the clothing fulfils, the higher the green degree.
		Lifespan of clothing C_{413}	Including colour fastness, stability of fabric, contact durability of accessory, etc., the more conditions the clothing fulfils, the higher the green degree.
	Functional attributes C_{42}	Use the function of clothing C_{421}	Including essential use functions and other functions, the richer the function, the higher the green degree.
		Social function of clothing C_{422}	Including individual aesthetic, social status, and other social attributes that clothing can demonstrate, the richer the function, the higher the green degree.
	Economic attributes C_{43}	Production cost of clothing C_{431}	Including the cost of R&D, material, production, transport, storage, etc., the lower this cost, the higher the green degree.
		Maintenance cost of clothing C_{432}	The frequency of garment washing, dry cleaning, drying, ironing, etc., the lower the frequency, the higher the green degree.
Green packaging C_5	Packaging materials C_{51}	Sustainability of raw materials C_{511}	The more environmentally friendly the packaging material, the higher the green degree.
		Reusability of packaging C_{512}	The degree of direct reuse of the packaging, the higher this degree, the higher the green degree.
	Packaging body C_{52}	Ease of unpacking C_{521}	Packaging is designed to be as simple as possible, with less tape, glue, etc., to hinder disassembly and recycling. The easier the packaging is to disassemble, the higher the green degree.
		The degree of volume minimisation of packaging C_{522}	Provided there is enough packaging space for the clothing, the smaller the package volume, the higher the green degree.

We validated the third-class index through a questionnaire survey to ensure that they all describe the evaluation target. Applying the Likert 5-point Scale, we investigate the impact of 27 third-class indexes on the clothing green degree evaluation system, which requires at least 135 questionnaires [40]. A total of 255 people were interviewed, and they can be divided into two categories: 1) In-service teachers and graduate students of textile and fashion related majors (from Donghua University, Jiangnan University, Zhejiang Sci-Tech University, and Xi'an Polytechnic University); 2) Employees with textile and fashion product development experience of 3 years or more (from Guangdong Esquel Textiles Co., Ltd, Semir Group Co., Ltd, Anzheng Fashion Group Co., Ltd).

A total of 232 valid questionnaires were collected, with an effective rate of 90.98%. Importing sampling data into SPSS 23.0, the overall Cronbach's α of the sampling data is $0.848 > 0.7$, the KMO is $0.837 > 0.6$, and the Sig. is $0.000 < 0.05$, which shows a good result. Then, we validated the value of α after deletion of the index and the CITC of the 27 indexes, as shown in table 2. The CITC of the 27 indexes were all

Table 2

DATA TESTING OF INDEX

Index	α after deletion of index	*CITC*	Index	α after deletion of index	*CITC*
C_{111}	0.844	0.358	C_{321}	0.846	0.311
C_{112}	0.842	0.417	C_{322}	0.844	0.339
C_{113}	0.842	0.407	C_{411}	0.843	0.379
C_{121}	0.843	0.373	C_{412}	0.844	0.357
C_{122}	0.843	0.387	C_{413}	0.843	0.372
C_{123}	0.843	0.391	C_{421}	0.842	0.424
C_{211}	0.843	0.380	C_{422}	0.840	0.460
C_{212}	0.843	0.374	C_{431}	0.845	0.309
C_{213}	0.843	0.379	C_{432}	0.843	0.390
C_{221}	0.845	0.303	C_{511}	0.841	0.444
C_{222}	0.845	0.318	C_{512}	0.841	0.440
C_{311}	0.842	0.398	C_{521}	0.840	0.472
C_{312}	0.843	0.366	C_{522}	0.841	0.454
C_{313}	0.845	0.331			

higher than 0.3, and the values of α after deletion of the index were all lower than 0.848, indicating that deleting any index would reduce the credibility of the data. Thereby, all indices in the system are suitable for the description of the evaluation target.

METHODOLOGY

Method of weight calculation

The analytic hierarchy process (AHP) is limited by the singular characteristic of its evaluation scale, which cannot comprehensively represent the assessment results provided by experts. To further reduce the impact of ambiguity in expert evaluations on the accuracy of the results, we have introduced the concepts of fuzzy mathematics. TFN-AHP is a better weighting method that combines triangular fuzzy numbers with the analytic hierarchy process. Compared with the analytic hierarchy process, TFN-AHP establishes the fuzzy judgment matrix by introducing triangular fuzzy numbers, which can fully consider the influence of the ambiguity of expert judgments on the evaluation results [41].

Assume that the fuzzy set of the argument domain R in the interval [0,1] is $\tilde{S}$, and its arbitrary map $\mu_{\tilde{S}} \in [0,1]$. Where, $\mu_{\tilde{S}}$ is the membership function of $\tilde{S}$, $\mu_{\tilde{S}}(x)$ is the degree of membership of the eigenvalue x to $\tilde{S}$, which can be expressed as a triangular function, as shown in equation 2:

$$\mu_{\tilde{S}}(x) = \begin{cases} 0, & x < l,\ x > u \\ \dfrac{x-l}{m-l'}, & l \le x \le m \\ \dfrac{x-u}{m-u'}, & m \le x \le u \end{cases} \tag{2}$$

where l and u are the upper and lower bounds of the fuzzy set $\tilde{S}$, respectively. m is the value for which the degree of membership of $\tilde{S}$ is 1. The triangular fuzzy number is denoted as $\tilde{S} = (l, m, u)$, let the two triangular fuzzy numbers be $\tilde{S}_i = (l_i, m_i, u_i)$, $\tilde{S}_j = (l_j, m_j, u_j)$, respectively, and the calculation rules are shown in equations 3 to equation 6.φ

$$\tilde{S}_i + \tilde{S}_j = (l_i, m_i, u_i) + (l_j, m_j, u_j) = (l_i + l_j, m_i + m_j, u_i + u_j) \tag{3}$$

$$\tilde{S}_i \times \tilde{S}_j = (l_i, m_i, u_i) \times (l_j, m_j, u_j) = (l_i \times l_j, m_i \times m_j, u_i \times u_j) \tag{4}$$

$$\varphi\tilde{S}_i = \varphi(l_i, m_i, u_i) = (\varphi l_i, \varphi m_i, \varphi u_i) \tag{5}$$

$$(\tilde{S}_i)^{-1} = [(l_i, m_i, u_i)]^{-1} = \left(\frac{1}{l_i}, \frac{1}{m_i}, \frac{1}{u_i}\right) \tag{6}$$

Compare the importance of all indexes in the same layer to generate the judgment result, which is expressed by the triangular fuzzy number and generate the judgment matrix $\tilde{C} = (\tilde{c}_{ij})_{n\times n}$, where $\tilde{c}_{ij} = (l_{ij}, m_{ij}, u_{ij})$, $\tilde{c}_{ij} = (\tilde{c}_{ij})^{-1}$. Judgment rule as shown in table 3.

Based on the judgment matrix $\tilde{C}$, calculate the fuzzy weight vector $\tilde{\omega}_i$ for the same layer of n indexes, as shown in equation 7.

Table 3

LINGUISTIC VARIABLES AND TRIANGULAR FUZZY NUMBERS WITH QUANTITATIVE SCALES

Linguistic terms	Fuzzy number	Triangular fuzzy number
Equally important	1	(1, 1, 1)
Moderately more important	3	(2, 3, 4)
Strongly more important	5	(4, 5, 6)
Very strong more important	7	(6, 7, 8)
Extremely more important	9	(8, 9, 9)
Intermediate values	2, 4, 6, 8	Between the values above

$$\tilde{\omega}_i = \frac{\sum_{j=1}^n \tilde{c}_{ij}}{\sum_{k=1}^n \sum_{j=1}^n \tilde{c}_{ij}} = \left(\frac{\sum_{j=1}^n l_{ij}}{\sum_{j=1}^n l_{ij} + \sum_{k=1,k\neq i}^n \sum_{j=1}^n u_{kj}}, \frac{\sum_{j=1}^n m_{ij}}{\sum_{k=1}^n \sum_{j=1}^n m_{kj}}, \frac{\sum_{j=1}^n u_{ij}}{\sum_{j=1}^n u_{ij} + \sum_{k=1,k\neq i}^n \sum_{j=1}^n l_{kj}}\right) \tag{7}$$

To performing the consistency checking on $\tilde{C}$, a non-fuzzy judgment matrix C needs to be formed using m_{ij}, and then the consistency checking is performed on the matrix C.

Firstly, calculate the weight vector ω_i after normalizing the n row vectors of the matrix C, as shown in equation 8.

$$\omega_i = \left(\frac{\sum_{j=1}^n m_{ij}}{\sum_{j=1}^n \sum_{k=1}^n m_{ij}}\right)^T \tag{8}$$

Secondly, calculate the maximal characteristic root λ_{max} of the matrix C, as shown in equation 9.

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^n \frac{\sum_{j=1}^n c_{ij}\,\omega_j}{\omega_i} \tag{9}$$

Thirdly, calculate the consistency checking index CI, then combine it with the random consistency index RI to calculate the CR, where $CI = (\lambda_{max} - n)/(n-1)$, $CR = CI/RI$. The matrix C passes the consistency checking if $CR < 0.1$. After passing the consistency checking, the fuzzy weight vector of each index in the judgment matrix is performed Monte Carlo simulation, which achieves defuzzification and obtains the weights of each index. We performed a Monte Carlo simulation by using the triangular distribution function, which is shown in equation 10:

$$f(x|a,b,c) = \begin{cases} \dfrac{2(x-a)}{(b-a)(c-a)}, & a \le x \le c \\ \dfrac{2(x-b)}{(b-a)(c-b)}, & c \le x \le b \end{cases} \tag{10}$$

where a, b, and c are the lower limit value, the upper limit value, and the mode number, respectively, which together form the continuous probability density function. According to equation 10, the fuzzy weight was transformed into the form of the triangular distribution function, and then a Monte Carlo simulation was carried out to generate several random sets of sample data, and the mode number of these sample data was the index weight. The weight of each index is synthesised according to the layer to form the synthetic weight $W_i^{(e)}$ of each index for the target layer, as shown in equation 11:

$$W_i^{(e)} = \prod_{e=1}^{n-1} \varpi_i^{(e)} \quad (11)$$

where $i = 1,2,\ldots,n$, $\varpi_i^{(e)}$ is the weight of the i-th index at layer e. $W_i^{(e)}$ is the synthetic weight of the i-th index at layer e for the target layer.

Method of evaluation model establishment

Clothing green degree evaluation indexes have the characteristics of a large number, a wide range, and low measurability, which leads to an unknown degree of impact among the indexes. thereby, we use the grey clustering method to establish the evaluation model. Grey clustering method quantifies the similarity of evaluation data using the whitening weight function to achieve rank classification, which is suitable for evaluation systems with a small sample size and clear grade.

To achieve better evaluation results, the green degree evaluation usually divides the grade into 5 levels [32], thereby, we divide the clothing green degree into 5 evaluation grades: dark green, green, quasi-green, light green and grey, and assign scores of 5, 4, 3, 2 and 1 to form the grey class grade vector. Z experts are invited to establish the grey evaluation matrix by scoring the grades of evaluation indexes C_{111}–C_{522}. Then we established the valued vector $V = (v_1,v_2,v_3,v_4,v_5) = (5,4,3,2,1)$ based on the 5 evaluation grades, and established the whitening weight function f_j^S for the K^{th} grey class corresponding to the j-th index, as shown in figure 2, where $j = 1,2,\ldots,27$; $K = 1,2,3,4,5$.

For any third-class index C_{rst} of the evaluated target, the corresponding score h_{Crst}, and the grey evaluation weight q_{Crst}^k of the K^{th} grey class is shown in **equation 12**, where $k = 1,2,3,4,5$:

$$q_{Crst}^k = \frac{\sum_{v=1}^{Z} f^K(h_{Crst}^v)}{\sum_{K=1}^{5}\sum_{v=1}^{Z} f^K(h_{Crst}^v)} \quad (12)$$

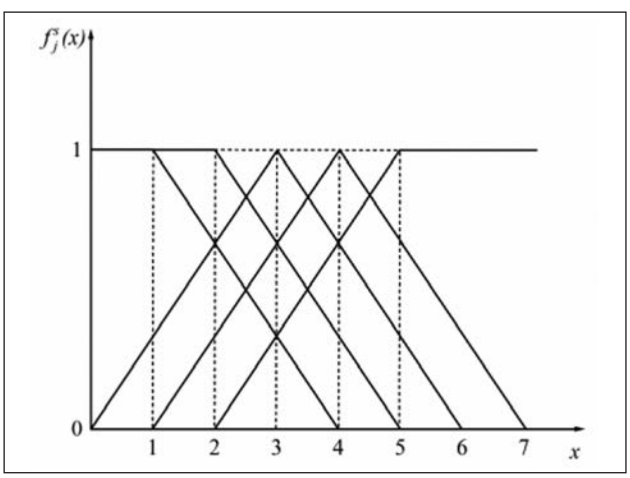


Fig. 2. Whitening weight function for 5 types of grey classes

where $f^K(h_{Crst}^v)$ is the whitening weight coefficient of the K^{th} grey class judged by the expert. h_{Crst}^v is the evaluation grade of the v^{th} expert on the third-class index. By calculating the grey evaluation weight of each index, the grey evaluation weight matrix $Q_{Crs} = (q_{Crs1}, q_{Crs2},\ldots, q_{Crsy})^T$ can be obtained, as we can perform the comprehensive evaluation. The grey evaluation weight matrix of each index at the layer of third-class index can be used to obtain the grey evaluation weight matrix Q_{Cr} of each index at the layer of second-class index, and then the comprehensive evaluation result G_i at the layer of first-class index and the final comprehensive evaluation result G can be obtained, as shown in equations 13 to 14.

$$G_i = W_{Crs} Q_{Cr} = (g_i^1\, g_i^2\, g_i^3\, g_i^4\, g_i^5) \quad (13)$$

$$G = W_{Cr} Q = (g_1 g_2 g_3 g_4 g_5) \quad (14)$$

where W_{Crs} is the weight of the index at the layer of the second-class index. W_{Cr} is the weight of the index at the layer of the first-class index. The result of the evaluation grade can be obtained according to the maximum membership degree principle, and the result of the evaluation score can be obtained according to the vector V.

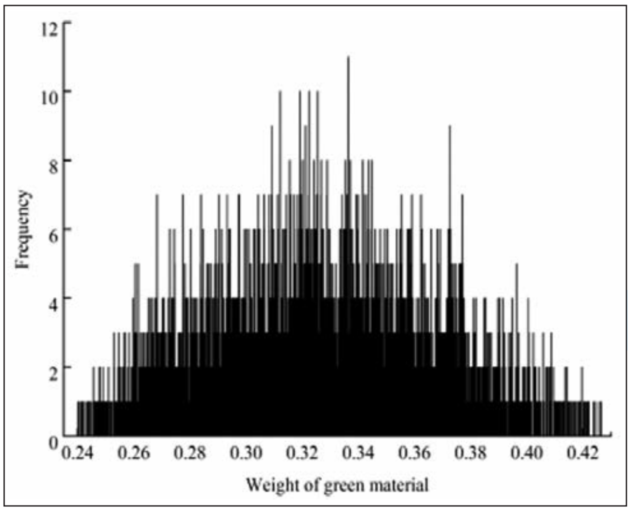
RESULTS

Results of index weight

We invited 8 textile and fashion-related professional teachers with 10 years or more work experience (1 from Donghua University, 1 from Jiangnan University and 6 from Xi'an Polytechnic University) and 3 fashion company employees with 10 years or more working experience (1 from Guangdong Esquel Textiles Co., Ltd and 2 from Semir Group Co., Ltd) to score the evaluation index. A total of 17 sets of fuzzy judgment matrix were generated according to table 3 and equations 3–6, and the weight vector of each index in the fuzzy judgment matrix of each layer can be calculated according to equation 7. We took the layer of the first-class index as an example, as follows.

$$\tilde{\omega}_{C_i} = \begin{bmatrix} (0.2379,0.3259,0.4281) \\ (0.0636,0.0979,0.1493) \\ (0.2779,0.3762,0.4819) \\ (0.1026,0.1569,0.2298) \\ (0.0319,0.0431,0.0638) \end{bmatrix}$$

The m_{ij} of the fuzzy judgment matrix $\tilde{C}_{C_i}$ was used to establish the 5-order matrices ($RI = 1.12$), which leads to the consistency checking of the non-fuzzy judgment matrix. The weight vector of the non-fuzzy judgment matrix is calculated as $\omega = (0.3259,0.0979,0.3762,0.1569,0.0431)$ by equation 8, and the λ_{max} is calculated as 5.1519 by equation 9; thereby, the CR is $0.0339 < 0.1$, which means the matrix passes the consistency checking. Then, firstly, we converted the weight vectors of C_1-C_5 into a triangular distribution function, which, in the case of C_1, is $f_{C1}(x_{C1}|a_{C1},b_{C1},c_{C1}) = f(x_{C1}|0.2379,0.3259,0.4281)$. Secondly, we combined equation 10 for Monte Carlo simulation, and performed 5000 random sampling on the triangular distribution function of C_1-C_5 to obtain the weight frequency figures, and the figures show that the weights are 0.3364, 0.0935, 0.3689, 0.1556, 0.0456. Take C_1 as an example, as shown in figure 3.



By following the steps above, the weights of C_{11}-C_{52}, C_{111}-C_{522} and the synthetic weights were calculated, as shown in table 4; all indexes in this evaluation system pass the consistency checking.

Application of the evaluation model

To verify the accuracy of the evaluation index and its model, we selected a Men's POLO shirt of a brand in spring 2022 for green degree evaluation, as shown in table 5. This shirt is positioned by the brand as sustainable clothing; thereby, if this shirt achieves the grade of quasi-green or above, it shows that the shirt is indeed sustainable clothing, and the accuracy of the evaluation index and its model is also verified.

We investigated the source of raw material, design detail, production equipment, process technology, workshop environment, storage cost, packaging, etc. of this shirt, then we invited 5 experts (3 teachers from Xi'an Polytechnic University with senior titles and 2 engineers from China Textile Planning Institute of Construction with senior titles) to rate this shirt. Then, we calculated the value of the whitening weight

Table 4

INDEX WEIGHTS AND THE CONSISTENCY CHECKING

Layer of first-class index		Layer of the second-class index			Layer of the third-class index			
Index	Weight	Index	Consistency checking	Weight	Index	Consistency checking	Weight	Synthetic weight
C_1	0.3364	C_{11}	λ=2, n=2 CI=CR=0	0.5565	C_{111}	λ=3.0059, n=3 CI=0.0030 CR=0.0051	0.2558	0.0479
					C_{112}		0.4214	0.0789
					C_{113}		0.3228	0.0604
		C_{12}		0.4435	C_{121}	λ=3.0363, n=3 CI=0.0181 CR=0.0313	0.1491	0.0222
					C_{122}		0.3965	0.0592
					C_{123}		0.4544	0.0678
C_2	0.0935	C_{21}	λ=2, n=2 CI=CR=0	0.3318	C_{211}	λ=3.0046, n=3 CI=0.0023 CR=0.0039	0.3717	0.0115
					C_{212}		0.3212	0.0100
					C_{213}		0.3071	0.0095
		C_{22}		0.6682	C_{221}	λ=2, n=2 CI=CR=0	0.7444	0.0465
					C_{222}		0.2556	0.0160
C_3	0.3689	C_{31}	λ=2, n=2 CI=CR=0	0.5929	C_{311}	λ=3.0029, n=3 CI=0.0014 CR=0.0025	0.3598	0.0787
					C_{312}		0.3295	0.0721
					C_{313}		0.3107	0.0679
		C_{32}		0.4071	C_{321}	λ=2, n=2 CI=CR=0	0.4806	0.0722
					C_{322}		0.5194	0.0780
C_4	0.1556	C_{41}	λ=3.0162, n=3 CI=0.0081 CR=0.0140	0.4174	C_{411}	λ=3.0228, n=3 CI=0.0114 CR=0.0197	0.4612	0.0300
					C_{412}		0.3078	0.0200
					C_{413}		0.2310	0.0150
		C_{42}		0.2578	C_{421}	λ=2, n=2 CI=CR=0	0.6950	0.0279
					C_{422}		0.3050	0.0122
		C_{43}		0.3248	C_{431}	λ=2, n=2 CI=CR=0	0.5345	0.0270
					C_{432}		0.4655	0.0235
C_5	0.0456	C_{51}	λ=2, n=2 CI=CR=0	0.6738	C_{511}	λ=2, n=2 CI=CR=0	0.4712	0.0145
					C_{512}		0.5288	0.0162
		C_{52}		0.3262	C_{521}	λ=2, n=2 CI=CR=0	0.4036	0.0060
					C_{522}		0.5964	0.0089

Table 5

PRODUCT INFORMATION FOR THE MEN'S POLO SHIRT			
			Type: Men's POLO shirt Standard: GB/T 14272-2011 Safety category: GB18401-2010 Type B Grade: First class

function for each evaluation index for each of the 5 grey classes separately according to figure 2, then, we established the grey evaluation weight matrix for each index according to equation 12, then, we performed the comprehensive evaluation of C_{11}-C_{52} and then we calculated the grey evaluation weight matrix Q_{C1}-Q_{C5} for C_1-C_5 according to the grey evaluation weight matrix, as follows.

$$Q_{C_1} = \begin{bmatrix} 0.2820 & 0.3153 & 0.2508 & 0.1176 & 0.0343 \\ 0.2149 & 0.2989 & 0.2789 & 0.1555 & 0.0517 \end{bmatrix}$$

$$Q_{C_2} = \begin{bmatrix} 0.2140 & 0.2844 & 0.2739 & 0.1629 & 0.0648 \\ 0.1313 & 0.2456 & 0.3141 & 0.2117 & 0.0974 \end{bmatrix}$$

$$Q_{C_3} = \begin{bmatrix} 0.3279 & 0.3176 & 0.2334 & 0.0931 & 0.0281 \\ 0.2564 & 0.3333 & 0.2564 & 0.1282 & 0.0256 \end{bmatrix}$$

$$Q_{C_4} = \begin{bmatrix} 0.3078 & 0.3093 & 0.2426 & 0.1050 & 0.0356 \\ 0.3053 & 0.3226 & 0.2407 & 0.1042 & 0.0273 \\ 0.2863 & 0.2919 & 0.2541 & 0.1190 & 0.0487 \end{bmatrix}$$

$$Q_{C_5} = \begin{bmatrix} 0.2972 & 0.3243 & 0.2433 & 0.1082 & 0.0270 \\ 0.3157 & 0.3203 & 0.2373 & 0.0991 & 0.0276 \end{bmatrix}$$

Based on the above results, we calculated the comprehensive evaluation result G_1-G_5 according to **equation 13**, which can be used to calculate the grey evaluation weight matrix Q, as follows.

$$Q = \begin{bmatrix} 0.25220.30800.26330.13440.0420 \\ 0.15870.25840.30080.19550.0866 \\ 0.29880.32400.24280.10740.0271 \\ 0.30020.30690.24590.10930.0377 \\ 0.30320.32300.24130.10520.0272 \end{bmatrix}$$

Based on the grey evaluation weight matrix Q and equation 14, we calculated the final comprehensive evaluation result G, G = [0.2704, 0.3098, 0.2555, 0.1249, 0.0393].

Based on the final comprehensive evaluation result G and the maximum membership degree principle, we judged that this shirt was evaluated as a 'green' grade, and we calculated the comprehensive evaluation score of this shirt is 3.6470 according to the valued vector V.

DISCUSSION

Contribution and limitation

According to the evaluation results, the Men's POLO shirt was rated as 'Green' grade, indicating a high level of sustainability that aligns with its actual properties. This outcome validates the clothing green degree evaluation framework, demonstrating its critical role in determining results and its applicability for evaluating the environmental sustainability of apparel. Furthermore, clothing is different from general textile products, and there is a lack of related works on sustainable evaluation based on clothing characteristics, which also provides us with a certain research opportunity. Thereby, we introduced the green degree evaluation, whose core evaluation dimensions are environmental friendliness, technological advancement, and economic rationality. Based on this theory, the clothing green degree evaluation system and evaluation model are established, which consists of green material, green design, green production, green quality, and green packaging to evaluate the environmental sustainability of clothing.

This evaluation framework provides a robust measure of the environmental sustainability of clothing, offering a novel approach for related research, moreover, the effective application of the TFN-AHP and grey clustering methods was instrumental in its development.

A primary limitation of this study is that the proposed framework is tailored for common clothing; it does not encompass the environmental sustainability evaluation of special-purpose clothing. Evaluating such products would necessitate the development of a dedicated framework.

The clothing green degree evaluation system aims to reflect the product characteristics of clothing and aims to distinguish it from general textile products, which is also the highlight of our research. Thereby, from the perspective of clothing products, using the index in our work to evaluate the clothing green degree can minimise the deviation of evaluation results and facilitate practical operation.

Practical suggestion

Among the 5 evaluation dimensions of the clothing green degree evaluation system, green production and green material have a higher weight, accounting for 36.89% and 33.64% respectively. Although our research is based on China and represents the views of some experts in the field of textile and fashion in China, achieving sustainable production is still a problem that needs to be solved in the textile and clothing industry of most countries in the world [2, 42]. Both efficient and clean production conditions and the sustainability of raw materials represent the sustainable production and R&D level of the clothing enterprise. Thereby, the improvement of the clothing sustainability still requires the clothing enterprise to use advanced equipment, develop environmental friendly technology, simplify manufacturing processes, and make effective use of waste materials, which can effectively reduce the emission of waste gas, wastewater and other pollutants during the production of clothing, and allocate these environmental benefits to each piece of clothing, which can significantly improve the sustainable level of clothing. Although improving the level of green production will cause significant financial pressure on textile and garment enterprises in the early stage, it also means higher production efficiency, lower production costs, a cleaner production environment and environmentally friendly products in the future. At present, relevant government departments and financial institutions are vigorously promoting green finance, and it is suggested that textile and apparel enterprises flexibly combine different green financial products according to their own needs to finance in stages, gradually improving the level of green production. In addition, with the awakening of sustainable consumption awareness, in the future, clothing with a high green degree will be favoured by consumers, and enterprises with higher levels of green production will have a broader market.

CONCLUSION

This study develops the clothing green degree evaluation system based on the concept of green degree evaluation and employs the TFN-AHP and grey clustering method to develop a corresponding evaluation model. The main conclusions are summarised as follows:

- The green degree evaluation serves as a practical tool for evaluating the environmental sustainability of clothing. Based on the evaluation principles of environmental friendliness, technological advancement and economic rationality, the clothing green degree evaluation system, established from 5 dimensions of green materials, green design, green production, green quality, and green packaging, can comprehensively describe the environmental sustainability of clothing.
- TFN-AHP and grey clustering methods are well-suited for application within the clothing green degree evaluation model. While the proposed clothing green degree evaluation framework demonstrates practical value, the refinement of evaluation criteria and further improvement of the evaluation methodology warrant additional investigation.
- Among the 5 first-class indexes of the clothing green degree evaluation system, green production and green material have a greater weight on green degree, accounting for 36.89% and 33.64% respectively, followed by green quality, green design, and green packaging. The clothing R&D plan can be formulated according to the indexes with larger weights in this evaluation system, to guide production and product classification.

ACKNOLEDGEMENTS

This research was funded by the basic research fund provided by the China Textile Planning Institute of Construction.

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Application of *Olea Europea L.* barks as eco-friendly adsorbent material: mechanism studies and efficiency evaluation

DOI: 10.35530/IT.076.05.2024115

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HIND ALGAMDY

ABSTRACT – REZUMAT

Application of *Olea Europea L.* barks as eco-friendly adsorbent material: mechanism studies and efficiency evaluation

The olive tree (Olea europaea L.) holds significant nutritional importance due to the therapeutic properties of virgin olive oil. Consequently, there has been a growing interest in exploring novel applications for the agricultural and industrial waste generated by the olive industry. This study investigates the performance of bark material derived from olive trees in removing dyes from textile wastewater. The study elucidates the influence of pH, ionic strength, adsorbent concentration, and chemical structure on the adsorption process. For direct dye removal, a basic pH value demonstrated superior depollution results. However, an acidic medium was necessary to achieve complete decolourisation of reactive dyes. Notably, the Olea europaea L. bark exhibited remarkable decolourisation and COD abatement capacities, surpassing 75% and 65%, respectively.

The experimental data were further validated by comparing them with classical calculations obtained using activated carbon. A relatively high level of agreement was observed, suggesting that bio-sorption using olive bark presents a promising alternative to the utilisation of expensive adsorbent materials.

***Keywords**: Olea europea L., olive bark, biomaterial, dye uptake, reactive dye, direct dye*

Aplicarea scoarței de *Olea Europea L.* ca material adsorbant ecologic: studii privind mecanismul și evaluarea eficienței

Măslinul (Olea europaea L.) are o importanță nutrițională semnificativă datorită proprietăților terapeutice ale uleiului de măsline virgin. În consecință, a crescut interesul pentru explorarea de noi aplicații pentru deșeurile agricole și industriale generate de industria măslinelor. Acest studiu investighează performanța materialului din scoarță provenit de la măslini în eliminarea coloranților din apele uzate rezultate din industria textilă. Studiul elucidează influența pH-ului, a puterii ionice, a concentrației adsorbantului și a structurii chimice asupra procesului de adsorbție. Pentru îndepărtarea directă a coloranților, o valoare bazică a pH-ului a demonstrat rezultate superioare de depoluare. Cu toate acestea, a fost necesar un mediu acid pentru a obține decolorarea completă a coloranților reactivi. În mod remarcabil, scoarța de Olea europaea L. a prezentat capacități remarcabile de decolorare și reducere a COD, depășind 75% și, respectiv, 65%. Datele experimentale au fost validate în continuare prin compararea lor cu calculele clasice obținute folosind cărbune activ. S-a observat un nivel relativ ridicat de concordanță, ceea ce sugerează că biosorbția folosind scoarță de măslin reprezintă o alternativă promițătoare la utilizarea materialelor adsorbante costisitoare.

***Cuvinte-cheie:** Olea europea L., scoarță de măslin, biomaterial, absorbție de colorant, colorant reactiv, colorant direct*

INTRODUCTION

The textile dyeing industry utilises substantial quantities of fresh water and generates substantial volumes of contaminated wastewater that contain residual colour, elevated salt concentrations, and high Biological Oxygen Demand (BOD) or Chemical Oxygen Demand (COD) values [1–6]. It is reported that there are over 100,000 commercially available dyes, with a production output exceeding 7×105 metric tons annually. Consequently, 280,000 tons of textile dyes are discharged globally each year [7].

Although cotton is an environmentally friendly and sustainable textile, it contributes significantly to environmental emissions. Cotton factories generate substantial amounts of wastewater daily, which contains organic dyes such as Direct and Reactive dyes, along with other contaminants exhibiting high levels of colour and total organic content [8].

Reactive dyes are typically azo-based chromophores combined with various reactive groups, including vinyl sulfone, chlorotriazine, trichloropyrimidine, and difluorochloropyrimidine [8, 9]. Direct dyes are predominantly azoic and also contain vinyl sulfone compounds. Direct and Reactive dyes are widely used in cotton dyeing factories due to their favourable characteristics, such as bright colours, simple application techniques with minimal energy consumption, and excellent fastness to washing and rubbing, particularly for reactive dyes [10–12]. However, these dyes pose significant environmental challenges. They are scarcely eliminated under standard aerobic conditions and can be transformed into carcinogenic aromatic by-products. Furthermore, chemical coagulation is ineffective in removing reactive and direct dyes due to their high solubility in water [13–15]. Consequently, the rate of reactive dye discharge is low, and its hydrolysis cannot be avoided.

Consequently, highly coloured effluents that do not meet environmental standards and cannot be reused are discharged daily.

Adsorption has been extensively used in industrial processes for the separation and purification of coloured industrial effluents. A low number of applications has been noted for the case of textile effluents, where treatment is mostly based on coagulation and flocculation, followed by aerobic degradation techniques [16–20]. The implementation of biological treatments has inherent drawbacks of being technically unfeasible because of the non-biodegradability of such organic and recalcitrant compounds.

Adsorption is a more promising option for non-biodegradable organics. This technique requires less land area (half or a quarter of what is required in a biological system), gives lower sensitivity to diurnal variation, is not affected by toxic chemicals and ensures greater flexibility in the design and operation and superior removal of organic contaminants [21–24].

The activated carbon adsorbent is now considered to be the best prospect for eliminating residual colour. Despite its effectiveness and versatility, this adsorbent is prohibitively expensive and difficult to regenerate after use [25]. To be more attractive, there is a growing interest in using other low-cost adsorbents. Being an inexpensive and non-abundant adsorbent, some lower-cost bio-adsorption compounds have been proposed [9]. Natural compounds, including agricultural by-products such as nut shells, wood, bone, and peat, processed into activated carbons, have also been proposed [26–29]. For example, sawdust, which is an abundant and low-cost by-product, has been used as a precursor for the preparation of activated carbons and successfully explored as an adsorbent for the removal of dyes from wastewater [30]. Some other by-products, either synthetic but non-expensive, were also employed for the decolourisation of textile wastewater. The β-cyclodextrin grafted nonwoven polypropylene (PP) was effective for the removal of cationic dyes [31]. N6-PPI nanofiber also showed its effectiveness and rapidity in removing anionic dyes from aqueous media [32, 33].

Olive (*Olea europaea L.*) has been cultivated in the Mediterranean region since ancient times. Olive trees are extremely long-lived (up to 1000 years). The consumption of Virgin Olive Oil is increasing worldwide due to its recognised nutritional benefits [34]. A young olive tree has smooth grey bark, but with age, the bark becomes gnarled and gradually disintegrates into rectangular pieces. It is believed that cuticular photosynthesis plays a vital role in recapturing respiratory CO_2 and, thus, contributes to internal CO_2 recycling in stems and overall annual carbon balance. Dry barks result from the photosynthesis of sun-exposed corticular [35]. The resulting biomaterial is considered waste and left without any valorisation. Therefore, such wastes are low-cost, available in abundance, and could be suitable for the decolourisation of cotton effluent thanks to their mainly cellulosic composition. So far, no studies have been reported on the mechanisms of adsorption.

To gain a comprehensive understanding of the potential applicability of olive tree bark, we have conducted a meticulous study on its absorbency capacity for the removal of direct and reactive dyes from synthetic dyeing wastewater. The effluent, which contains residual dyes and their associated auxiliaries, is substituted for actual dyeing wastewater from the textile industry to replicate comparable conditions. The impact of pH, chemical structure, and dye concentration was investigated to optimise dye removal, maximise adsorption capacity, and elucidate the underlying adsorption mechanism. Additionally, the adsorption process with activated carbon was examined for both tested dyes to provide comparative data.

EXPERIMENTAL

Chemicals

Commercial Reactive and Direct dyes were supplied from the Dyeing Factory and used directly for adsorption experiments without further purification. Chemical structures are presented in figure 1.

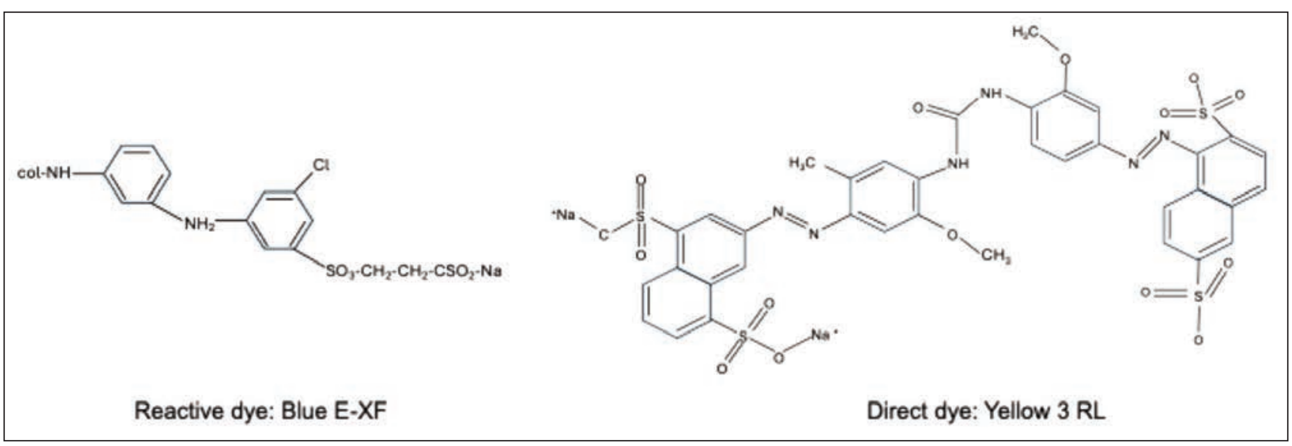

Fig. 1. Chemical structures of the tested dyes

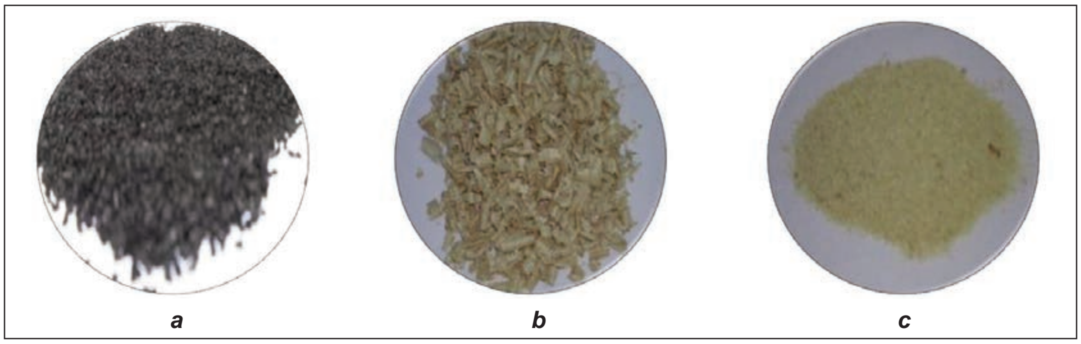

Fig. 2. Adsorbent materials: *a* – activated carbon; *b* – olive barks slices; *c* – olive barks powder after preparation

Bioadsorbents preparation

Olive Barks were dried at 110°C for 12 hours, powdered and sieved to a particle size range of 40–60 meshes, or maintained as slices and then stored in sealed containers for experimentation. Activated carbon granulates were also used to make the comparison (figure 2).

Method

Batch absorption study

Adsorption experiments were determined by shaking a 500 ml vial with 1% (w/v) of adsorbent material collected from olive trees and previously treated with caustic soda (1M of NaOH for 2 hours). The dye concentration varied from 5 to 40 mg/l. Experiments were also conducted at different pH levels (from 2 to 10). The pH adjustments were done with 1.0 M HCl and 1.0 M NaOH.

After shaking at 90 rpm for 120 min, the samples were taken, and the solution was separated from the precipitate by centrifugation at a speed of 4000 rpm for 5 min. The remaining concentrations of dye were determined spectrophotometrically by monitoring the absorbance at λ_{max}. The effects of the chemical structure of pollutants were also studied.

Evaluation of the adsorption efficiency

The surface images of the used adsorbents were captured by scanning electron microscopy (SEM). The SEM used was a Hitachi S-2360N.

The amount of dye adsorbed per unit of mass of adsorbent at equilibrium conditions Q_e (mg/g) was calculated as follows (equation 1):

$$Q_e = \frac{C_0 - C_t}{m} \times V \qquad (1)$$

where C_0 (mg·l^{-1}) is the initial concentration of dye, C_t (mg·l^{-1}) is the residual dye concentration in solution at time *t*, *V* (l) is the volume of solution and *m* (g) is the mass of the adsorbent material.

The measurement of each sample was replicated twice and averaged. To calculate the dye adsorption efficiency by Activated carbon and Bark powder, the following equation 2 was used.

$$Adsorption = \frac{C_0 - C_t}{C_0} \times 100 \qquad (2)$$

Evaluation of the depollution efficiency

pH measurements were performed with a pH meter (Model 2906, Jenway Ltd., UK). Chemical Oxygen Demand tests were performed by oxidation with dichromate according to Standard Methods of Examination of Water and Wastewater [36, 37].

Absorbance measurements were carried out with a UV-visible spectrophotometer (Shimadzu UV-256), recording the spectra over the 190–900 nm range. Direct and reactive dyes with different absorbance peaks were presented in the studied wastewater. The maximum absorbance of the real wastewater is nonstable. So, before each experiment, UV-Vis spectra of dye solutions were plotted to establish their maximum.

The disappearance of the absorbance peaks of the treated solutions was monitored, and the colour removal ratio was calculated as follows (equation 3):

$$abs\,(\%) = \frac{abs\,(\lambda_{max})_{ini} - abs\,(\lambda_{max})_t}{abs\,(\lambda_{max})_{ini}} \times 100 \qquad (3)$$

where $abs\,(\lambda_{max})_{ini}$ is the average value of absorbency at λ_{max} of the concerned wastewater, and $abs\,(\lambda_{max})_t$ is the value obtained at time *t*.

Chemical Oxygen Demand tests were performed according to the Standard Methods of Examination of Water and Wastewater [38]. The percentage of dye mineralisation was evaluated from the measurement of COD removal using this formula (equation 4):

$$abs\,(\%) = \frac{COD_i - COD_t}{COD_i} \times 100 \qquad (4)$$

where COD_i corresponds to the initial value and COD_t is the value obtained at time *t*.

RESULTS AND DISCUSSIONS

Physical character of adsorbents

The physical character of the tested adsorbents is detailed in table 1.

With a relatively similar physical property, the topography of each adsorbent was also investigated using a scanning electron microscope. Figure 3 shows the SEM images of microstructures of the *Olea europaea L.* Bark powder compared to the Activated carbon structure under different magnifications. Images show that the surface of activated carbon is fairly

Table 1

PHYSICAL PROPERTIES OF OLIVE BARKS AND ACTIVATED CARBON GRANULAR		
Properties	**Olive barks**	**Activated carbon**
Bulk density (kg/m^3)	1650	2000
BET surface Area (m^2/g)	479	698
Moisture (%)	8	4

smooth with few cracks and voids. The SEM of the Bark powder has an extensive external surface with quite irregular cavities and pores in terms of shape and length. The high porosity observed on the external surface of Bark powder can be attributed to the swelling step with caustic soda of this material, mainly cellulosic. High porosity was also noted for activated carbon.

This porosity results from the evaporation of the chemical reagent (H_3PO_4) during the preparation of the activated carbon [35]. The microstructure of each adsorbent has an important role in defining further the adsorption capacity.

Adsorption evolution experiments

For the adsorption study, two dyes (Direct and Reactive) and two adsorbent materials (Activated carbon and Olive tree bark) were considered. Initial experimental conditions were 120 min of absorbance duration, 10 mg/l of Dye, pH 6 and ambient temperature. At the selected conditions, the absorbance kinetics are described in figure 4.

In each studied case, the results demonstrated the feasibility of achieving a substantial colour removal value through the utilisation of Activated carbon or Olive bark. Notably, the evolution of absorbance curves revealed two distinct zones. The initial zone exhibited a rapid decline in absorbance, attributed to the enhanced availability of vacuums and active sites on the adsorbent material.

Experimental results presented in figure 4 also showed that a good degree of colour removal might be reached using the bioadsorbent. High removal rates (over 70%) were achieved using Activated carbon for Direct and Reactive dyes. Using *Olea europaea L.* barks, decolourisation was similar for direct dyes, but lower performance was mentioned with the Reactive dye. Side experiments showed that this performance could be improved using massive dosages of adsorbent material.

Study of the experimental effect of pH, dye type and concentration

Effect of initial pH on dye adsorption

pH of the medium defines the surface charge of the adsorbent, which is related to the ionisation degree of the adsorbate. The relationship between the initial solution pH and dye removal is illustrated in figure 5. The experiments carried out at different pH values showed that there is a progressive increase in the capacity of removal of Direct dye over the entire pH range of 2 to 10. The interaction between dye and Olive bark powder is becoming stronger at higher pH values. Better results were reached with pH 8 and 10. However, at pH 10 and after 20 min of adsorption, the attached dye molecules showed a slight disturbance, which can be related to the swelling evolution of the introduced Olive barks in the basic medium. In fact, at the beginning of the process, the adsorbed dye molecules were attached to the surface by physical Van Der Waals bonds. By progressive swelling onto Olive tree barks, two simultaneous and antagonistic phenomena can take place:

- The absorbance of Direct dye is due to its affinity for cellulosic material.
- Physical repulsion between the nearest dye molecules and the surface of the cellulosic material due to its progressive swelling at basic pH.

After 30 minutes of the absorbency evolution, the adsorbed dye molecules formed stronger bonds. Indeed, the cellulosic adsorbent became deprotonated at this pH value. So, the electrostatic interaction between dye and adsorbent developed the main force controlling the absorbance. Figure 5 shows that the effect of pH on the amount of dye adsorbed was different for the Reactive dye. Better results were obtained in an acidic medium. When the solution pH was less than 6, the nitrogen groups, especially those involved in aromatic systems of the tested Reactive dye, became positively charged by protonation. This finding is in accordance with previous studies [39]. Subsequently, the attraction between reactive dyes (positively charged in an acidic medium) and Olive bark

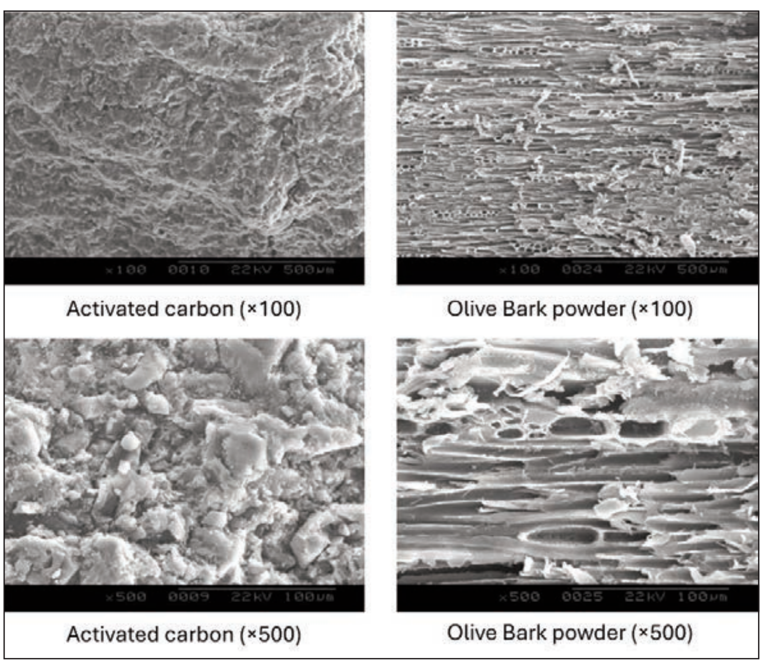

Fig. 3. SEM images of Activated carbon (at the left) and Olive Bark powder (at the right) under a magnification of ×100 and ×500

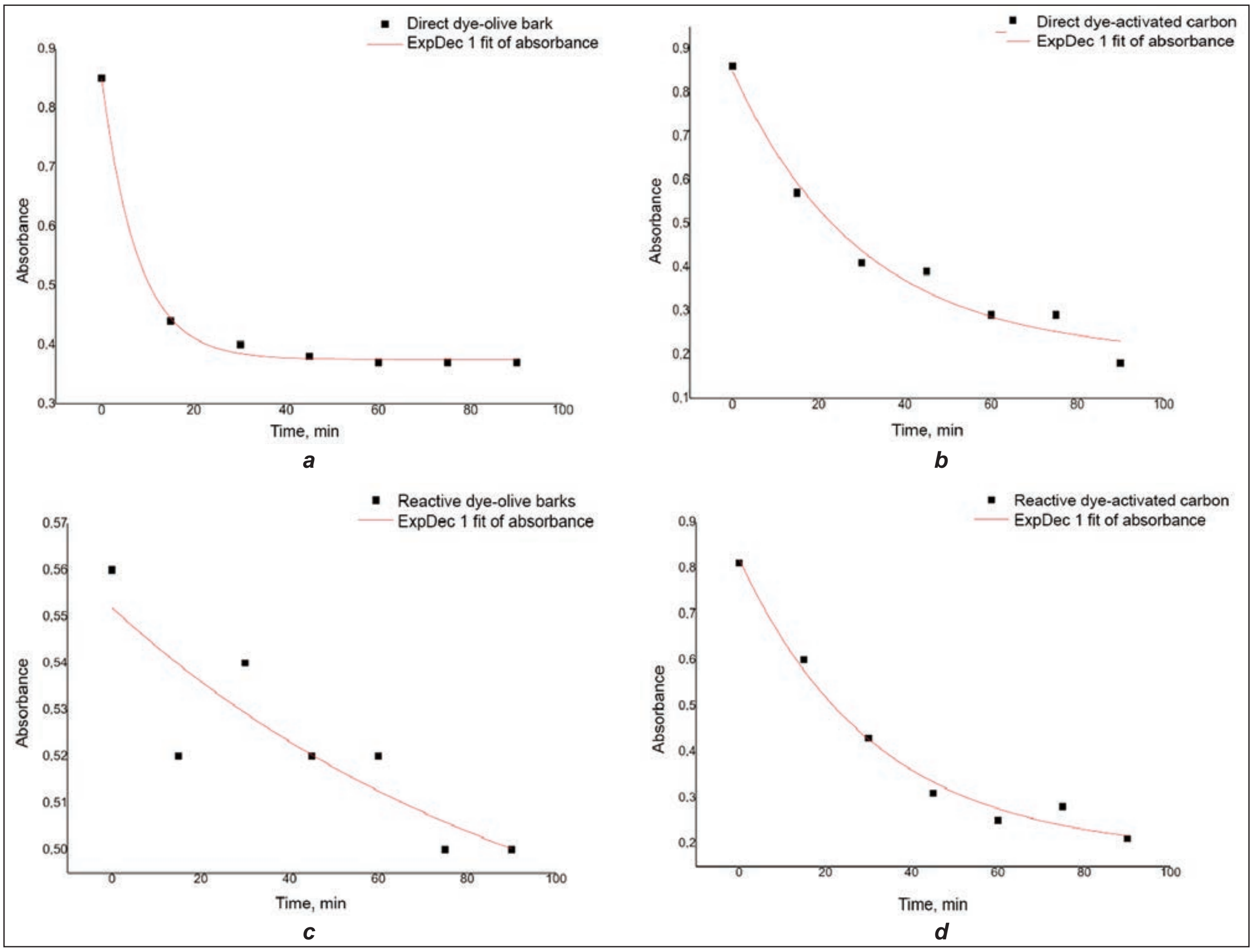

Fig. 4. Absorbance kinetics: *a* – Direct dye with Olive bark; *b* – Direct dye with Activated carbon; *c* – Reactive dye with Olive bark; *d* – Reactive dye with Activated carbon

increases, resulting in a slight increase in the amount of dye adsorbed.

The low dye removal at a highly basic solution was related to the strong repulsion interaction between the negatively charged adsorbent and the deprotonated reactive dye molecules. At the same time, hydroxide ion concentration increased with the incremental solution pH, and it could be adsorbed preferentially on the surface of the activated carbon.

In turn, variations in the pH value with Activated carbon did not evoke such a considerable increase in the adsorption affinity. Elsewhere, the adsorbent quantity was not explored to confirm its effect on the adsorption affinity.

Effect of dye concentration on the amount of dye adsorbed

Adsorption of dye on the adsorbent surface was determined for different concentrations of Direct and

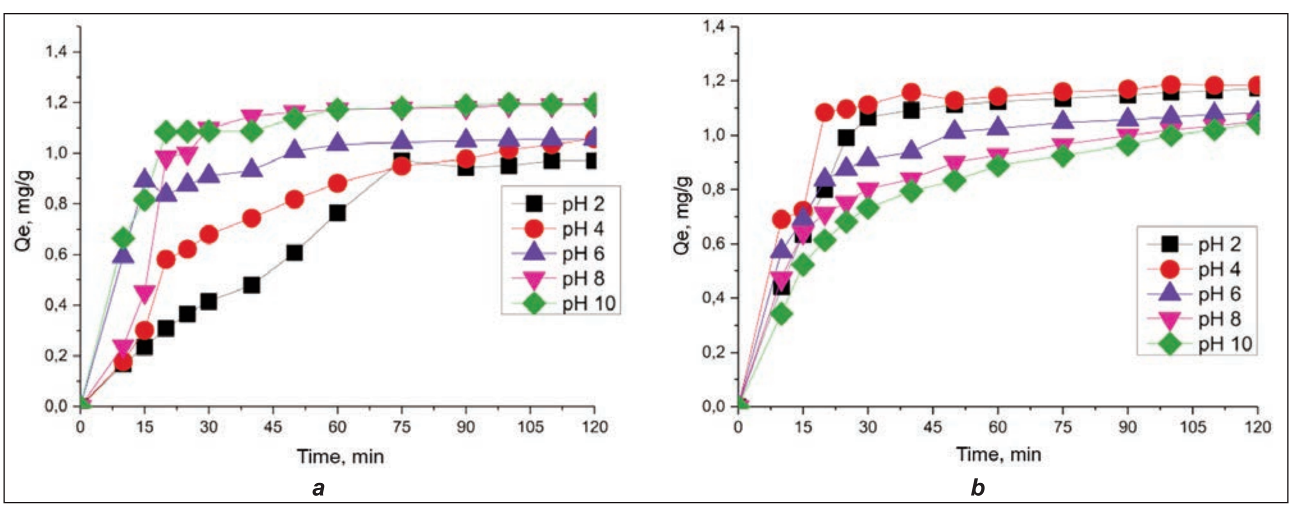

Fig. 5. Effect of pH on the dye uptake kinetics: *a* – Direct dye; *b* – Reactive dye

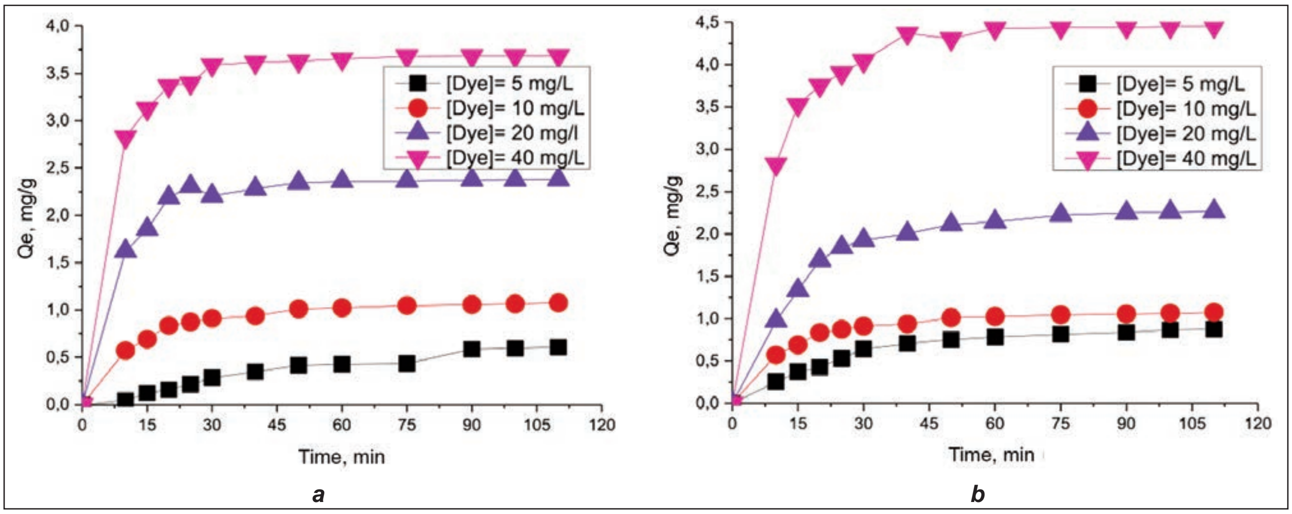

Fig. 6. Dye uptake kinetics as a function of dye concentration: *a* – Direct dye; *b* – Reactive dye

Reactive dyes while maintaining the same quantities of adsorbent. Results are presented in figure 6.

The effect of dye concentration was also investigated in the case of the Direct dye treated with Olive bark powder. Initially, during the adsorption process, the equilibrium value of the amount adsorbed was observed to increase with the increasing dye concentration. For dye concentrations exceeding 30 mg/l, the equilibrium value of the amount adsorbed reached its maximum within a few minutes. This phenomenon can be attributed to the rapid decrease in the availability of surface-active sites due to the increased dose and accumulation of the adsorbent.

Consequently, the amount of the adsorbed dye exhibited exponential variation at these concentrations.

On the other hand, the contact time reached saturation within 60 minutes for all tested concentrations. Subsequently, the equilibrium value of the amount of adsorbed exhibited a smooth and continuous curve, indicating the formation of a monolayer coverage of the adsorbate on the outer surface of the adsorbent. This linearity at higher contact times confirmed the absence of desorption, which can also be attributed to the strong crosslinking between the dye and the adsorbents. Olive bark possesses a cellulosic composition. It is well-known that polysaccharides can establish physical and chemical interactions with a diverse range of molecules [40]. This property enhances the degree of crosslinking and effectively prevents desorption even during extended periods of adsorption.

The reactive dye concentration also exhibited a significant influence on its removal from the aqueous phase. This trend was attributed to the high driving force for mass transfer at a high initial dye concentration. Furthermore, for higher dye concentrations, a greater number of dye molecules surrounded the active sites of the adsorbent, leading to more efficient adsorption. Consequently, dye uptake increased with the increase in the initial dye concentration.

UV-Vis spectra changes

The spectrum of Reactive dye evolution in the visible region exhibits a main peak with a maximum at 610 nm. The decrease of the absorption peak at λ_{max} in figure 7 indicated a rapid adsorption of the dye in the first 15 min. The main absorbance peak disappeared within approximately 75 minutes. This result indicates that the colour removal by Olive bark powder is attributed to elimination without decomposition.

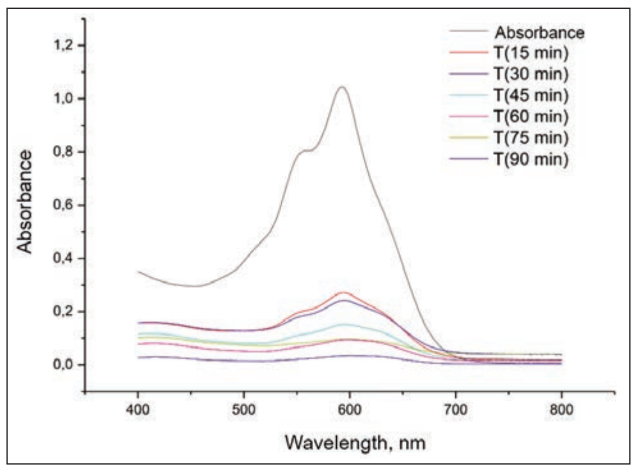

Fig. 7. UV-Vis evolution on Olive Bark support for Reactive dye

Adsorption experiments at optimal conditions showed that colour and COD removals of the direct dye were 87% and 70% respectively. As shown in table 2, Olive barks showed similar performance in terms of colour and COD removals, either for direct or reactive dye experiments. Absorbance measurements were also found to be in good accord with COD and colour results.

CONCLUSIONS

This research study investigated the potential of Olive Bark as an agro-waste and compared its performance with a commercial granular activated carbon (GAC) as a reference material in the adsorption

Table 2

DEPOLLUTION RESULTS EVALUATION WITH BIO-ADSORBENT VERSUS CONVENTIONAL ADSORBENT MATERIAL				
Parameter	**Direct Dye depollution results**		**Reactive Dye depollution results**	
	Activated carbon	**Olive Barks**	**Activated carbon**	**Olive Barks**
Colour removal (%)	87	83	86	75
COD removal (%)	73	70	77	69

and depollution of wastewater contaminated with reactive and direct dyes. The findings demonstrated the feasibility of utilising Olive Bark powder and slides as effective adsorbents for Vinyl Sulfone reactive dyes and azoic direct dyes. The efficacy of the adsorption process was found to be influenced by the chemical structure of the adsorbate, the amount of adsorbent applied, and the pH value of the solution. The results indicated that Olive Bark powder exhibited a rapid, efficient, and economical adsorption process compared to conventional methods. For direct dyes, the adsorption treatment resulted in a faster and complete decolourisation of the contaminated wastewater. Colour and Chemical Oxygen Demand (COD) reductions were approximately 83% and 70%, respectively. Similarly, 87% and 73% colour and COD removals were achieved using granules of activated carbon.

The improvement in depollution parameters observed for the direct dye sample was permitted, considering its high affinity for the cellulosic composition. Furthermore, the selected direct dye exhibited enhanced reactivity due to its superior global electric charge.

Consequently, a comprehensive analysis of the adsorption kinetics is imperative and necessitates a substantial number of experiments under varying conditions. Additionally, the study of the isotherm and kinetics of the adsorption of both dyes onto the proposed adsorbent should be undertaken.

ACKNOWLEDGMENT

The researchers would like to acknowledge Deanship of Scientific Research, Taif University for funding this work.

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Analysis of risk factors affecting occupational health and safety in textile firms in the framework of sustainability

DOI: 10.35530/IT.076.05.202512

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ABSTRACT – REZUMAT

Analysis of risk factors affecting occupational health and safety in textile firms in the framework of sustainability

Determining risk factors affecting occupational health and safety is crucial for textile firms today. Identifying these risks helps firms assess their current situation and take stronger steps toward the future. In this study, the DEMATEL method was used to calculate the interactions and weighting of risk factors based on expert opinions, enabling a realistic and applicable occupational health and safety management approach. The analysis revealed that management perceptions, education, and employee expectations have the greatest impact on other criteria, while chemical factors are the most influenced by them. The criteria that do not significantly affect any of the criteria are employee psychology, biological factors, and technology. Implementing occupational health and safety practices while considering these factors will lead to more effective and efficient outcomes. Textile firms must prioritise such analyses and recognise their role in enhancing overall efficiency. Furthermore, firms that successfully foster an occupational health and safety culture will be better positioned to achieve their sustainability goals. By integrating these practices into their operational strategies, textile firms can create a safer and healthier environment for employees, ensure production continuity, and contribute to long-term growth and stability. Ultimately, understanding risk factors is key to aligning occupational health and safety with broader sustainability objectives, benefiting both firms and their stakeholders.

Keywords: *textile industry, sustainability, occupational health and safety, DEMATEL method, risk factors*

Analiza factorilor de risc care afectează sănătatea și siguranța la locul de muncă în întreprinderile textile în contextul sustenabilității

Determinarea factorilor de risc care afectează sănătatea și siguranța la locul de muncă este crucială pentru firmele textile în prezent. Identificarea acestor riscuri ajută firmele să își evalueze situația actuală și să ia măsuri mai ferme pentru viitor. În acest studiu, metoda DEMATEL a fost utilizată pentru a calcula interacțiunile și ponderarea factorilor de risc pe baza opiniilor experților, permițând o abordare realistă și aplicabilă a managementului sănătății și siguranței la locul de muncă. Analiza a relevat că percepțiile conducerii, educația și așteptările angajaților au cel mai mare impact asupra altor criterii, în timp ce factorii chimici sunt cei mai influențați de acestea. Criteriile care nu afectează în mod semnificativ sunt psihologia angajaților, factorii biologici și tehnologia. Implementarea practicilor de sănătate și siguranță la locul de muncă, luând în considerare acești factori, va conduce la rezultate mai eficiente și mai eficace. Firmele textile trebuie să acorde prioritate acestor analize și să recunoască rolul lor în îmbunătățirea eficienței generale. În plus, firmele care promovează cu succes o cultură a sănătății și securității în muncă vor fi mai bine poziționate pentru a-și atinge obiectivele de sustenabilitate. Prin integrarea acestor practici în strategiile lor operaționale, firmele textile pot crea un mediu mai sigur și mai sănătos pentru angajați, pot asigura continuitatea producției și pot contribui la creșterea și stabilitatea pe termen lung. În cele din urmă, înțelegerea factorilor de risc este esențială pentru alinierea sănătății și securității în muncă la obiectivele mai largi de sustenabilitate, aducând beneficii atât firmelor, cât și părților interesate.

Cuvinte-cheie: *industria textilă, sustenabilitate, sănătate și securitate în muncă, metoda DEMATEL, factori de risc*

INTRODUCTION

There is a consensus that the world's resources are approaching the limit of depletion due to human activities [1]. From an environmental perspective, sustainability can only be achieved by enabling the renewal of world resources. From a social perspective, it can be expressed as meeting the needs of today's human generation without harming the needs of future generations [2, 3]. From an economic perspective, it can be defined as addressing sustainable development, turning to renewable resources in production and being responsible for the environmental impacts of production [3]. Considering the contributions of the textile sector to the income and employment created, it is of great importance for the sector to consider both the environmental, economic and social dimensions of sustainability. Sustainable production can only be achieved by adopting approaches that consider human health and safety while acting with environmental awareness.

Sustainability is vital for textile firms, especially in production activities. Beyond economic concerns, addressing labour issues, social needs, climate change, and pollution is crucial [4, 5]. Employee health and safety are key components of sustainability, as healthy workers in safe environments form the foundation of sustainable production [4]. Occupational accidents and illnesses can lower productivity and firm performance [6]. Protecting employees' physical health and minimising work-related injuries are essential for sustainability. Therefore, firms must prioritise occupational health and safety measures to ensure long-term success and resilience [7]. Occupational health refers to the employee's ability to work in peace, free from risks posed by working conditions and equipment [8]. Occupational safety involves technical, medical, and legal measures to reduce or eliminate dangers, preventing physical and mental harm [9, 10]. Together, occupational health and safety aim to protect employees from adverse conditions, ensure workplace safety, maintain production continuity, and boost efficiency [11]. Both sustainability and occupational health and safety share a common goal: protecting and improving society, the economy, and the environment [12].

Many factors impact occupational health and safety in textile firms, including hazardous chemicals, noise, dust-related diseases, risks from machine parts, and non-ergonomic working styles [13]. Occupational accidents and physical illnesses related to ergonomics are more common in this sector [14]. Risk factors such as dust, temperature, humidity, noise, and lighting present significant dangers in the textile industry [15]. To prevent accidents, it's essential to analyse and address the underlying risk factors and take necessary precautions [16].

Özdemir identified garment-cutting workshops as having the poorest occupational health and safety conditions among textile facilities, followed by finishing and plain dye workshops [17]. Efe and Efe, analysing workplace accident records in a textile firm, found that 37% of accidents stemmed from ergonomic risks, rising to 95% when combined with psychosocial factors, emphasising the need for employee-focused environments to mitigate accidents [18]. Şener and Gülmez highlighted the importance of creating comfortable working conditions to boost employee motivation and production in ready-made clothing firms [19]. Bozkurt and Değirmenci addressed hazards and risks in the textile industry, relevant legislation, and associated practices [20]. Efe demonstrated that occupational accidents and illnesses caused by psychosocial and chemical risks significantly affect production, quality, and performance in the textile sector [21]. Efe and Efe emphasised the management-employer perception criterion as a critical factor influencing risk dynamics, with biological factors being the least impactful but most influenced [22]. Tatlıcan and Çöğenli examined job satisfaction levels in a textile firm, showing how occupational health and safety measures improve productivity [23]. Ağırgan noted that strict inspections under Law No. 6331 have increased employees' knowledge and awareness of occupational health and safety through mandatory training [24]. Çat et al. analysed risk evaluation forms, identifying "machinery, work equipment, and hand tools" as the primary hazard criterion, with "moving-rotating parts" as the most critical sub-criterion [25].

Nowadays, the concept of sustainability is gaining importance in the textile and apparel sector. This sector can both directly and indirectly harm human health and the environment with its production processes and waste [26]. When literature is investigated, it is seen that there are studies analysing the risks of occupational accidents, but these studies do not examine the relationship between the field and sustainability. In this study, risk factors affecting occupational health and safety in the textile sector were examined first. Height risk factor criteria were determined because of literature research and expert opinions. Relationships and dependencies between the criteria were examined using the DEMATEL method, and dependent criteria weights were also calculated. Unlike other studies, the results were evaluated within the framework of sustainability. In this way, it was aimed to provide experts in the field of occupational health and safety with a different perspective and an effective perspective in evaluating risks.

MATERIAL AND METHOD

Data were collected using 8 risk factor criteria determined according to literature research [17, 22, 27] and expert opinions using face-to-face interview methods. A total of 40 experts were interviewed in 20 firms. Decision Making Trial and Evaluation Laboratory (DEMATEL) method, which is a multi-criteria decision-making method, was used in the analysis of the data. The DEMATEL method is expressed as studies aimed at developing a framework designed to identify the interdependent relationships of the elements in the mixed problem set and to prioritise the effects on each other within the scope of these determined relationships [28]. The steps of the DEMATEL method are as follows [29–31].

Step 1: Obtaining Direct Relationship Matrix: This matrix shows the relationships between the criteria in the pairwise comparisons made by experts. A scale consisting of the values 0, 1, 2, 3, 4, seen in table 1, is used for comparison [32].

In this step, experts are asked to answer the question "Level of influence between criteria?" according to the scale in table 1, and k $n{\times}n$ dimensional direct relationship matrices are created according to the

Table 1

COMPARISON SCALE FOR DEMATEL METHOD

Numerical value	Verbal expression
0	Ineffective
1	Low effective
2	Moderate effective
3	High effective
4	Very highly effective

evaluations of each expert. Each (*i, j*) element of this matrix shows the direct relationship from criterion *i* to criterion *j*. The average of the *k* direct relationship matrices obtained is taken using equation 1, and the average direct relationship matrix (*X*) is created using equation 2.

$$a_{ij} = \frac{1}{k}\Sigma_{n=1}^{k} x_{ij}^{n} \quad (1)$$

$$X = \begin{bmatrix} 0 & x_{11} & \cdots & x_{1n} \\ x_{21} & 0 & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1} & x_{n2} & \cdots & 0 \end{bmatrix} \quad (2)$$

Step 2: Obtaining the Normalised Direct Relationship Matrix: The normalised direct relationship matrix (*C*) is obtained using equations 3 and 4.

$$s = maks\ (maks\ \Sigma_{j=1}^{n} x_{ij}\, , maks\ \Sigma_{i=1}^{n} x_{ij}) \quad (3)$$

$$C = \frac{X}{S} \quad (4)$$

Step 3: Obtaining the Total Relationship Matrix: Equations 5 and 6 are used to obtain the total relationship matrix (*F*).

$$\lim_{k\to\infty} c + c^2 + c^3 + \ldots + c^k \quad (5)$$

$$F = C + C^2 + C^3 + \ldots + C^k = C\,(I - C)^{-1} \quad (6)$$

Step 4: Determining Affected and Affecting Criteria Groups: Using the (*F*) matrix obtained in the previous step; the sum of the i^{th} row (*Di*) of this matrix shows the sum of the effects (direct and indirect) sent by the ith criterion to other criteria. The column sum (*Rj*) represents the sum of the effects coming from other criteria for the same criterion.

RESULTS AND DISCUSSION

In the first step of the study, the risk factors causing work accidents were determined, and then the results obtained by applying the DEMATEL method were interpreted within the framework of sustainability.

Step 1: Determination of Criteria and Obtaining the Direct Relationship Matrix: The risk factor criteria determined according to the literature research and expert opinions are given below. The average direct relationship matrix (*X*) is given in table 2.

1. Management Perceptions: Management's approaches and practices regarding occupational health and safety policies.
2. Employee Psychology: Situations such as stress, motivation, absent-mindedness, and mobbing.
3. Education: The education, knowledge, skills and experience that the employee receives regarding the job he/she does.
4. Employee Expectations: The demands and needs of the employees.
5. Biological Factors: Factors such as bacteria, viruses, parasites, fungi, etc.
6. Technology: The use of technologies that take into account the safety of the employee.
7. Chemical Factors: Factors such as explosive, flammable, combustible, poisonous, suffocating, and irritating.
8. Physical Factors: Factors such as noise, lighting, thermal comfort, vibration, etc. In addition, the movements of the employee such as heavy lifting, reaching, pulling, and standing for long periods of time.

Table 2

DIRECT RELATIONSHIP MATRIX

X	K1	K2	K3	K4	K5	K6	K7	K8
K1	0	4	4	3	4	3	4	4
K2	2	0	2	2	3	2	1	2
K3	4	3	0	3	3	4	4	3
K4	3	4	4	0	2	3	4	3
K5	3	1	2	1	0	2	3	2
K6	3	3	2	1	3	0	3	2
K7	2	3	4	4	4	3	0	2
K8	2	3	2	4	3	3	4	0

Step 2: Obtaining the Normalised Direct Relationship Matrix: table 3 provides the normalised direct relationship matrix.

Step 3: Obtaining the Total Relationship Matrix: The total relationship matrix is given in table 4.

To interpret the findings, the average of all figures was taken, and the resulting value of 0.417 was determined as the threshold value. Values above this value were considered significant, while values below were considered insignificant.

It was determined that the criteria with the highest impact on other criteria were K1 management perceptions, K3 training and K4 employee expectations (table 4). Accidents can be prevented, and management must take responsibility for this. What is important in occupational health and safety is not individual action but collective action in accordance with the

Table 3

NORMALIZED DIRECT RELATIONSHIP MATRIX

C	K1	K2	K3	K4	K5	K6	K7	K8
K1	0	0.15385	0.1538	0.1154	0.15385	0.1154	0.15385	0.154
K2	0.0769	0	0.0769	0.0769	0.11538	0.0769	0.03846	0.077
K3	0.1538	0.11538	0	0.1154	0.11538	0.1538	0.15385	0.115
K4	0.1154	0.15385	0.1538	0	0.07692	0.1154	0.15385	0.115
K5	0.1154	0.03846	0.0769	0.0385	0	0.0769	0.11538	0.077
K6	0.1154	0.11538	0.0769	0.0385	0.11538	0	0.11538	0.077
K7	0.0769	0.11538	0.1538	0.1538	0.15385	0.1154	0	0.077
K8	0.0769	0.11538	0.0769	0.1538	0.11538	0.1154	0.15385	0

Table 4

TOTAL RELATIONSHIP MATRIX								
F	**K1**	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**
K1	0.3967	0.56284	0.5491	0.4812	0.59115	0.518	0.60127	0.509
K2	0.296	0.24007	0.3034	0.2801	0.35944	0.3038	0.303	0.283
K3	0.508	0.50954	0.3929	0.458	0.53465	0.5251	0.57505	0.457
K4	0.4632	0.52693	0.5129	0.3443	0.48702	0.4809	0.55715	0.443
K5	0.3364	0.29172	0.3176	0.2624	0.27094	0.3158	0.38029	0.292
K6	0.3696	0.39072	0.3506	0.2918	0.41343	0.2773	0.41552	0.323
K7	0.416	0.47102	0.4918	0.4549	0.52413	0.4598	0.40174	0.393
K8	0.3974	0.45785	0.4161	0.4453	0.47799	0.4438	0.51864	0.307

rules [24]. Therefore, the management's approaches and practices regarding occupational health and safety policies are very important. It has been shown in other studies that management perceptions are an important factor in the effectiveness of occupational health and safety practices. Occupational health and safety practices should not be seen as a financial loss, but as an element that will provide an advantage with its economic return in the competitive environment [22]. When occupational health and safety management is poor, corporate culture, safety culture and firm performance will be negatively affected by this situation [33]. The general level of education of employees in textile firms is low. This situation requires more intensive training activities to develop the occupational health and safety awareness of employees and to apply what is learned. Especially the high number of technical employees requires more technical education and occupational health and safety training [11]. All problems arising from the workplace environment can be solved through training [34]. It is a fact that this training will be more efficient with employees whose demands and needs are met. It is important to determine and eliminate all factors that have a negative effect on the health and safety of employees [22]. Regulations regarding occupational health and safety are included in the legislation, and the greatest responsibility for contributing to these regulations falls on employers, followed by employees [20].

The criterion most affected by management perceptions was determined as chemical factors (0.601), the criterion most affected by training was determined as chemical factors (0.575), and the criterion most affected by employee expectations was determined as chemical factors (0.557). The criteria that did not significantly affect any criteria were K2 employee psychology, K5 biological factors and K6 technology. The criteria with the highest impact were the chemical factors that were most affected. It is thought that this situation is because most of the firms from which the data was obtained are finishing firms. It is thought that physical factors may also come to the fore if the number of weaving and yarn firms is high. It has been concluded that for sustainable production, it would be a more realistic approach to conduct risk factor analyses with multi-criteria decision-making methods such as DEMATEL according to the type of production. The criteria most affected by other criteria were determined as K2 employee psychology, K5 biological factors and K6 technology (table 4). It was observed that the criterion that affects employee psychology the most is management perception (0.562), the criterion that affects biological factors the most is management perception (0.591), and the criterion that affects technology the most is education (0.525).

Step 4: Determining Affected and Affecting Criteria Groups.

Table 5 shows the degree of influence and being influenced by the criteria. Accordingly, the criterion that is most related to other criteria and has the highest effectiveness in the system is management perceptions, with a value of 7.39. This criterion is followed by chemical factors with a value of 7.36. However, the criterion that has the least relationship density with other criteria and has the lowest effectiveness in the system is the employee psychology criterion, with a value of 5.81.

Table 5

INFLUENCING AND BEING INFLUENCED BY CRITERIA				
	Di	**Rj**	**Di+Rj**	**Di-Rj**
K1	4.2089	3.18314	7.3921	1.0258
K2	2.3683	3.4507	5.819	–1.082
K3	3.96	3.33449	7.2945	0.6255
K4	3.8158	3.01821	6.834	0.7976
K5	2.4677	3.65876	6.1264	–1.191
K6	2.8321	3.32453	6.1566	–0.492
K7	3.6123	3.75266	7.365	–0.14
K8	3.4636	3.00631	6.4699	0.4573

When the D-R value is examined, the direction of the relationship of the criteria is obtained. It is seen that the degree of influence of the criteria with positive D-R values on other criteria is greater than the degree of being influenced (table 5). Accordingly, the criteria with a greater degree of influence than the degree of being influenced are K1 management perceptions (1.02>0), K4 employee expectations (0.79>0), K3 education (0.62>0), and K8 physical factors (0.45>0), respectively. The degree of being influenced by other criteria with negative D-R values is greater than the degree of influencing. Among these, the criteria with the highest degree of impact are K5 biological factors with a value of –1.19, K2 employee psychology with a value of –1.08, K6 technology with a value of –0.49, and K7 chemical factors with a value of –0.14.

CONCLUSIONS

In this study, risk factors affecting occupational health and safety in the textile sector were evaluated within the framework of sustainability. The data obtained using 8 criteria determined according to literature research and expert opinions were analysed using the DEMATEL method, one of the multi-criteria decision-making methods. As a result of the research, it was seen that the criteria that had the most impact on others were management perceptions, training and employee expectations. It was concluded that more efficient results would be obtained if occupational health and safety studies were carried out by taking these factors into consideration.

The most influential criterion in the system was identified as management perceptions. Ensuring the efficiency of occupational health and safety practices primarily depends on management perceptions. Management should not perceive these practices as a financial burden but as a competitive advantage and a necessity for a sustainable economy. A safe work environment increases employee motivation [35], enhances productivity, and reduces occupational health and safety-related costs, leading to economic gains [36]. Poor occupational health and safety management negatively impacts firm performance [37]. Other important factors in ensuring the efficiency of occupational health and safety practices have been determined as training and employee expectations. Training employees and efforts to eliminate situations such as fatigue and uninterrupted work will significantly affect the efficiency of the firm. When we look at the working and rest periods, we see that the rest periods are quite short in comparison. Considering these needs during planning will contribute to the physical and mental rest of the employee [18]. Improving working conditions, providing training to employees, improving strategic decisions based on employee health and safety, and conducting workplace controls to reduce risks contribute to sustainability [4]. For occupational health and safety practices in firms to be sustainable, improvements are required in some areas, such as minimising work accidents, reducing or eliminating occupational diseases, developing occupational health and safety management systems, and ensuring employee participation. Management focused on occupational health and safety results in sustainable development [38].

The criteria most influenced by management perceptions, education, and employee expectations were identified as chemical factors, likely because 16 of the 20 firms in the study are dyehouses. If the included firms were spinning or weaving mills, physical factors might have had a greater impact. For instance, an expert in a dyehouse may prioritise chemical risks, whereas an expert in a weaving mill might focus more on physical risks. Thus, analysing risk factors individually for each stage of textile production is essential for sustainable operations. The criteria most affected by other factors were found to be employee psychology, biological factors, and technology. The physical and mental integrity of employees, who are the most valuable assets in maintaining production and efficiency, must be protected.

Adopting, implementing, and sustaining an occupational health and safety management approach is key to achieving this. Fostering awareness of occupational health and safety and establishing a safe, healthy working environment reflects a firm's perspective on employee value. Firms should prioritise health and safety in all aspects, from equipment and infrastructure to processes, using technologies that enhance employee safety. When firms view occupational health and safety expenses not as costs but as investments, they achieve sustainability [39].

Cultivating a safety culture also enables firms to thrive in competitive environments [4]. Economic efficiency, which is one of the principles underlying sustainability that requires an integrated approach, is directly proportional to competitiveness.

Today, determining the risk factors affecting occupational health and safety has become a very important issue for textile firms. Determining the risks that negatively affect the health and safety of employees will enable firms to see their current situation and thus reach the future with more solid steps. Understanding risk factors is the first step in aligning occupational health and safety with sustainability goals. Risk factors and importance levels are different for each sector and field of work. Conducting occupational health and safety studies by considering the weights between the factors determined according to different areas of the textile industry will provide more efficient and effective results. Textile firms should attach importance to such analyses conducted to determine the risk factors affecting occupational health and safety and should see these analyses as a means of increasing efficiency. Sustainable production will only be possible in this way.

The fact that this research was conducted with 16 finishing and 4 weaving companies from the textile sector is one of the limitations of the research. Because the criteria and their weights may differ depending on the field of study. Therefore, the results obtained are general and are a guide for the studies to be conducted in this field. It is thought that in future studies, grouping field-based studies such as yarn, weaving, finishing, and determining and weighting criteria will make occupational health and safety practices much more effective. There are also some potential limitations of the DEMATEL method. The method is based on the opinions of the evaluator. The subjective perspectives of the evaluators may affect the accuracy of the method. Considering this situation, the evaluators were selected from experts who are knowledgeable in the field, and an objective evaluation was tried to be made. However, for larger-scale problems with many criteria and factors, the DEMATEL matrix can be quite complex and difficult to analyse. DEMATEL analyses relationships over a certain time. However, if there are dynamics that change over time in the system, the model needs to be updated. To overcome these limitations, it is considered that DEMATEL will be supported with artificial intelligence-supported analyses in future studies.

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Leadership for sustainability: A study of the impact of sustainable leadership on sustainable performance in the textile industry

DOI: 10.35530/IT.076.05.2024187

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ABSTRACT – REZUMAT

Leadership for sustainability: A study of the impact of sustainable leadership on sustainable performance in the textile industry

The textile industry is under increasing pressure to implement sustainable practices because of its labour-intensive operations and substantial environmental impact. This study looks into how sustainable leadership affects the economic, environmental, and social facets of sustainable performance for textile sector workers. Based on theories of organisational behaviour and sustainable leadership, the study looks at how leaders who put sustainability first affect social well-being, eco-friendly practices, and worker productivity. Through surveys and interviews with employees and leadership representatives, data was gathered from workers in different textile organisations in the Indian states of Punjab and Jammu & Kashmir union territory. The results show that sustainable leadership improves social performance by encouraging employee involvement and well-being, improves environmental performance through green practices, and increases economic performance by promoting productivity and innovation. The study emphasises how important leadership is in coordinating organisational objectives with sustainability, and it provides managers and policymakers with practical advice on how to include sustainable leadership frameworks for sustained performance enhancements in the textile sector.

Keywords: *sustainable leadership, sustainable performance, textile industry, economic performance, environmental performance, social performance*

Leadership pentru sustenabilitate: Un studiu al impactului leadership-ului sustenabil asupra performanței sustenabile în industria textilă

Industria textilă este supusă unei presiuni tot mai mari de a implementa practici sustenabile din cauza operațiilor sale care necesită multă forță de muncă și a impactului substanțial asupra mediului înconjurător. Acest studiu analizează modul în care leadership-ul sustenabil afectează aspectele economice, de mediu și sociale ale performanței sustenabile pentru angajații din sectorul textil. Bazat pe teorii ale comportamentului organizațional și ale leadershipului sustenabil, studiul analizează modul în care liderii care pun sustenabilitatea pe primul loc influențează bunăstarea socială, practicile ecologice și productivitatea angajaților. Prin intermediul sondajelor și interviurilor cu angajați și reprezentanți ai conducerii, au fost colectate date de la angajații din diferite organizații textile din statele indiene Punjab și Jammu & Kashmir. Rezultatele arată că leadership-ul sustenabil îmbunătățește performanța socială prin încurajarea implicării și bunăstării angajaților, îmbunătățește performanța de mediu prin practici ecologice și crește performanța economică prin promovarea productivității și inovării. Studiul subliniază cât de important este leadership-ul în coordonarea obiectivelor organizaționale cu sustenabilitatea și oferă managerilor și factorilor de decizie sfaturi practice despre cum să includă practici de leadership sustenabil, pentru îmbunătățiri sustenabile ale performanței în sectorul textil.

Cuvinte-cheie*: leadership sustenabil, performanță sustenabilă, industria textilă, performanță economică, performanță de mediu, performanță socială*

INTRODUCTION

The U.S. National Centres for Environmental Information estimates that in 2017, extreme weather and climate change combined to generate $306.2 billion in damages [1]. Environmental information reports from 2017 and 2018 also indicated that the intensity of climate change has increased, requiring the implementation of appropriate measures to address this concerning scenario [2]. The increasing amount of damage caused by climate change emphasises how urgently comprehensive solutions for mitigating and adapting to climate change are needed. The Intergovernmental Panel on Climate Change (IPCC) has emphasised how critical it is to cut greenhouse gas emissions to keep global warming to 1.5°C over pre-industrial levels. To meet this aim, all facets of society must act immediately and consistently (IPCC, 2018).

According to a recent research by Business for Social Responsibility (BSR) titled “The Future of

Sustainable Business", firms worldwide will be impacted by climate change [3]. Consequently, companies are under pressure to adapt their traditional business methods to tackle environmental issues. Companies are implementing sustainable practices more often to reduce their environmental impact in light of these developments. This entails making investments in waste reduction, energy efficiency improvements, and renewable energy sources. For instance, a lot of businesses are aiming high to reach net-zero carbon emissions, which calls for major adjustments to supply chains, operations, and product design.

Organisational leaders must keep a careful eye on local and global environmental situations in light of climate change. The United Nations developed the "Sustainable Development Goals" (SDGs) in response to the difficulties posed by climate change. These goals apply to organisations globally in all sectors. To address several global concerns, such as climate action, renewable energy, and sustainable economic growth, the SDGs offer a comprehensive framework. These objectives motivate organisations to implement policies that support social justice, economic growth, and environmental sustainability. Businesses may improve their resilience and competitiveness while simultaneously contributing to the fight against climate change by integrating the SDGs into their strategy.

Businesses must incorporate their social, economic, and environmental objectives into their operations in a way that protects resources for future generations to comply with sustainable development standards [4–10]. To do this, companies need to take a comprehensive strategy that strikes a balance between purpose and profit. This entails putting into action strategies that lessen their negative effects on the environment, like cutting back on waste, water use, and carbon emissions. For example, in an effort to lessen their dependency on fossil fuels and their environmental impact, many businesses are now investing in green technologies and renewable energy sources.

Leaders who can promote sustainable practices in their communities and organisations and stimulate economic growth are essential to sustainability [4]. According to this perspective, effective leadership can take the shape of sustainable leadership [5]. The goal of sustainable leadership is to increase an organisation's short- and long-term financial gains while also enhancing the lives of all stakeholders [6]. Integrating sustainability into the fundamental strategy and day-to-day operations of their organisations is a crucial responsibility of sustainable leaders. They make ethical decision-making, social responsibility, and environmental stewardship a priority, making sure that their companies run in a way that benefits both the environment and society. This strategy not only fits in with the objectives of global sustainability, but it also responds to the rising demands of workers, investors, and customers for ethical business practices.

The purpose of this article is to investigate the idea of sustainable leadership in relation to the textile sector. The data for the study were gathered from employees who worked in a variety of textile firms. The study looks at how sustainable leadership affects sustainable performance. The results show that sustainable leadership has a positive and significant effect on many different aspects of sustainable performance.

LITERATURE REVIEW

In this day and age, the human way of life is greatly impacted by technological progress, unpredictable weather, political unrest, and financial integration. This entire situation increases the pressure on the public, non-governmental organisations, and the government to prioritise environmental issues by incorporating sustainable elements [7, 8]. Sustainability has become a major concern for companies because it provides potential for development, long-term growth, competitive advantages, and financial viability, according to [9–11]. The leaders and top-level management of organisations are beginning to understand that addressing challenges related to sustainable development can improve the quality of their relationships with stakeholders and potentially help them stand out in the market [12–15]. Also, top-level managers in an organisation can play a central role among distinct stakeholders because they are responsible for acquiring and implementing essential resources, mounting suitable strategies, and pointing out the best way to accomplish sustainable development [16].

Rubel et al. [17] conducted a study that found that to improve sustainable performance, an organisation must be able to achieve valuable high performance in both financial and societal aspects. This can be accomplished through the use of an appropriate leadership style and the ability to instil a sense of responsibility, mutual learning, and norms to encourage employees to engage in voluntary environmental behaviour [18–20]. Dey et al. [21] and Moreno-Monsalve et al. [22] state that leadership style is important for achieving sustainable development. This is because employees act like frontline soldiers when they receive positive and fair vibes from their supervisors, playing an active role in developing and implementing the ideas and values of their leaders. This can have a significant impact on the performance of the organisation. According to the study by Xuecheng et al. [23], an organisation's sustainable performance may be described as the entire performance of the organisation for all stakeholders and in all dimensions. This definition is based on three factors: environmental performance, social performance, and economic performance. The current research is based on the idea that responsible leadership can be a catalyst and a booster of sustainable development within an organisation.

Sustainable leadership

According to Metcalf and Benn [4], leaders in the sustainability space must be able to create plans, regulations, and programs that advance sustainable organisational and social practices while fostering financial success. Sustainable leadership is highly valued by a wide range of stakeholders who see it as an essential component of the green economy [7]. According to Afsar et al. [7], sustainable leadership entails actions and methods that produce long-term benefits for a variety of stakeholders, such as the environment, society, and future generations. It gives businesses a competitive edge by providing chances for long-term success, innovation, continuous improvement, and a sustained competitive edge [6]. Sustainable leadership is essential for green initiatives and ecological performance at the organisational level because it fosters an environmental vision through cultural shifts and builds networks with various stakeholders to address climate change [8].

Furthermore, through reducing expenses and increasing prospective revenue, sustainable leadership improves organisational performance. Proactive in their approach, sustainable leaders build long-lasting relationships with internal and external stakeholders while also continuously monitoring the environment to track changes in the external market [9]. When it comes to internal operations, sustainable leaders develop a long-term strategy, give green projects top priority, deal with sustainability issues, put green management systems in place, and promote both gradual and radical innovation [7]. These leaders concentrate on attaining the best possible results for society and the environment from the outside [7]. Organisations benefit greatly from sustainable leadership in many ways, including the preservation of natural resources and the economic use of resources.

Sustainable performance

There's been a discernible change in how corporate organisations evaluate their performance lately. In the past, businesses evaluated their success using measurable criteria, including their market position, assets, and liabilities [10]. But the idea of sustainable performance has emerged as a result of a developing trend in which financial performance is being integrated with social and environmental factors [11]. This adjustment reflects a wider understanding that the capacity to produce favourable social and environmental results is just as important to long-term success as financial measures. Employing triple bottom line strategies, which strike a balance between profit and the environment and human well-being, helps companies better connect their objectives with global sustainability agendas. Stakeholder demands for accountability, openness, and moral behaviour have fuelled this growth in performance assessment, which in turn has improved business reputation and resilience in a world that is changing quickly.

The recognition of sustainability as a crucial business strategy that is strongly associated with corporate social responsibility (CSR) is growing. Sustainable methods frequently result in positive outcomes that benefit organisations, the environment, and society as a whole. Organisations obtain a major competitive advantage when they successfully incorporate ecological, environmental, and social performance into their operations [11, 12]. This all-encompassing strategy promotes innovation, resource efficiency, and long-term viability in addition to improving a company's reputation. Companies can better satisfy the increasing demands of stakeholders that place a high value on morality and responsibility by coordinating corporate objectives with sustainable practices. Additionally, by reducing the risks connected to social and environmental challenges, this alignment enables businesses to create more flexible and resilient business models. Businesses that implement these strategies are better positioned to prosper over the long run in a world where investors and customers are becoming more and more concerned about sustainability. According to Blind and Heß [13], organisations can attain sustained success by reducing the adverse effects of their activities on the environment and society.

To secure long-term success, organisations are being compelled more and more to embrace sustainable practices as a fundamental business strategy [14]. Currently, a diverse array of stakeholders is exerting pressure on companies to reconcile their environmental and social goals with their overarching business objectives, regarding these as essential components of their purpose [10]. This change represents a growing understanding that sustainability is a strategic necessity that can result in competitive advantage, increased brand loyalty, and stronger stakeholder relationships, rather than just a legal mandate or a moral obligation. Businesses can enhance their ability to meet market needs, draw in socially conscious investors and customers, and lower the dangers of social inequity and environmental degradation by integrating sustainability concepts into their operations. This all-encompassing approach to business strengthens an organisation's resilience and adaptability in a constantly changing global market, in addition to making a positive impact on a more sustainable future.

Organisations measure sustainable performance by concurrently analysing their effects on the environment, society, and economics. This all-inclusive method takes into account the interests of all stakeholders while measuring and assessing a company's performance from a variety of angles. Organisations function without boundaries in this domain by involving stakeholders from both upstream and downstream in their assessments [16]. Similarly, Pureza and Lee [20] claim that in addition to enhancing their financial performance, sustainable organisations place a high priority on minimising resource consumption, lowering petrol emissions, supporting environmental activities, and producing value for a variety of stakeholders. Furthermore, the achievement of sustainable performance is contingent upon sustainable leaders who prioritise long-term outlooks, systemic thinking, and continuous management growth [7].

HYPOTHESES DEVELOPMENT

Sustainable leadership and sustainable performance

The Triple Bottom Line (TBL) concept, which prioritises profit, people, and the planet, is centred on sustainable leadership and performance [1, 17].

Performance is improved by sustainable leaders who inspire workers, foster a happy work environment, and match company objectives with worker goals [18]. According to Tariq et al. [19], sustainable leadership encourages sustainability at all levels and secures financial gains through environmentally friendly methods, community support, and the production of sustainable value [20]. It emphasises long-term gains and capacity growth, both of which significantly improve organisational performance.

Several benefits come with being sustainable for business organisations [21, 22]. These include acquiring a competitive advantage, strengthening financial performance, and improving corporate governance and social responsibility. Sustainable business strategies, according to Xuecheng et al. [23], have a favourable impact on performance by encouraging employee dedication and corporate citizenship behaviour. Furthermore, sustainability initiatives support the development of an ethical climate within the company by assisting employees in aligning with ethical conduct. Companies that prioritise sustainability generally use both financial and non-financial measures, have longer-term goals, and more comprehensive stakeholder involvement methods. In terms of accounting and stock market performance, they gradually beat businesses with low sustainability [24–28].

According to Golgeci et al. [8], sustainable leadership (SL) is a beneficial approach for long-term success and a persistent competitive advantage since it creates value for all stakeholders and encourages innovation and continual improvement. Organisations that use SL practices also benefit in other ways, such as increased productivity, decreased expenses, better organisational image, decreased employee turnover, increased energy and resource efficiency, and increased community engagement. Thus, the following hypothesis is put forth:

H1: ***Sustainable leadership has a significantly positive impact on economic performance.***

H2: ***Sustainable leadership has a significant impact on environmental performance.***

H3: ***Sustainable leadership has a positive and significant impact on social performance.***

Research Gaps

The majority of current research on sustainable leadership is centred on the manufacturing, retail, or service industries in general, with little focus on the textile industry. The textile industry faces several distinct environmental and social concerns, including high water consumption, chemical waste, and labour issues. More research that is specific to the industry is needed to understand how sustainable leadership may effectively handle these challenges. There is a lack of study on the impact of cultural and regional differences on the implementation and effectiveness of sustainable leadership in the textile sector. In nations with major textile centres, leadership styles and sustainability practices might differ greatly because of socio-cultural norms and legal frameworks, both of which are especially important in these countries.

EMPIRICAL SETTING AND PROCEDURE OF TESTING

With a focus on migrant women workers, this study mainly investigates how sustainable leadership (SL) promotes sustainable performance (SP) in the ready-made clothing industry. Additionally, it seeks to verify the suggested theories empirically. The study is motivated by several important factors. Migrant labourers, many of whom are women from underprivileged backgrounds, are a major component of the ready-made clothing industry. Assuring ethical standards and social responsibility through fair labour practices, equal pay, and safe working conditions is consistent with sustainable leadership values. The study emphasises the significance of SL in addressing concerns of exploitation and promoting fair treatment by concentrating on migratory women workers. Because of its resource-intensive production methods and waste creation, the apparel sector is regularly examined for its effects on the environment. Initiatives aimed at lessening environmental impact, like promoting eco-friendly behaviours, cutting waste, and maximising resource utilisation, can be fueled by sustainable leadership. This strategy responds to the increased demand from consumers for ecologically friendly practices and is in line with more general sustainability objectives.

Sample and data description

Any research must have a thorough, accurate, and current sampling frame. Convenience sampling was used in the absence of such a sampling frame. By maintaining an audit record throughout the data collecting phase and consciously choosing samples with uniform characteristics, care has been taken to guarantee representativeness and minimise bias. 358 workers from the ready-made garment industry in the Indian states of Punjab and J&K Union Territory were given a well-structured questionnaire to complete throughout the six months from March 2024 to August 2024 to collect the primary data.

For the sampling unit, the study employed the following inclusion criteria.

- Women who are not permanent residents of J&K and Punjab but work in factories that produce ready-made clothing.
- Contract, temporary, and permanent female employees who are older than eighteen.
- Depending on the type of question, the instrument uses a five-point Likert scale with 5 representing "strongly agree" and 1 representing "strongly disagree". It is a non-comparative, detailed rating scale. The cross-sectional approach serves as the foundation for the data gathering process, and Smart PLS-4.0, a second-generation data analysis program, is used.

Measures

With a reliability value of 0.93, the 14-item sustainable leadership measuring scale created by McCann and Holt [6] was used in this study [29]. With a reported reliability value of 0.83, a 15-item scale developed by Khan and Quaddus was used to evaluate sustainable performance across economic, environmental, and social aspects [30-36].

Research design and analysis

The study used a descriptive research approach to examine how sustainable leadership affects sustainable performance. To analyse the data, the study used partial least squares structural equation modelling, or PLS-SEM. The study was conducted in two primary steps using SmartPLS Version 4.0: assessing the measurement model and examining the structural model. Examining convergent and discriminant validity was the main goal of the measurement model evaluation. Discriminant validity measures how distinct things are across constructs, whereas convergent validity measures how related items are within constructs.

The study's methodology largely examined the proposed connections between the constructs to assess the structural model. This evaluation included looking at the relationships in the structural model's collinearity, significance, and applicability. The evaluation also looked at factors including the coefficient of determination (R^2), effect size (f^2), and predictive relevance (Q^2) to better comprehend the model's performance.

FINDINGS

Measurement model assessment

The metrics used to assess the measurement model, such as factor loading, composite reliability (CR), and average extracted variance (AVE), are displayed in table 1. A factor loading of 0.700 is typically considered average, while values as low as 0.4, 0.5, and 0.6 can be acceptable in some circumstances. Due to extremely low factor loadings, a few items on the Sustainable Leadership scale (SL10, SL11, SL12, SL13, SL15, and SoP01) were removed. The results in table 1 demonstrate that all of the conditions have been met, with AVE and CR benchmarks being 0.5 and 0.7, respectively. This implies that the measurement model's convergent validity is appropriate. Figure 1 displays the measurement model evaluation's SmartPLS output.

Table 1

FACTOR LOADING, COMPOSITE RELIABILITY, AND AVERAGE VARIANCE EXTRACTED

	Item code	Factor loadings	Composite reliability (CR)	Average Variance Extracted (AVE)
Economic performance	EP01 EP02 EP03 EP04 EP05	0.683 0.78 0.839 0.776 0.588	0.855	0.545
Environmental performance	EnP01 EnP02 EnP03 EnP04 EnP05	0.748 0.706 0.725 0.776 0.746	0.858	0.548
Social performance	SoP02 SoP03 SoP04 SoP05	0.665 0.713 0.759 0.777	0.82	0.533
Sustainable leadership	SL01 SL02 SL03 SL04 SL05 SL06 SL07 SL08 SL09 SL14	0.696 0.747 0.738 0.711 0.665 0.756 0.732 0.73 0.685 0.708	0.914	0.514

Table 2

HTMT assessment of discriminant validity				
Column1	**Column2**	**Column3**	**Column4**	**Column5**
	Economic performance	**Environmental performance**	**Social performance**	**Sustainable leadership**
Economic performance				
Environmental performance	0.718			
Social performance	0.85	0.894		
Sustainable leadership	0.845	0.842	0.822	

The heterotrait–monotrait correlation ratio (HTMT) was endorsed by Henseler, Ringle, and Sarstedt as a criterion for evaluating the discriminant validity of the measurement model. Gold, Malhotra, and Segars suggested a criterion of 0.9, whereas Kline said that it should not be higher than 0.85. Table 2 indicates that all of these conditions were satisfied, indicating that the measurement model did, in fact, exhibit discriminant validity.

Structural model assessment

To ascertain whether multicollinearity was present in the model, the Variance Inflation Factor (VIF) was employed. Every VIF value was comfortably below 3.3, indicating that the model did not have any issues with multicollinearity. According to table 3's results, which were derived by bootstrapping the structural model analysis, the hypotheses are supported when $p<0.001$ ($t>1.645$), $p<0.05$ ($t>1.96$), or $p<0.001$ ($t>2.58$). The results unequivocally demonstrate that each hypothesis is validated. Additionally, according to Cohen, R^2 must be at least 0.35 for significance; the calculated model for this study's R^2 of 0.566 is regarded as significant.

A blindfolding procedure with a distance omission of $D=7$ was used to evaluate the predictive significance. PLS-SEM analysis criteria are well-aligned with the Q^2 value computation, which is based on a cross-validated redundancy technique. According to the data, all endogenous factors have predictive importance, as indicated by the Q^2 value of 0.541. The degree to which an endogenous variable influences an exogenous variable is referred to as its effect size. According to Cohen, an f^2 value of 0.35 or higher indicates a large influence, $0.15<f^2\leq 0.349$ indicates a moderate effect, and $f^2\leq 0.03$ indicates a modest effect. Every connection shows either a minor or moderate effect size, based on the results shown in table 3.

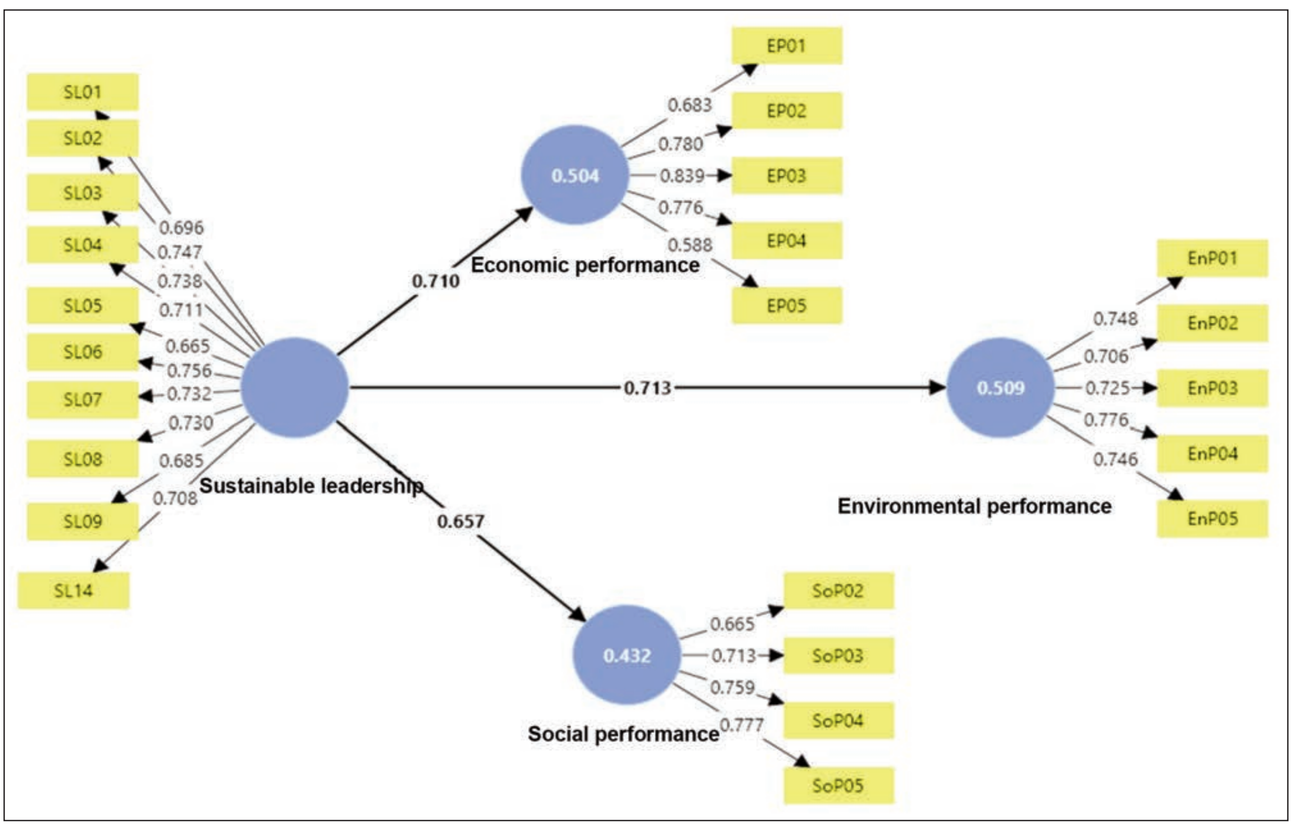

Fig. 1. SmartPLS output of the measurement model

Table 3

RESULTS OF PATH ANALYSIS, VIF, f^2, R^2, AND Q^2									
Column1	**Original sample (O)**	**Sample mean (M)**	**Standard deviation (STDEV)**	**T statistics (|O/STDEV|)**	**P values**	**VIF**	**f^2**	**R^2**	**Q^2**
Sustainable leadership > Economic performance	0.71	0.713	0.037	19.255	0.000	1	1.061	0.054 0.509	0.495
Sustainable leadership > Environmental performance	0.713	0.717	0.038	18.835	0.000	1	1.037	0.43	0.499
Sustainable leadership > Social performance	0.656	0.66	0.039	16.878	0.000	1	0.754		0.418

ADDRESSING RESPONSE BIAS

Researchers have put several techniques into place to ensure that the data is reliable and legitimate to address response bias. When anonymity and confidentiality are guaranteed, social desirability bias is reduced, which encourages people to respond honestly. The surveys used neutral language and balanced response scales to prevent participants from being led or influenced. In addition, the inclusion of reverse-coded questions and the randomisation of the order of items helped to reduce automatic answering tendencies and order effects.

DISCUSSION

Three hypotheses were established for the present study. Since the P values are less than 0.05, all three hypotheses have been accepted. The findings of this investigation are consistent with other earlier research carried out in various fields. Businesses play a significant role in advancing sustainable development, and contemporary businesses are shifting from a strategy that prioritises increasing short-term shareholder value to one that recognises the interdependence of the economy, business, society, and environment. SL takes into account how business, society, and the environment are interconnected, and value is generated through long-term strategic decision-making. The study looked at how SL affected textile companies' SP. Indicators of the economy, society, and environment were employed to gauge sustainable performance. The findings showed a strong positive correlation between FP and SL. The study's first hypothesis is validated.

Maintaining positive labour relations, training personnel, succession planning, and social responsibility through positive community interactions are all skills that a sustainable leader should possess.

Additionally, the results offer empirical evidence in favour of a favourable correlation between SL and EP. The study's third hypothesis is validated. A sustainable leader must minimise pollution, use resources like energy and water effectively, and practice environmental responsibility, claim [7]. According to Liao and Zhang [18], a sustainable leader implements a plan for long-term sustainable performance and generates value for all stakeholders. According to Iqbal and Ahmad [16], organisational learning mediates the link between SL and SP. Iqbal and Ahmad discovered in another investigation that SL indirectly and favourably affects SP through psychological safety.

The current research builds on prior studies by investigating the mediating function of knowledge integration in the relationship between sustainable leadership and sustainable project performance. Previous studies have failed to investigate how sustainable leaders combine sustainability principles with their management style [25]. In large-scale construction projects, the success of the project often depends on the team's capacity to integrate and absorb knowledge and techniques linked to sustainable development goals (SDGs). Our research helps to improve the understanding of sustainable management by examining a variety of methods for integrating information that connect sustainable leadership directly to the results of the project. Our research indicates that sustainable leadership practices can improve the performance of sustainable projects by encouraging the integration of information.

This is especially significant because achieving the Sustainable Development Goals (SDGs) demands an awareness of different types of knowledge to ensure that projects are sustainable. Our research highlights the importance of knowledge integration as a mediating component, which provides insight into how sustainable leadership practices can result in sustainable project performance.

The findings of this study suggest that the value of top management knowledge is essential for improving the working relationships between sustainable leadership and the integration of staff knowledge. This finding is in agreement with prior research conducted by Thakhathi et al. [27], which indicates that the value of top management knowledge is determined by a variety of novel techniques and procedures that promote sustainable leadership and knowledge integration. This is especially crucial in the context of building projects because of the frequent occurrence of unexpected situations, such as changes to the design, code outcomes, and growing client needs during the project. Top management knowledge value enables employee participation and encourages speedy solutions for new challenges, which is different from old systems, where only elite decision-makers can update or adjust the job that has been assigned. Our research shows that the value of knowledge possessed by top management has a strong interaction with sustainable leadership and knowledge integration. This emphasises the need for businesses to prioritise the knowledge value of top management to promote sustainability practices and achieve sustainable project performance [26, 37–44].

CONCLUSION AND LIMITATIONS OF THE STUDY

The relationship between SL and the performance of textile organisations was examined in this study. To gauge sustainable performance, financial, social, and environmental metrics were employed. The findings showed a strong positive correlation between SP and SL. The study theoretically connected business, financial, and nonfinancial factors with SL. The study connected SL not just to financial performance but also to sustainable performance (financial, social, and environmental metrics). This provides a comprehensive view of how SL may affect business performance. Therefore, the study's conclusions demonstrate that a sustainable leader will enhance a company's social and environmental performance in addition to its financial performance. A CEO who is sustainable will be able to generate value for more than just shareholders, but also for other parties involved. The study contributes empirically to the limited research on SL and firm performance, particularly when it comes to developing-nation textile firms. The study offers several suggestions for how textile businesses might enhance SL.

While evaluating success, textile companies ought to employ both financial and nonfinancial metrics. The operation and performance of textile businesses should incorporate sustainability reporting and practices. Leaders ought to create sustainability rules and policies for their companies. Textile companies' incentive programs ought to emphasise long-term performance and leadership. There are several restrictions on the study. First, it prioritised subjective metrics for sustainable performance over objective ones. The survey's respondents are primarily small and medium-sized businesses, and achieving their desired outcomes is frequently challenging. Second, sampling bias may have resulted from the survey's convenient sampling of participants.

Third, the survey was only completed by 358 employees; thus, caution should be used when extrapolating the study's conclusions. Fourth, the survey was conducted using a cross-sectional approach, which restricts the capacity to identify the cause and impact. A longitudinal technique can be used in other investigations. The employees of textile companies were the study's main focus. The McCann and Holt [6] 15-item sustainable leadership questionnaire can be used to find out how textile company employees feel about sustainable leadership. It is also possible to look into the moderating influence of the employee's age, gender, and educational attainment.

Implications of the study

By linking sustainable leadership with sustainable performance metrics in a labour-intensive industry like textiles, the study will add to the growing body of research on the topic. It might offer a theoretical foundation for comprehending how employee performance and behaviour are influenced by leadership styles in sectors with significant social and environmental consequences. Managers in the textile sector should use sustainable leadership techniques to match employee performance to the organisation's long-term sustainability objectives. In textile factories, sustainable leadership frequently promotes worker engagement, well-being, and satisfaction, which boosts output and lowers turnover. Employees who are inspired by sustainable leadership are more likely to increase quality control, use resources more efficiently, and implement eco-friendly practices.

Companies could achieve Corporate Social Responsibility (CSR) standards and enhance their brand image by utilising sustainable leadership methods. In the hierarchical structure of textile companies, trust and improved communication are essential, and sustainable leadership can help to cultivate both.

This study may help legislators create labour and environmental regulations that support eco-friendly textile sector practices. It might promote the establishment of industry-wide standards for long-term worker performance and leadership. Textile companies that effectively adopt sustainable leadership models may be eligible for incentives from governments or trade associations. Employee involvement in sustainability initiatives may result in decreased waste and enhanced environmentally friendly procedures as a result of sustainable leadership in the textile sector. It backs the global agenda for attaining the Sustainable Development Goals (SDGs), especially those about responsible consumption and production (SDG 12) and decent work (SDG 8).

Recommendations

Textile firms need to take a comprehensive approach to their operations to effectively implement sustainable leadership practices. This means integrating environmental, social, and economic sustainability into their business models. This includes accepting responsibility for the environment by lowering carbon emissions, making the most of available resources, and using renewable energy sources. Businesses should put closed-loop systems in place for recycling garbage and conserving water to minimise their influence on the environment. Leaders should promote a culture of employee involvement by promoting active participation in sustainability projects, offering skill development programs, and creating venues for workers to voice creative ideas. It is important to develop clear and verifiable sustainability goals that are in line with global standards, such as the UN

SDGs. Leaders must also set an example by publicly practising and prioritising sustainability.

It is essential to manage the supply chain in an ethical manner, which includes working with suppliers who follow fair labour practices and environmental standards. Businesses need to put money into innovation, which includes the creation of biodegradable materials, low-impact colours, and smart production methods that minimise energy use. Regular sustainability reporting and certifications improve transparency, which helps to create trust with stakeholders like as consumers, investors, and staff. Textile firms can also make community engagement a priority by starting programs that assist local economies, improve working conditions, and empower underprivileged groups in the industry.

In addition, using digital tools such as blockchain for supply chain traceability and artificial intelligence for energy optimisation can improve operational efficiency and sustainability results. Textile firms may keep ahead of sustainability trends and promote systemic change by collaborating with industry associations, non-governmental organisations (NGOs), and government agencies. In the end, incorporating these principles into every aspect of operations and decision-making will allow textile companies to achieve long-term sustainable performance while also contributing to broader environmental and social goals.

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Design improvement and performance of the inflatable anti-immersion suit

DOI: 10.35530/IT.076.05.2024152

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ABSTRACT – REZUMAT

Design improvement and performance of the inflatable anti-immersion suit

The human body's exposure to cold water can lead to rapid heat loss, even frostbite, cold stress and drowning. To protect the lives of individuals working in cold water environments, an anti-immersion suit is worn as protective equipment. But active anti-immersion suit faces problems such as single function, lack of warmth, poor floatability, poor thermal, wet comfort, poor body suitability and so on. In this paper, the performance of the anti-immersion suit was tested and evaluated by changing the inflatable thermal fabric as part of the inner layer and optimising the structure of key parts of the suit. It was found that the use of inflatable thermal inner layer materials and the improved design of the garment structure caused significant improvement of floating and thermal properties of the suit, inhibited the average skin temperature drop of the human body in a cold water environment, and improved the subjective comfort of the human body in a human subject experiment. Therefore, the results of this study may form the basis for research into a new anti-immersion suit.

Keywords: *anti-immersion suit, inflatable thermal fabric, buoyancy, thermal manikin, average skin temperature*

Îmbunătățirea designului și performanței costumului gonflabil anti-imersiune

Expunerea corpului uman la apă rece poate duce la pierderea rapidă a căldurii, chiar la degerături, stres din cauza frigului și înec. Pentru a proteja viața persoanelor care lucrează în medii cu apă rece, se utilizează costume anti-imersiune ca echipament de protecție. Dar costumele anti-imersiune active se confruntă cu probleme precum funcționalitatea redusă, lipsa căldurii, flotabilitate slabă, confort termic redus, confort redus în condiții de umiditate, adaptabilitate slabă la corp și așa mai departe. În această lucrare, performanța costumului anti-imersiune a fost testată și evaluată prin schimbarea materialului textil termic gonflabil care face parte din stratul interior și optimizarea structurii părților cheie ale costumului. S-a constatat că utilizarea materialelor termice gonflabile pentru stratul interior și îmbunătățirea designului structurii costumului au dus la o îmbunătățire semnificativă a proprietăților de flotabilitate și a celor termice ale costumului, au inhibat scăderea temperaturii medii a pielii corpului uman în medii cu apă rece și au îmbunătățit confortul subiectiv al corpului uman în cadrul experimentului pe subiecți umani. Prin urmare, rezultatele acestui studiu pot constitui baza pentru cercetarea unui nou costum anti-imersiune.

Cuvinte-cheie: *costum anti-imersiune, material termic gonflabil, flotabilitate, manechin termic, temperatura medie a pielii*

INTRODUCTION

In the process of sea rescue, due to the low sea temperature, a series of problems such as cold shock, hypothermia, respiratory failure and other problems will be caused if the operation time is too long or the rescue is not enough, which seriously threatens the health of the rescue workers [1, 2]. Studies have pointed out that the main cause of sea rescue and shipwreck deaths has been cold water immersion caused by hypothermia, and leading to a series of cases, the mortality rate was about 60% to 80% [3, 4]. Anti-immersion suits were indispensable personal protective equipment and used to prevent loss of temperature and drowning [5], thus prolonging the survival time and increasing the chances of rescue, and maximising the safety of search and rescue personnel [6]. By comparing the three types of anti-immersion suits in the market at present, including SANTI Poland, HENSON Norway and SURVITEC England, and found that to meet the use requirements, the style of anti-immersion suit was basically a joint-type design and consisted of two layers. The outer layer was made of waterproof material as an anti-immersion layer, and the inner layer was made of warm material as an anti-cold layer. The anti-immersion suit also needs to be easy to wear and take off, thin and fit well, comfortable for sports, and to ensure the protective safety of the wearers to the maximum extent [7, 8].

Anti-immersion layer was mainly used to block water infiltration into clothing, to avoid direct contact between the human body and water, which could cause increased heat loss. Anti-immersion layer fabric should have good waterproof performance, in addition to preventing sweat condensation and frostbite human body. Anti-immersion layer fabric should also have a certain degree of hygroscopicity and breathability. At present, anti-immersion fabrics mainly include coated fabrics, laminated composite fabrics, high-density fabrics with water repellent finishing, intelligent fabrics with anti-impregnation properties, and so on [9–12]. Positive thermal insulation materials, also known as energy collection and management materials, not only isolate or reduce the loss of human body heat like passive insulation materials, but also absorb and store external heat and transfer it to the human body through additional heating effects. They mainly include electric heating materials, moisture-absorbing heating materials, energy storage materials, and chemical thermal materials [13–15].

To enhance the protection effect of immersion suits, Lenfeldová et al. [16] suggested that inflating clothing could effectively enhance the thermal resistance of immersion-resistant suits and improve thermal insulation. Meanwhile, the outer layer fabric should utilise warp-knitted spacer fabrics with superior structural stability, which could effectively prevent the reduction in thickness and decline in thermal insulation performance caused by increased immersion depth. Jim et al. [17] improved the passive reflective system of immersion suits by increasing the area of reflective material and designing the position of reflective material. Jonathan et al. [18] conducted human wearing tests by using a hydraulic wave generator to create wave simulations of real sea conditions. They found that wind and waves increase the possibility of heat loss and immersion suit leakage, with actual performance lower than estimated laboratory performance. Based on the above experimental results, Jonathan et al. [19] calculated the minimum thermal insulation required to maintain heat balance in the human body, so that the laboratory test performance is closer to the actual use performance. To the best of our knowledge, at present, to improve the anti-immersion function, the main methods are the application of new materials, material function modification and theoretical optimisation. This paper analysed the thermal insulation principles of various materials, applied inflatable fabrics to an anti-immersion suit, and designed the clothing structure of an anti-immersion suit based on ergonomics principles. The comprehensive protective performance and comfort of the anti-immersion suit were tested and evaluated from aspects such as safety protection, convenient wearing and removal, physiological comfort, accessory functions, and visual aesthetics, making the anti-immersion suit have both thermal insulation and buoyancy properties.

EXPERIMENTAL SECTION

Clothes design

Insulating layer design

The anti-drenching clothing's inner layer insulation was made by combining an airbag material composed of Saty Gard nylon 6 filament produced by Allied Signal Company (surface density: 46 g/m^2) and a Thermoplastic Polyurethane (TPU) waterproof film developed by our research group (surface density: 45 g/m^2). As shown in figure 1, the U-shaped floating life-saving device structure was combined with the clothing structure to form the anti-drenching clothing's inner layer insulation. The raised collar at the back and the front of the garment forms a U-shape, providing support for the back of the neck.

Anti-immersion layer design

The design process of the Anti-immersion layer is flow in figure 2. The design of reflective material should meet the requirements of International Organisation for Standardisation (ISO) 15027-1 Immersion suits – Part 1, which states that the total area of retro reflective material shall be no less than 400 cm^2, with at least 100 cm^2 on the hat and 50 cm^2 on the back, while the rest is distributed throughout the body. To meet the requirements of good waterproof performance, certain tensile strength and tear

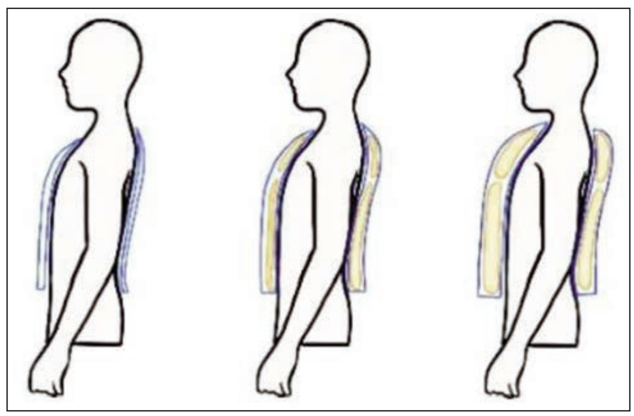


Fig. 1. Structure diagram of the insulating layer of the inflatable anti-immersion suit

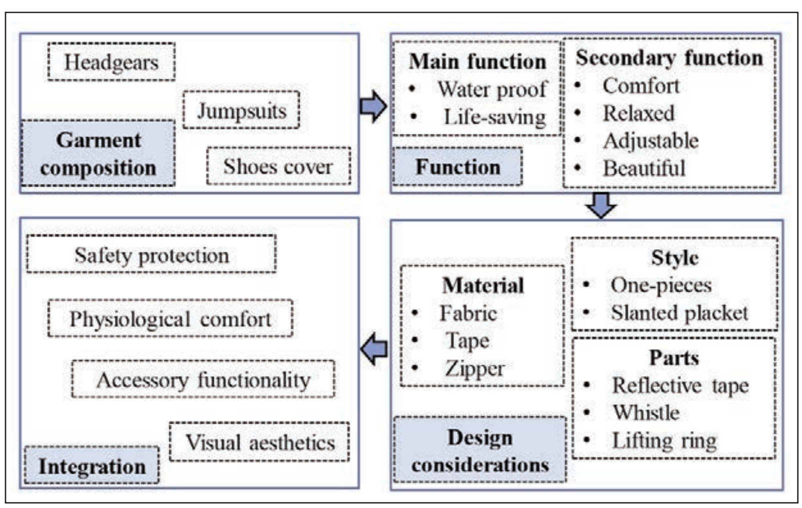


Fig. 2. Outer design flow of inflatable anti-immersion suit

Table 1

MATERIAL AND PERFORMANCE ANALYSIS OF SHELL FABRICS AND ACCESSORIES			
Type	**Material**	**Property**	**Application site**
Shell fabric	Three-layer waterproof fabric (Nylon + Polytetrafluoroethylene film + mesh fabric)	Thickness: 0.82 mm; Thermal Resistance: 1.5 clo; Compressive strength: 15.2 Mpa; Hydrostatic pressure: 10000 mmH_2O; Warp tensile strength: 1600 N; Weft tensile strength: 1300 N	Whole costume except for headgear and cuffs
Accessory	Chloroprene Rubber light skin neoprene; IZIP airtight zipper; Nylon mesh fabric pocket; Safety of Life at Sea maritime reflective tape; YETOM company waterproof sticker	Skin-friendly, high elasticity, tightly sealed and waterproof; High strength, wear-resistant; No water retention; High reflectivity, excellent visibility at sea; Hydrostatic pressure at the cross seams:3000 mmH_2O; Peel strength: 35.6 N/cm	Headgear; cuff placket; head of all front outer layer pockets; body of the garment; all interior seams

resistance, and good thermal insulation properties for an anti-immersion suit, the selection and performance characteristics of the materials used are shown in table 1. The anti-drenching clothing parts were bonded and assembled using adhesive technology to form an inflatable anti-immersion suit.

Performance test and evaluation

Floating ability

According to ISO 12402-1: 2005 Personal flotation devices – Part 1: Lifejackets for seagoing ships – Safety requirements and Archimedes' principle, the buoyancy of the sample was measured and calculated in air and water, respectively. The testing method was shown in figure 3.

Buoyancy calculation formula of an anti-immersion suit:

$$F_i = M \cdot g = (M_1 - M_2) \times 9.8 \tag{1}$$

$$F_s = M \cdot g = (M_1 - M_3) \times 9.8 \tag{2}$$

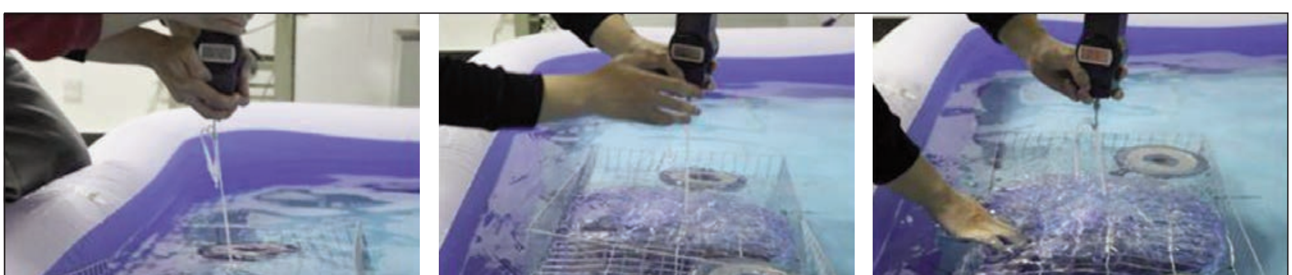
$$P_b = \frac{F_i - F_s}{F_i} \times 100\% \tag{3}$$

where F_i is the initial flotation of the inflatable anti-immersion suit; M_1 is the total mass of the metal cage and weight suspended in water; M_2 and M_3 are the total mass of the metal cage, weight and anti-immersion suit before and after soak for 24 hours, respectively; P_b is the loss of anti-immersion suit soaked in water for 24 hours.

Thermal resistance

Thermal resistance is a parameter indicative of the thermal insulation performance of clothing. Its value is inversely proportional to the thermal conductivity of the clothing. According to ISO 15831-2004 Clothing-Physiological effects-Measurement of thermal insulation by means of a thermal manikin, the thermal resistance performance of an anti-immersion suit was tested using a walk-in environmental chamber (ESPEC Corporation, Osaka, Japan) and a 34-segment sweating thermal manikin "Newton" (Measurement Technology Northwest, Seattle, USA). The immersion suit produced by Helly Henson Company from Norway (H-suit) was selected as the control group, and its performance was compared with that of the inflatable immersion suit (S-suit) designed in this paper. Before testing, the immersion suit was placed in an environmental chamber at a temperature of 20±5°C and a relative humidity of 50±5% for 12 hours. The skin temperature of the thermal manikin was set to 34°C, and the immersion suit was worn on the surface of the thermal manikin. The thermal manikin consisted of 34 independent segments with different temperatures, heat fluxes, and sweating rates (figure 4), and data were recorded through sensors in each segment, lasting for 20 minutes, and tested three times to obtain the average value.

The formula for calculating the total thermal resistance, $I_{t,}$ of the immersion suit was as follows:



a *b* *c*

Fig. 3. Buoyancy test process: weigh the mass of: *a* – metal cage and weight; *b* – metal cage, weight and anti-immersion suit; *c* – metal cage, weight and anti-immersion suit after soaking 24 h in water

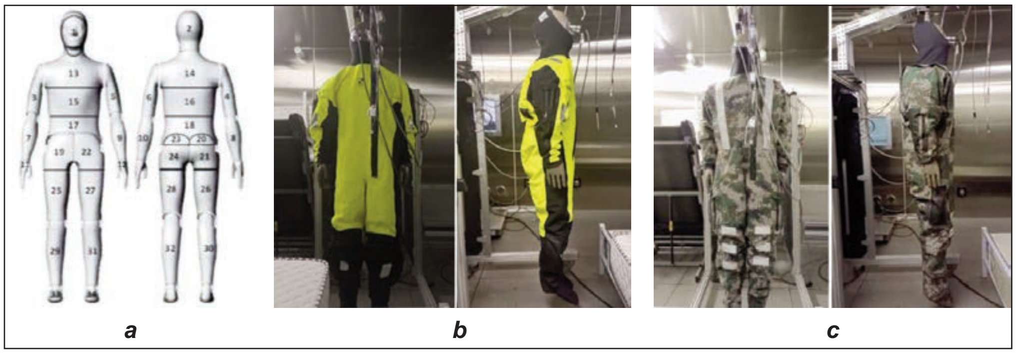


Fig. 4. Photos of: *a* – Newton 34-zone thermal manikin; *b* – test procedure of HENSON anti-immersion suit (H-suit); *c* – test procedure of inflatable anti-immersion suit (S-suit)

$$I_t = \Sigma_i \frac{S_i}{S} \times \frac{T_i - T_a}{H_i} \quad (4)$$

The local thermal resistance I_{tp} was calculated as follows:

$$I_{tp} = \frac{S_i}{S} \times \frac{T_i - T_a}{H_i} \quad (5)$$

where I_t is total thermal resistance of anti-immersion suit, col; I_{tp} is local thermal resistance in section *i* of anti-immersion suit, col; *S* is total body surface area of thermal manikin, m^2; S_i is local body surface area in section *i* of thermal manikin, m^2; T_i is shell temperature in section *i* of thermal manikin, °C; H_i is heat flow rate in section *i* of thermal manikin, W/m^2.

Heat-moisture comfort

Clothing heat-moisture comfort refers to the performance of garments that enables the clothed human body to exchange heat and moisture with the environment under varying environmental conditions and levels of physical activity, ultimately reaching equilibrium and providing a comfortable sensation. This property is collectively determined by the thermal conductivity and moisture transfer capabilities of the clothing. So, six healthy and proportionate adult males were selected for the real-life underwater test of immersion suits to test their heat-moisture comfort. Each subject participated in two experiments with a time interval of two days. The experimental procedure followed the flow chart shown in figure 5, *a* and *b*. After entering the water at a depth of 30 cm and a temperature of 15°C lasted for 2.5 hours. During the experiment, the physiological indicators of the subjects were tested and recorded using a thermocouple sensor MSR®145-100 (MSR Electronics GmbH, Zurich, Switzerland), a heart rate monitor Polar® (Polar Electro Oy, Kempele, Finland), and a cardio-respiratory function tester COSMED® (Cosmed Srl, Rome, Italy).

1. Mean skin temperature (MST): The collection point of human body temperature was shown in figure 5, *c*, and the calculation formula of *MST* was as follows:

$$MST = 0.07 \cdot S_1 + 0.175 \cdot S_2 + 0.175 \cdot S_3 + 0.07 \cdot S_4 + 0.07 \cdot S_5 + 0.05 \cdot S_6 + 0.19 \cdot S_7 + 0.2 \cdot S_8$$

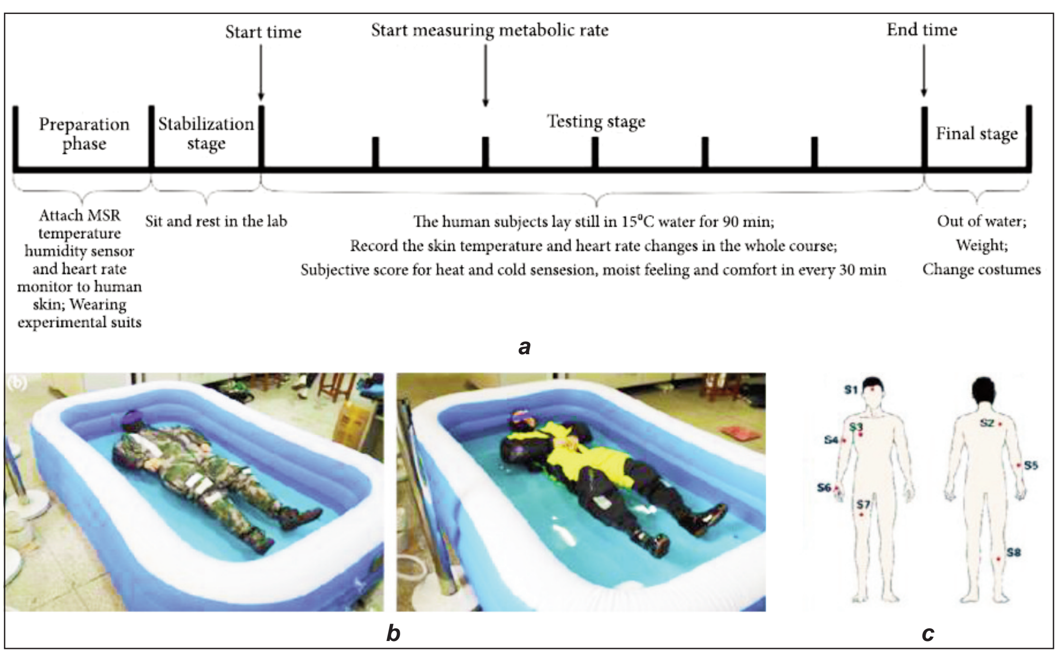


Fig. 5. Graphical representation of: *a* – the test process flow diagram; *b* – actual test pictures; *c* – location of heat flow sensors of human subject experiment

Table 2

SUBJECTIVE RATING SCALE					
Cold-heat sensation		**Comfort level**		**Humidity sensation**	
Very warm	3	Very Comfortable	3	Very Dry	3
Warm	2	Comfortable	2	Dry	2
Slightly Warm	1	Somewhat Comfortable	1	Slightly Dry	1
Neutral	0	Neutral	0	Neutral	0
Slightly Cold	–1	Somewhat Uncomfortable	–1	Slightly Humid	–1
Cold	–2	Uncomfortable	–2	Humid	–2
Very cold	–3	Very Uncomfortable	–3	Very Humid	–3

2. Heart rate (HR): Heart rate collection was recorded every 30 s.
3. Metabolic rate (MR): 30 minutes after the start of the experiment, the metabolic rate was continuously collected for 5 min under the stable state.

Subjective psychological feelings were evaluated using a questionnaire, which included ratings of local (measured points), and overall cold-heat sensation, comfort level and humidity sensation (table 2). During the experiment, subjective evaluations were performed every 30 minutes, with a total of four evaluations.

RESULTS AND DISCUSSIONS

Floating ability

The buoyancy performance of the anti-immersion suit was tested and calculated according to formulas 1–3. The initial buoyancy of the anti-immersion suit was found to be 200.6 N, and after being immersed for 24 hours, the buoyancy measured was 197.6 N. The loss of buoyancy of the suit was 1.4%, which met the requirement of ISO 12402 that the buoyancy loss after 24 hours of immersion in fresh water should be less than 5% for a survival suit (table 3).

Table 3

FLOATING ABILITY OF ANTI-IMMERSION SUIT	
Samples	**Values**
Initial buoyancy of anti-immersion suit (N)	200.6
Buoyancy of anti-immersion suit after soaking in water for 24h (N)	197.6
Buoyancy loss of anti-immersion suit after soaking in water for 24h (%)	1.4

Thermal resistance

Thermal resistance of clothing refers to the resistance of clothing to heat flow in the process of heat exchange between the human body and the environment. It was a basic indicator for measuring the thermal insulation performance of clothing. In our previous work [20], the insulation performance of the inflation layer was optimal with the inflation thickness of 1.5 cm, and the thermal resistance was basically stable at 0.21 clo. The total thermal resistance of the H-suit, S-suit in the un-inflated state (S-suit+con) and S-suit in the inflated state (S-suit+full) was 1.88 clo, 2 clo and 2.10 clo, respectively (figure 6, *a*). This indicated that the overall thermal resistance performance of the inflatable anti-immersion suit was better than that of the H-suit, and the thermal resistance performance was significantly improved after inflation, which was similar to the previous research findings [16, 20]. It could be seen in figure 6, *b* and *c*, the thermal resistance of H-suit, S-suit-con and S-suit-full in section upper body section was 3.21 col, 3.20 col and 3.60 col, in the arm was 2.90 col, 3.37 col and 3.80 col, in the lower part of the body was 2.58 col, 3.16 col and 3.16 col, respectively. The results indicated that inflation had an impact on the local thermal resistance of the clothing, with an increase in thermal resistance and improved warmth. The local thermal resistance of the S-suit was significantly higher than that of the H-suit in the inflated state, indicating that the insulation of the inflated inner layer was superior to that of traditional cotton materials.

Heat-moisture comfort

The subjects wore two sets of anti-immersion suits during the test, with metabolic rates of 1.65 metabolic equivalents (METS) (S-suit) and 1.61 METS (H-suit), respectively. The linear fit of the subject's heart rate and average skin temperature is shown in figure 7, *a* and *b*, respectively. Throughout the experiment, the trend of heart rate change for both sets of anti-immersion suits was basically the same, gradually decreasing with time. The heart rate of subjects was higher in the S-suit than in the H-suit. As shown in figure 7, *b*, at the beginning of the experiment, the average skin temperature of the subjects wearing both sets of anti-immersion suits was roughly the same. With the progress of the experiment, the average skin temperature of the subjects wearing the S-suit gradually increased, reaching its highest value (about 32.2°C) at 20 minutes, and then decreased with the extension of underwater time, with a temperature difference of 0.55°C before and after. The average skin temperature of the subjects wearing the H-suit slowly decreased over time during the experiment, with a temperature difference of 1.05°C before and after.

The subjects conducted a subjective evaluation of the overall comfort of the two sets of anti-immersion

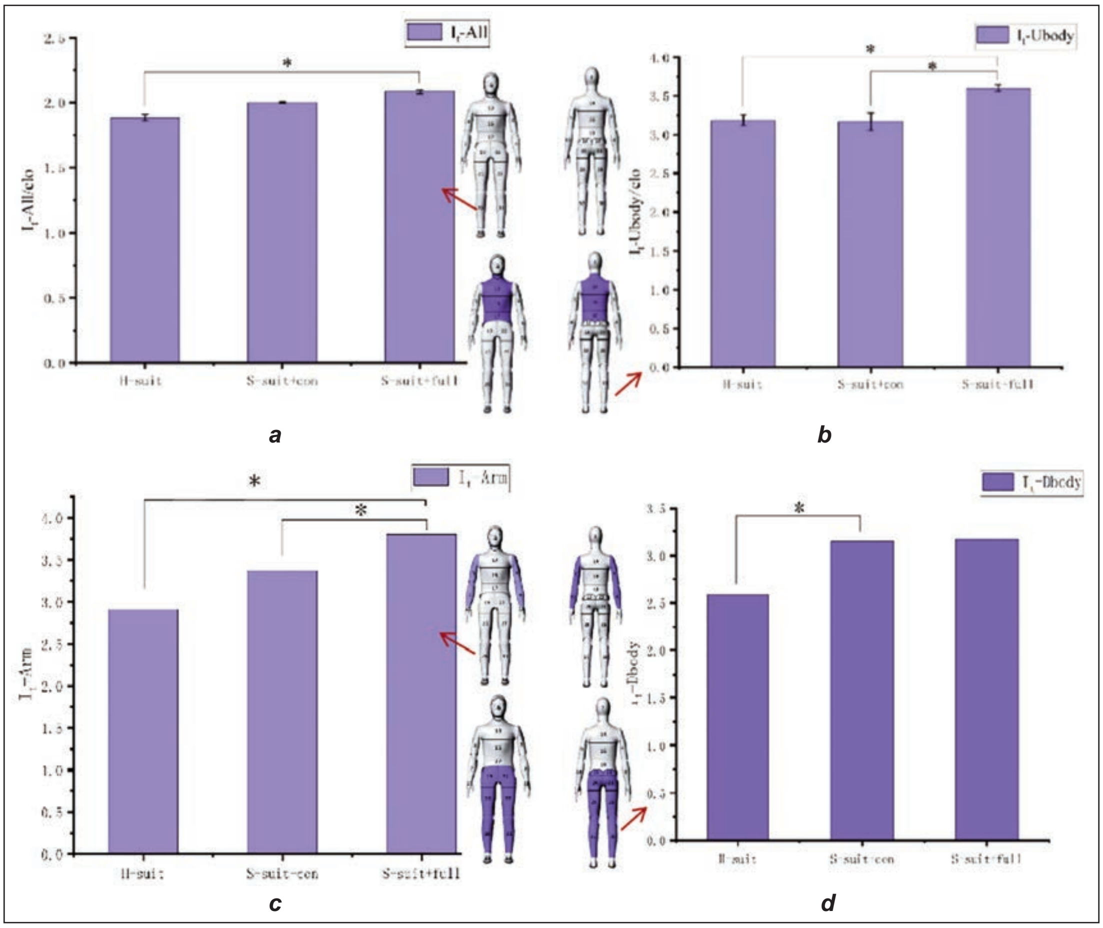


Fig. 6. Graphical representation of: *a* – total thermal resistance of H-suit and S-suit and thermal resistance of H-suit and S-suit in section; *b* – upper body (Ubody); *c* – arm; *d* – the lower part of the body (Dbody)

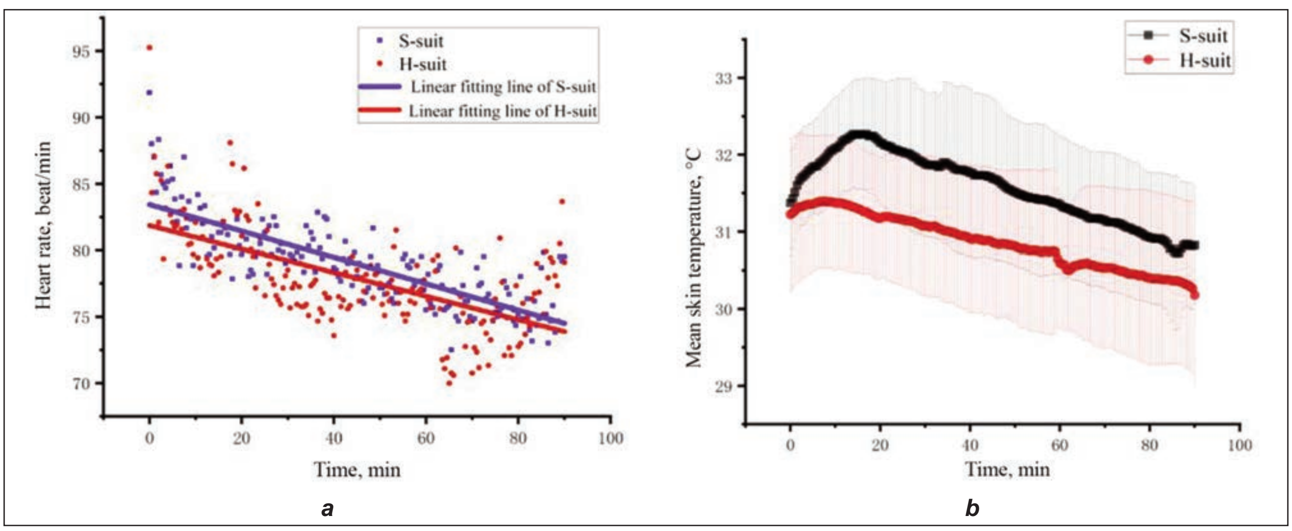


Fig. 7. The change of: *a* – heart rate; *b* – mean skin temperature of subjects in S-suit and H-suit

suits, including comfort, warmth, and humidity, while wearing them underwater. The results were shown in figure 8. From the evaluation results, the subjective scores for the S-suit were higher than those for the H-suit. The subjects wearing the S-suit remained in a state of thermal neutrality or above throughout the experiment, with a cold-hot score of 0.16 at the end of the experiment, while those wearing the H-suit felt colder after 20 minutes of the experiment, with a cold-hot score of –1, indicating that the S-suit had better cold protection (figure 8, *a*). As shown in figure 8, *b*, the subjects wearing the S-suit remained dry for 0–60 min, and then began to feel wet, with a score of –0.17. The subjects wearing the H-suit remained dry in 0–45 min, and then gradually began to feel wet, with a score of –0.33. Furthermore, as shown in

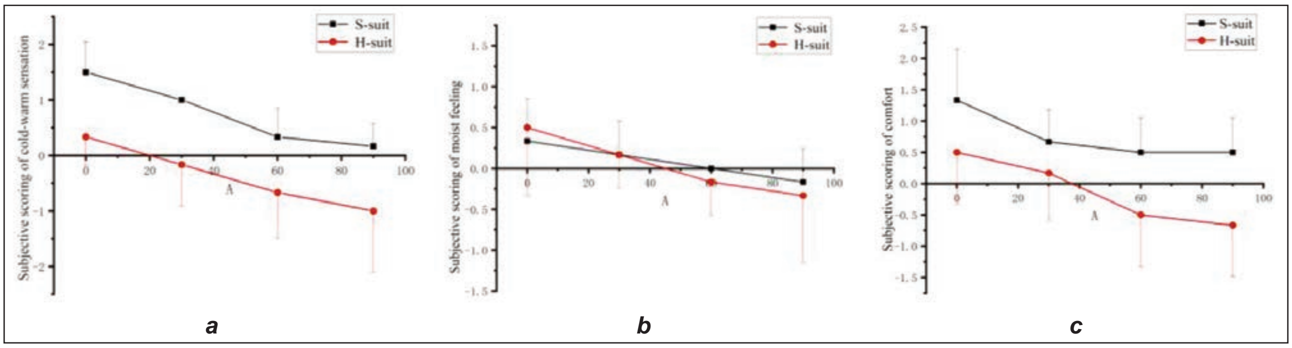


Fig. 8. Subjective scoring of: *a* – cold-warm sensation; *b* – moisture feeling; *c* – comfort

figure 8, *c*, the subjective scoring of comfort of S-suit was always positive and the end value was 0.51, while after 40 minutes, the scoring of H-suit was negative and the end value was –1.14.

CONCLUSION

In this work, based on human ergonomics, the function, style, and structure of a new type of inflatable anti-immersion suit were designed and produced. A multi-functional new type of inflatable anti-immersion suit was designed, and the protective performance and comfort of the anti-immersion suit were subjectively and objectively evaluated. The test results showed that adding airbag patches to the inner layer of the suit can provide some buoyancy to the suit. When fully inflated, the inherent buoyancy is 200.6 N, and after 24 hours of immersion, the buoyancy is 197.6 N, with a buoyancy loss of 1.4%. It can also improve the thermal insulation performance of the anti-immersion suit: after soaking in low-temperature water for 1.5 hours, the average skin temperature decreases from 31.37°C to 30.82°C, with a temperature decrease of only 0.55°C.

ACKNOWLEDGEMENTS

This work was supported by Jiangsu Provincial Social Development project – Surface project (SBE2022741233), China Postdoctoral Science Foundation General Fund (2024M752321).

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Investigation of the effect of sewing parameters on the bursting strength of knitted fabrics

DOI: 10.35530/IT.076.05.202542

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ABSTRACT – REZUMAT

Investigation of the effect of sewing parameters on the bursting strength of knitted fabrics

Knitted fabrics are extensively employed in the textile and apparel industries due to their structural adaptability, favourable mechanical behaviour, and cost-efficient production. Nevertheless, their inherent loop-based architecture renders them susceptible to complex, multidirectional loading conditions, including tensile, compressive, and shear stresses. Bursting strength is considered a more representative mechanical property for evaluating the multidirectional load-bearing capacity of knitted fabrics than the uniaxial tensile strength, which is limited to wale and course directions. Moreover, seam performance under such stresses is influenced by the intricate interaction of fabric structure, stitch configuration, and sewing parameters. This study is a continuation of the previous research. The findings of this study aim to enhance the understanding of seam-fabric interactions and contribute to the optimisation of knitted garment durability and performance. The results indicated that optimal bursting resistance varied depending on fabric type and sewing configuration. Specifically, Interlock fabrics achieved superior bursting strength with chain stitch, 5-step stitch density, Nm 70 needle thickness, and sewing in the loop bar direction. For Lacoste fabrics, the optimal configuration involved lock stitch, 5-step stitch density, Nm 70 needle thickness, and sewing in the seam bar direction. For Single Jersey fabrics, chain stitch, Nm 70 needle thickness, and loop bar direction yielded the most favourable results. Statistical analysis using regression models confirmed that sewing direction, stitch type, and needle thickness statistically significantly affected bursting pressure across all fabric types.

Keywords: *knitted fabrics, bursting strength, multiaxial loading, sewing parameters, textile*

Analiza efectului parametrilor de coasere asupra rezistenței la rupere a tricoturilor

Tricoturile sunt utilizate pe scară largă în industria textilă și de îmbrăcăminte datorită adaptabilității lor structurale, comportamentului mecanic favorabil și producției eficiente din punct de vedere al costurilor. Cu toate acestea, arhitectura lor inerentă bazată pe ochiuri le face susceptibile la condiții de încărcare complexe, multidirecționale, inclusiv solicitări de tracțiune, compresiune și forfecare. Rezistența la rupere este considerată o proprietate mecanică mai reprezentativă pentru evaluarea capacității portante multidirecționale a materialelor tricotate decât rezistența la tracțiune uniaxială, care este limitată la direcția rândului de ochiuri. Mai mult, performanța îmbinării sub astfel de solicitări este influențată de interacțiunea complexă dintre structura tricotului, configurația cusăturii și parametrii de coasere. Acest studiu este o continuare a cercetării anterioare. Rezultatele acestui studiu își propun să îmbunătățească înțelegerea interacțiunilor cusătură-tricot și să contribuie la optimizarea durabilității și performanței articolelor de îmbrăcăminte tricotate. Rezultatele au indicat că rezistența optimă la rupere a variat în funcție de tipul de tricot și configurația cusăturii. Mai exact, tricoturile Interlock au atins o rezistență superioară la rupere cu cusătura în punct de lănțișor, desimea cusăturii de 5 pași, grosimea acului Nm 70 și coaserea în direcția rândului de ochiuri. Pentru tricotul Lacoste, configurația optimă a implicat cusătura de acoperire, desimea cusăturii în 5 pași, grosimea acului Nm 70 și coaserea în direcția șirului de ochiuri. Pentru tricoturile glat, cusătura în punct de lănțișor, grosimea acului Nm 70 și direcția rândului de ochiuri au dat cele mai favorabile rezultate. Analiza statistică utilizând modele de regresie a confirmat că direcția cusăturii, tipul cusăturii și grosimea acului au afectat semnificativ statistic presiunea de rupere la toate tipurile de tricoturi.

Cuvinte-cheie*: tricoturi, rezistență la rupere, încărcare multiaxială, parametri de coasere, textil*

INTRODUCTION

Knitted fabrics are widely used in the fashion industry due to their versatility in fabric, design, and production methods, supported by technological advancements. Knitted fabrics have gained popularity in the textile and fashion world due to the comfort, functionality, and style alternatives they offer to consumers. The features offered by knitted fabrics, such as drape, flexibility, wrinkle resistance, softness, comfort and ease of care, allow them to be in increasing demand [1–7]. Today, consumers' increasing demand for knitted clothing attracts attention as an attractive market for manufacturers since fabric and clothing production takes place in a short time, with little labour and low production costs [6, 8].

Popular in casual and athletic wear, these garments endure various stresses and tensions during use. During wear, knitted garments are subjected to multidirectional forces, including tensile, compressive, and shear stresses, which can affect their durability and performance. Therefore, ensuring optimal mechanical properties, elasticity, and resilience is essential to meeting the dynamic demands of body movement, garment functionality, and environmental conditions [9].

Knitted fabrics are widely used in various fields, including fashion and industrial applications, and possess critical physical and mechanical properties that directly impact their performance in these applications. The bursting strength is an essential quality parameter of knit fabric is a key parameter that evaluates the fabric's resistance to multidirectional tensile forces, providing insight into its overall strength and elasticity [10–13]. Knitted fabrics must exhibit adequate mechanical resistance during dyeing and finishing processes and throughout their use and service life, where they are subjected to various external forces [13].

The bursting strength of knitted fabrics is determined by various factors, including raw material composition, pattern configuration, elastomer ratio, and yarn count [14]. Due to knitted fabrics' unique elastic nature, their mechanical behaviour is more accurately evaluated using bursting strength tests rather than conventional tensile tests, which are limited to uniaxial directions and unsuitable for looped structures [1, 15, 16]. Bursting strength testing, involving the application of multidirectional pressure perpendicular to the fabric surface until rupture, offers a reliable assessment of the fabric's resistance to three-dimensional stress and deformation [1, 10, 12]. Stitching, as the primary method of fabric joining in garment production, is a complex process that alters textiles' structural and mechanical behaviour [17–20]. The interaction between stitch parameters and fabric structure affects not only seam integrity but also the garments' overall quality and appearance. Therefore, understanding the structural composition of fabrics is essential for optimising fabric and seam performance [21]. A product's functional performance and seam quality are evaluated based on the structural and mechanical properties of the fabric, the seam parameters reflecting its aesthetic appearance, and the damage it sustains during use and care. Both the fabric and the seams that join it are subjected to various mechanical stresses throughout the manufacturing process and the product's lifespan, including elongation, bending, stiffness, abrasion resistance, seam shear strength, shrinkage, tightness, thickness, and resistance to washing and dry cleaning [22–26]. The ability of seams to withstand these forces and stresses determines their extensibility, security, durability, appearance, and efficiency, which collectively define seam performance [18].

Research on the bursting strength of sewn fabrics remains limited. Several studies have examined various factors influencing multiaxial seam strength. Yusof investigated the effects of different seam types, sewn with ISO 401 stitch type, on the multiaxial strength of selected woven and knitted fabrics [27]. Kovalova et al. analysed the multiaxial seam strength of automobile seat covers, sewn with a lockstitch, using a self-developed bursting apparatus [28]. Rajput et al. explored the impact of three stitch types, three fabric types, and sewing yarn fineness on the hydraulic bursting strength of knitted fabrics [29]. Yesilpinar examined how different lockstitch techniques affect fabric bursting strength [30].

Additionally, Kara evaluated the influence of various stitch types and their combinations on the seam strength and bursting strength of workwear [31].

Mousazadegan et al. investigated the effects of sewing parameters on seam strength under both unidirectional and multidirectional load conditions. They employed the bursting test to simulate multidirectional loading and compared seam efficiency under bursting force with tensile seam efficiency [32].

MATERIALS AND METHODS

Material

The properties of the 100% cotton knitted fabrics – single jersey, pique, and interlock – used in this study, sourced from Ares Örme, Türkiye, are provided in table 1. Before the sewing process, all fabric samples

Table 1

KNITTED FABRIC CHARACTERISTICS

Knit face structure	Colour	Fibre content	Knit density		Weight (g/m^2)	Yarn Count (Ne)
			Wales (no./cm)	Courses (rows/cm)		
Single jersey	White	100% Cotton	15	20	150	30/1
	Red	100% Cotton	15	21	150	30/1
	Black	100% Cotton	15	20	150	30/1
Pique	White	100% Cotton	12	18	200	30/1
	Red	100% Cotton	11	18	200	30/1
	Black	100% Cotton	12	18	200	30/1
Interlock	White	100% Cotton	14	16	250	30/1
	Red	100% Cotton	14	16	250	30/1
	Black	100% Cotton	14	16	250	30/1

were conditioned for 24 hours under standard atmospheric conditions, maintaining a temperature of 20 ± 2°C and a relative humidity of 65 ± 4%, to ensure consistency and reliability in testing.

Due to variations in the structural properties of the tested fabrics, such as loop formation, thickness, and weight, the selection of sewing threads and needle sizes was adjusted accordingly to match each fabric's specific characteristics. Sewing machine needles exhibit specific characteristics based on their size and point type. The machine needles used in the study were obtained from Groz-Beckert. The needle sizes used in this research range from Nm 60 to Nm 90, each featuring an FFG/SES (Fine Fabric Gauge / Small Embroidery Scarf) point type. This point type is designed for delicate and lightweight fabrics, ensuring precise stitching and minimal fabric damage. These sizes include Nm 60, Nm 65, Nm 70, Nm 75, Nm 80, and Nm 90, catering to various sewing applications that require accuracy and fabric protection. The sewing threads exhibit specific properties based on their number, tex value, length, strength, and stretch percentage. The sewing threads used in the study were procured from Coats.

The available thread numbers are 150 and 120, with tex values of 24 and 21, respectively. Regarding tensile strength, the 150 thread has an average strength of 980 cN, while the 120 thread possesses a higher strength of 1,190 cN. Additionally, both thread types demonstrate an elongation range between 17% and 22%, ensuring flexibility and durability in various sewing applications. The sewing machines used in this study vary in type and operational speed. All machines belong to the JUKI brand and include three different types: lockstitch, 3-4 thread overlock, and chainstitch. The lockstitch machine operates at a speed range of 1,000 to 4,500 RPM, offering high precision for straight stitching. The 3-4 thread overlock machine and the chainstitch machine both function within a speed range of 2,860 to 3,450 RPM, ensuring efficiency in seam formation and fabric edge finishing.

METHOD

Sample preparation

For the seam bursting test, fabric samples measuring 15 × 15 cm were sewn along row and bar lines using two stitch pitch spacings, four needle thicknesses, and four stitch types. The bursting strength tests were conducted using the SDL Atlas M229 Autoburst Bursting Strength Tester by the ISO 13938-1 standard. Single jersey, pique, and interlock fabrics were cut into 15 × 15 cm swatches to carry out the bursting strength tests. For each fabric, two sets of samples were prepared: one along the lengthwise direction and the other along the widthwise direction. The first set of samples was sewn parallel to the loop bar for each stitch type to assess lengthwise bursting, while the second set was sewn parallel to the loop line for each stitch type to evaluate widthwise bursting. In subsequent analyses, the sample groups are referred to as lengthwise and widthwise for the bursting evaluations. Detailed information regarding the samples is provided in table 2.

FINDINGS

The statistical evaluation of the test results was conducted using the SPSS 26.0 software. Analyses were interpreted within 95% and 99% confidence intervals, considering significance levels of $p < 0.05$ and $p < 0.01$. To assess the bursting strength test data, the Shapiro-Wilk test was applied to examine univariate normality, along with assessments for the distribution

Table 2

STITCHING PARAMETERS FOR FABRIC SAMPLES

Fabric type	Colour	Width-wise samples pcs.	Length-wise samples pcs.	Needle sizes	Thread number	Stitch classes	Stitch Density (stitch/cm)
Single Jersey	White	32	32	60-65-70-75	150	301-401-504-514	3-5
	Red	32	32	60-65-70-75	150	301-401-504-514	3-5
	Black	32	32	60-65-70-75	150	301-401-504-514	3-5
	Total	192 pieces					
Pique	White	32	32	65-70-75-80	120	301-401-504-514	3-5
	Red	32	32	65-70-75-80	120	301-401-504-514	3-5
	Black	32	32	65-70-75-80	120	301-401-504-514	3-5
	Total	192 pieces					
Interlock	White	32	32	70-75-80-90	120	301-401-504-514	3-5
	Red	32	32	70-75-80-90	120	301-401-504-514	3-5
	Black	32	32	70-75-80-90	120	301-401-504-514	3-5
	Total	192 pieces					
Grand Total		576 pieces					

Note: * Width-wise samples pcs.: Number of samples sewn in parallel to the loop line; ** Length-wise samples pcs.: Number of samples sewn in parallel to the loop bar.

of quantitative variables. Based on the outcomes of these normality tests, non-parametric methods-specifically the Mann-Whitney U test and Kruskal-Wallis test-were employed for variables that did not follow a normal distribution. Furthermore, regression analysis was utilised to investigate causal relationships among the variables. Table 3 presents the descriptive statistical parameters for the fabric types used in the study, providing a comprehensive overview of their structural characteristics.

Table 3 shows that the tested samples' bursting pressure values ranged from 102.5 to 867.8 kPa. The mean bursting pressure was calculated as 335.4 ± 144.7 kPa, with a median value of 303.7 kPa.

Table 4 presents the statistical evaluation of bursting pressure in single jersey fabrics under experimental parameters. Based on fabric colour, no statistically significant difference was observed in bursting pressure ($p > 0.05$). Bursting pressure ($p < 0.01$) varied significantly according to stitching direction. Samples stitched length-wise exhibited a more significant bursting pressure ($M = 362.0$) than those stitched width-wise ($M = 20.9$ and $M = 203.2$, respectively). This finding implies that the orientation of stitching relative to the fabric's structural axis plays a critical role in its mechanical response under stress, possibly due to fibre alignment and tension distribution. Regarding Stitch Density, bursting pressure showed a statistically significant difference ($p < 0.05$). Fabrics sewn with a 5-stitch density demonstrated higher bursting pressure ($M = 256.7$) than those with a 3-stitch density ($M = 218.6$). Additionally, bursting pressure ($p < 0.01$) was significantly influenced by stitch type. Among the stitch types tested, the 4-thread overlock stitch yielded the highest values for bursting pressure ($M = 305.5$). This outcome suggests that the structural reinforcement provided by overlock stitching improves single jersey fabric stability under

Table 3

DESCRIPTIVE STATISTICS ON FABRICS

Variables	Frequency (N = 576)	Percentage (%)
Knit face structure		
Interlock	192	33.3
Pique	192	33.3
Single jersey	192	33.3
Colour		
White	192	33.3
Red	192	33.3
Black	192	33.3
Knit density		
Wales	288	50
Courses	288	50
Stitch density		
3	288	50
5	288	50
Stitch Classes		
3 Thread Overlock	144	25
4 Thread Overlock	144	25
Chainstitch	144	25
Lockstitch	144	25
Needle sizes		
60	48	8,3
65	96	16.7
70	144	25
75	144	25
80	96	16.7
90	48	8.3
	Avrg.±S.S	**Median (Min.-Max.)**
Pressure (Kpa)	335.4±144.7	303.7 (102.5-867.8)

Table 4

COMPARISON OF SINGLE JERSEY FABRICS' BURSTING PRESSURE WITH SEWING PARAMETERS

Variables		N	Avrg.	Median	S.s	Min.	Max.	H/Z	p
Colour	White	64	261.5	219.7	107.7	111.0	504.0	1.892^a	0.388
	Red	64	279.6	260.2	107.2	102.5	491.0		
	Black	64	260.6	222.8	91.7	114.2	493.7		
Stitch type	3 Thread Overlock	48	273.9	260.2	77.9	131.5	424.4	61.19^a	0.000**
	4 Thread Overlock	48	296.8	305.5	98.6	155.0	443.3		
	Lockstitch	48	178.2	169.1	58.1	102.5	380.5		
	Chainstitch	48	320.0	301.7	107.2	118.0	504.0		
Needle Sizes	60	48	247.304	213.4	94.6844	111.8	416.7	61.19^a	0.000**
	65	48	272.79	230.3	113.5544	102.5	476.9		
	70	48	290.573	265.35	91.8097	159	493.7		
	75	48	258.217	225.55	105.8389	111	111		
Stitching direction	Length	96	332.7	362.0	99.5	128.6	504.0	-8.207^b	0.000**
	Width	96	201.7	203.2	49.8	102.5	323.2		
Stitch density	3	96	253.6	218.6	99.7	102.5	471.3	-2.095^b	0.036*
	5	96	280.8	256.7	103.7	108.9	504.0		

Note: ^{a} Kruskall-Wallis H ,^{b} Z; ** p<0.01;* p<0.05

Table 5

COMPARISON OF PIQUE FABRICS' BURSTING PRESSURE WITH SEWING PARAMETERS									
Variables		**N**	**Avrg.**	**Median**	**S.s**	**Min.**	**Max.**	**H/Z**	**p**
Colour	White	64	267.8	241.9	70.3	178.7	458.2	17.849[a]	0.000**
	Red	64	316.5	308.1	74.5	138.8	537.1		
	Black	64	290.9	271.0	70.2	203.4	484.9		
Stitch type	3 Thread Overlock	48	235.9	228.0	41.9	178.7	374.4	117.702[a]	0.000**
	4 Thread Overlock	48	246.9	243.4	29.4	199.2	323.2		
	Lockstitch	48	382.6	379.2	59.1	278.5	537.1		
	Chainstitch	48	301.5	309.5	49.1	138.8	381.6		
Needle Sizes	65	48	303.3	277.2	77.6	210.3	537.1	4.946[a]	0.176
	70	48	303.6	289.2	74.4	186.1	484.9		
	75	48	282.2	269.9	72.6	138.8	435.6		
	80	48	277.8	257.6	70.0	178.7	464.1		
Stitching direction	Length	96	309.9	297.2	78.3	178.7	537.1	–3.266[b]	0.001**
	Width	96	273.6	256.0	65.1	138.8	432.1		
Stitch density	3	96	284.1	266.9	62.7	138.8	459.6	–0.652[b]	0.514
	5	96	299.4	277.2	83.5	184.5	537.1		

Note: [a] Kruskall-Wallis H ,[b] Z; ** p<0.01;* p<0.05

multidirectional force. Finally, needle size did not show any statistically significant effect on bursting strength ($p > 0.05$), indicating that within the range tested, needle thickness did not substantially affect the bursting behaviour of single jersey fabrics.

Table 5 summarises the statistical analysis results for bursting pressure in piqué fabrics. Bursting pressure ($p < 0.01$) was found to vary significantly according to the fabric colour. Among the colour variants tested, red fabrics exhibited the highest bursting pressure ($M = 308.1$). In the stitch direction, bursting pressure showed a statistically significant difference ($p < 0.01$). Length-wise sewn samples recorded higher bursting pressure ($M = 297.2$) than width-wise sewn samples ($M = 256.0$). This indicates that the seam orientation of the fabric's structural alignment plays a more critical role in pressure resistance than vertical deformation. Bursting pressure did not exhibit a statistically significant difference based on stitch density ($p > 0.05$). Stitch type had a highly significant effect on bursting pressure ($p < 0.01$). Fabrics constructed using lock stitch types demonstrated the highest performance, with bursting pressure ($M = 379.2$) exceeding those observed in other stitch types. These results emphasise the mechanical advantage of lock stitches in distributing stress across the fabric plane. Finally, no statistically significant difference was observed in bursting pressure based on needle size ($p > 0.05$).

Table 6

COMPARISON OF INTERLOCK FABRICS' BURSTING PRESSURE WITH SEWING PARAMETERS									
Variables		**N**	**Avrg.**	**Median**	**S.s**	**Min.**	**Max.**	**H/Z**	**p**
Colour	White	64	438.3	381.3	166.1	162.7	841.9	1.233[a]	0.540
	Red	64	464.1	423.5	174.5	192	867.8		
	Black	64	439.5	376.1	161.1	134.2	758.3		
Stitch type	3 Thread Overlock	48	374.4	328.5	135.4	134.2	646.2	18.060[a]	0.000**
	4 Thread Overlock	48	446.7	389.2	161.4	232.7	738.6		
	Lockstitch	48	455.2	423.5	146.7	276.4	741		
	Chainstitch	48	512.9	438.3	193.4	246	867.8		
Needle Sizes	70	48	496.5	448.2	176.1	242.0	841.9	23.507[a]	0.000**
	75	48	473.5	458.0	170.1	236.2	832.3		
	80	48	465.7	429.3	166.1	201.6	867.8		
	90	48	353.8	307.7	115.2	134.2	559.7		
Stitching direction	Length	96	574.8	589.7	136.1	266	867.8	–10.423[b]	0.000**
	Width	96	319.8	309.9	68.1	134.2	570.6		
Stitch density	3	96	429.313	352.4	160.5418	201.6	786.3	–1.944[b]	0.052
	5	96	465.404	403.15	172.0303	134.2	867.8		

Note: [a] Kruskall-Wallis H ,[b] Z; ** p<0.01;* p<0.05

This indicates that, unlike in interlock fabrics, needle size did not notably impact the structural behaviour of piqué knits under multidirectional stress conditions.

Table 6 presents the statistical analysis results for bursting pressure in interlock fabrics. The findings reveal several significant patterns. Firstly, bursting pressure did not exhibit a statistically significant difference based on fabric colour ($p > 0.05$). Colour does not influence the resistance of the fabric to pressure. Concerning stitching direction, bursting pressure demonstrated statistically significant differences ($p < 0.01$). Specifically, length-wise samples recorded higher bursting pressure ($M = 589.7$) than width-wise samples ($M = 24.2$ and $M = 309.9$, respectively). In terms of stitch density, bursting pressure did not differ significantly ($p>0.05$). The variable of stitch type also showed a statistically significant effect on bursting pressure ($p < 0.01$). Among the stitch types, the chain stitch yielded the highest bursting pressure ($M = 438.3$). These results underline the importance of stitch type selection in optimising fabric performance under multidirectional stress. Finally, needle size had a significant effect on bursting parameters. Bursting pressure ($p < 0.01$) was highest in samples sewn with a size 75 needle, showing values of $M = 25.3$ and $M = 458$, respectively. It suggests that finer needles reduce fabric damage during stitching, enhancing structural durability.

REGRESSION ANALYSIS AND MODEL EVALUATION

Regression analyses were conducted based on the bursting strength data to determine the influence of sewing parameters and optimise them. The regression models were constructed using sewing-related predictors, including needle size, fabric orientation, stitch density, and stitch type. The resulting models for single jersey, pique, and interlock knit fabrics are presented in table 7.

According to the ANOVA test, the regression model developed for single jersey fabric was statistically significant ($F = 76.207$, $p < 0.01$). Examination of the t-test results for model coefficients revealed several significant predictors. Sewing direction significantly affected bursting pressure ($\beta = -131.027$, $p < 0.01$). β values mean that the bursting test of the width-wise fabric samples resulted in 131.027 units of lower bursting pressure compared to length-wise oriented samples. The stitch density was also a significant predictor ($\beta = 27.231$, $p < 0.01$), sewing with a 5 stitch density increased bursting pressure by 27.231 units compared to 3 stitch density. Regarding stitch type, 3-thread overlock stitches significantly reduced bursting pressure compared to 4-thread overlock stitches ($\beta = -22.908$, $p < 0.05$). Lock stitch type also resulted in significantly lower bursting pressure than the 4-thread overlock ($\beta = -118.644$, $p < 0.01$), while chain stitch type contributed to an increase in bursting pressure ($\beta = 23.194$, $p < 0.05$). Needle size, however, was not found to have a statistically significant effect on bursting pressure ($p > 0.05$). The coefficient of determination for the model was $R^2 = 0.712$, indicating that sewing direction, stitch density, and stitch type can explain approximately 71.2% of the variance in bursting pressure for single jersey fabric.

The model developed for pique fabric was also statistically significant ($F = 75.705$, $p < 0.01$). Key findings from the regression analysis are as follows: Needle size significantly negatively affected bursting pressure ($\beta = -1.959$, $p < 0.01$), suggesting that a 1-unit increase in needle thickness resulted in a 1.959-unit decrease in bursting pressure. Sewing direction was also a significant factor ($\beta = -36.244$, $p < 0.01$), where width-wise fabrics led to 36.244 units lower bursting pressure than length-wise fabrics. Stitch density positively influenced ($\beta = 15.340$, $p < 0.01$); sewing with a 5 stitch density increased bursting pressure by 15.340 units compared to 3 stitch density. Among stitch types, the lock stitch had the most significant positive effect ($\beta = 135.717$, $p < 0.01$), followed by the chain stitch ($\beta = 54.544$, $p < 0.01$), both yielding higher bursting pressures than the 4-thread overlock stitch. In contrast, the 3-thread overlock stitch did not exhibit a statistically significant effect ($p > 0.05$). The model's explanatory power was confirmed with $R^2 = 0.711$, indicating that needle size, fabric orientation, stitch density, and stitch type collectively explained 71.1% of the variation in bursting pressure for pique fabric.

The interlock fabric regression model was highly significant ($F = 112.706$, $p < 0.01$), with more substantial explanatory capability than the previous two fabric types. Needle size had a statistically significant negative effect ($\beta = -7.122$, $p < 0.01$), where an increase in needle size corresponded to a 7.122-unit decrease in bursting pressure. Sewing direction was again a significant determinant ($\beta = -254.935$, $p < 0.01$), with width-wise fabric samples leading to substantially lower bursting pressures than length-wise samples. Stitch density also positively and significantly impacted ($\beta = 36.092$, $p < 0.01$), confirming that a high stitch density contributed to increased bursting strength. The 3-thread overlock stitch was associated with a significant decrease in bursting pressure ($\beta = -72.290$, $p < 0.01$), while the chain stitch significantly increased bursting pressure ($\beta = 66.192$, $p < 0.01$). Interestingly, the lock stitch type did not substantially affect bursting pressure in interlock fabrics ($p > 0.05$). The coefficient of determination for this model was $R^2 = 0.785$, suggesting that the combined predictors explained 78.5% of the variance in bursting pressure, making this the most robust model among the three fabric types.

Optimal seam parameters for 3 fabric types are given in table 8 according to the bursting test results.

CONCLUSION

This study comprehensively investigated the effects of key stitch parameters, including sewing direction, needle size, stitch density, and stitch type, on the bursting strength of single jersey, pique, and interlock

Table 7

REGRESSION ANALYSIS ON THE EFFECT OF SEAM PARAMETERS ON BURSTING PRESSURE										
Fabric type	**Variables**	**Unstandardized coefficients**	**Standardized coefficients**	**Unstandardized coefficients**	**t**	**p**	**Multicollinearity statistics**	**Multicollinearity statistics**	**F**	**p**
Single Jersey	Constant	280.505	49.627		5.652	0.000**			76.207	0.000**
	Needle Sizes	1.010	0.721	0.055	1.402	0.163	1	1		
	Length-wise	–131.027	8.056	–0.642	–16.265	0.000**	1	1		
	Stitch Density [5 Stitches]	27.231	8.056	0.133	3.38	0.001**	1	1		
	Stitch Type [3 Thread Overlock]	–22.908	11.393	–0.097	–2.011	0.046*	0.667	1.5		
	Stitch Type [Lockstitch]	–118.644	11.393	–0.503	–10.414	0.000**	0.667	1.5		
	Stitch Type [Chainstitch]	23.194	11.393	0.098	2.036	0.043	0.667	1.5		
Pique	Constant	399.364	38.559		10.357	0.000**			75.705	0.000**
	Needle Sizes	–1.959	0.523	–0.148	–3.748	0.000**	1	1		
	Length-wise	–36.244	5.843	–0.245	–6.203	0.000**	1	1		
	Stitch Density [5 Stitches]	15.340	5.843	0.104	2.625	0.009**	1	1		
	Stitch Type [3 Thread Overlock]	–10.977	8.263	–0.064	–1.328	0.186	0.667	1.5		
	Stitch Type [Lockstitch]	135.717	8.263	0,796	16.424	0.000**	0.667	1.5		
	Stitch Type [Chainstitch]	54.544	8.263	0.320	6.601	0.000**	0.667	1.5		
Interlock	Constant	1117.006	61.994		18.018	0.000**			112.706	0.000**
	Needle Sizes	–7.122	0.767	–0.316	–9.283	0.000**	1	1		
	Length-wise	–254.935	11.347	–0.766	–22.467	0.000**	1	1		
	Stitch Density [5 Stitches]	36.092	11.347	0.108	3.181	0.002**	1	1		
	Stitch Type [3 Thread Overlock]	–72.29	16.047	–0.188	–4.505	0.000**	0.667	1.5		
	Stitch Type [Lockstitch]	8.473	16.047	0.022	0.528	0.598	0.667	1.5		
	Stitch Type [Chainstitch]	66.192	16.047	0.172	4.125	0.000**	0.667	1.5		

Note: ** $p<0.01$; * $p<0.05$; Single Jersey Samples; R = 0.844; R2 = 0.712; Adjustedş R2 = 0.703; Durbin-Watson = 1.713; Pique Samples; R = 0.843; R2 = 0.711; Adjusted R2 = 0.701; Durbin-Watson = 1.586; Interlock Samples; R = 0.886; R2 = 0.785; Adjusted R2 = 0.778; Durbin-Watson = 1.861.

Table 8

OPTIMAL SEAM PARAMETERS ACCORDING TO BURSTING TEST RESULTS				
Fabric type	**Performance**	**Needle sizes**	**Stitch type**	**Stitch density**
Single Jersey	Optimal	Nm 70	Chainstitch	5
Pique	Optimal	Nm 70	Lockstitch	5
Interlock	Optimal	Nm 70	Chainstitch	5

fabrics. The statistical analyses and regression models indicated that sewing direction and stitch type consistently influenced seam performance across all fabric types. In contrast, the effect of needle size varied depending on the fabric structure. Among the models developed, the interlock fabric exhibited the highest explanatory power ($R^2 = 0.785$). It was observed that samples stitched in the length-wise direction exhibited higher bursting strength than those sewn in the width-wise direction, suggesting that seam direction is critical for load-bearing applications. High stitch density (5 stitch) was associated with improved seam durability, presumably due to better mechanical stress distribution. Among the stitch types tested, 4-thread overlock and chain stitch constructions provided superior resistance to bursting forces compared to straight and 3-thread overlock stitches. While thinner needles (e.g., size 75) enhanced performance in interlock fabrics, needle size had a limited effect in pique fabrics. These findings underscore the importance of tailoring stitch configurations to the specific properties of each fabric type. Incorporating such fabric-specific optimisation into the garment design and manufacturing process can significantly improve seam integrity and enhance knitwear's overall performance and durability, particularly in applications subjected to high multidirectional stress.

The findings of this study aim to enhance the understanding of seam-fabric interactions and contribute to the optimisation of garment durability and performance within the textile industry.

ACKNOWLEDGEMENTS

We want to thank Groz-Beckert, Coats, and Ares Örme for their unwavering support of this research. This study depends upon the doctorate thesis supported by Marmara University Scientific Research Projects with the project no of FDK-2023-11125.

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Modified Meek technique using pre-folded polyamide gauzes: a 10-patient case series with extensive burns

DOI: 10.35530/IT.076.05.2025113

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ABSTRACT – REZUMAT

Modified Meek technique using pre-folded polyamide gauzes: a 10-patient case series with extensive burns

Extensive burns still represent a major challenge due to high mortality rates and limited donor skin area availability, particularly in patients with inhalation injuries, advanced age, and large total body surface area (TBSA) burns. This case series presents the clinical outcomes of 10 patients treated with the modified Meek micrografting technique using pre-folded polyamide gauzes at the Emergency Clinical Hospital for Plastic, Reconstructive, and Burn Surgery in Bucharest between 2020 and 2025.

Patients included in this article sustained burns involving more than 20% TBSA, with an average of 56% and a mean Abbreviated Burn Severity Index (ABSI) score of 11. The Meek micrografting technique utilised expansion rates of up to 1:6 and was primarily employed in the initial grafting surgeries. The most commonly affected areas were the thorax, the upper limbs, and the lower limbs. A single Meek procedure was used in seven patients, while the remaining three patients required multiple surgeries, with one of them undergoing four Meek interventions.

In our cohort, the Meek technique demonstrated consistent performance, with actual expansion rates of 89% for the intended 1:6 ratio and 90.02% for the intended 1:4 ratio. Reliable graft take and coverage were achieved using the modified Meek procedure in all ten patients, with minimal regrafting (≤ 3% TBSA) required in initially grafted areas. Despite favorable local outcomes, overall mortality in our group remained high (90%), largely attributable to the severity of initial burn injuries and associated systemic complications.

The modified Meek micrografting technique has proven effective in maximising graft coverage in full-thickness, extensive burns with limited donor areas. However, patient prognosis primarily depends on the severity of burns and the extent of systemic compromise.

Keywords: *Meek grafting, burns, textile wound coverage, full-thickness burns, pre-folded gauze*

Tehnica Meek modificată utilizând comprese pre-plisate de poliamidă: serie clinică de 10 cazuri cu arsuri extinse

Arsurile extinse continuă să reprezinte o provocare majoră în practica medicală, din cauza mortalității ridicate și a disponibilității limitate a zonelor donatoare, în special in cazul pacienților cu leziuni inhalatorii, vârsta înaintată și suprafața corporală arsă (TBSA) extinsă. Prezenta serie de cazuri descrie rezultatele clinice obținute la 10 pacienți tratați prin tehnica de microgrefare Meek modificată, utilizând comprese pre-plisate de poliamidă, în cadrul Spitalului Clinic de Urgență de Chirurgie Plastică, Reparatorie și Arsuri din București, în perioada 2020–2025.

Pacienții incluși în studiu au prezentat arsuri afectând peste 20% din suprafața corporală totală, cu o medie de 56% și un scor ABSI (Abbreviated Burn Severity Index) mediu de 11. Tehnica Meek a fost aplicată în principal în intervențiile chirurgicale inițiale, folosind rapoarte de expandare de până la 1:6. Cele mai frecvent implicate regiuni au fost toracele, membrele superioare și membrele inferioare. Pentru șapte pacienți s-a efectuat o singură procedură de grefare Meek, iar ceilalți trei au necesitat intervenții multiple, unul dintre aceștia beneficiind de patru proceduri succesive.

În această serie, tehnica Meek a oferit rezultate constante, cu un raport efectiv de expandare de 89% pentru raportul teoretic de 1:6 și de 90,02% pentru raportul teoretic de 1:4. S-a obținut o supraviețuire și o integrare satisfăcătoare a grefelor pentru toți cei zece pacienți, cu o rată de regrefare minimă (≤3% TBSA) în zonele inițial grefate. În ciuda rezultatelor locale favorabile, mortalitatea generală a rămas ridicată (90%), aspect atribuibil în principal severității leziunilor inițiale și complicațiilor sistemice asociate.

Tehnica de microgrefare Meek modificată s-a dovedit eficientă în maximizarea acoperirii cutanate în cazul arsurilor extinse, de grosime totală, la pacienți cu zone donatoare limitate. Cu toate acestea, prognosticul vital rămâne strâns corelat cu severitatea arsurilor și cu gradul afectarii sistemice.

Cuvinte-cheie*: tehnica Meek modificată, arsuri, acoperirea plăgilor, arsuri de grosime completă, comprese preplisate*

INTRODUCTION

Extensive burn injuries remain one of the principal causes of morbidity and mortality among the general population. Advances in resuscitation protocols, surgical approaches by early excision and grafting, and improved metabolic support have significantly contributed to reducing mortality rates among burn victims in recent decades. Nonetheless, factors such as advanced age, a high percentage of total body surface area burned, the presence of full-thickness burns, and concomitant inhalation injury continue to be strong predictors of poor prognosis and high mortality rates [1].

Early burn injury excision and coverage with split-thickness skin grafts (STSGs) harvested from healthy donor areas using an electrical dermatome (autografting) remains the gold standard for treating deep burn injuries [2].

As the percentage of burned total body surface area (%TBSA) increases, the scarcity of available healthy donor areas becomes a significant challenge. To address this limitation, several skin graft expansion techniques have been developed to maximise graft coverage most efficiently and effectively.

The method described by Tanner in 1964 allows skin grafts to be expanded from 1.5 up to 9 times their initial surface using a meshing device [3]. However, an expansion ratio greater than 1:3 comes with several disadvantages, including a more fragile autograft that is harder to handle, a characteristic "fishnet" appearance, delayed re-epithelialization, and an increased risk of infection. Additionally, there may be a significant discrepancy between the declared and actual expansion rates [4–6]. Therefore, for extensive burn areas, the micrografting technique described by Meek in 1958 and widely adopted in the late 1990s has proven to be an effective solution for covering the remaining defects after excision. Comparing these two techniques (the mesh graft and the Meek micro grafts), the latter has a more reliable expansion rate, since it depends on the pre-folded fabrics rather than on the skin graft, the method of fixation onto the wound bed reduces the risk of shifting, and it uses smaller skin fragments [7].

METHODS

Study design

We conducted a retrospective analysis of patients admitted to the Burn Unit of the Emergency Clinical Hospital for Plastic, Reconstructive, and Burn Surgery in Bucharest from 2020 to 2025 who underwent one or more skin grafting procedures using the modified Meek technique. Medical records were reviewed, and the following data were collected for each patient: demographics, burn characteristics, operative management, and clinical outcomes. Patients who presented with burns on less than 20% of their body area were excluded, as in our practice, the Meek technique is dedicated exclusively to patients where the availability of uninjured skin is limited.

Surgical management

Once the patients had been adequately resuscitated and were confirmed to be hemodynamically and respiratory stable, they were taken to the operating room for early burn wound excision under general anesthesia. Full-thickness burn wounds were excised tangentially. When necessary, fascial excisions were performed. Hemostasis was achieved using topical epinephrine and electrocautery.

Description of the Meek technique

The split-thickness skin graft (STSG) is harvested using an electrical dermatome and then applied to a square piece of cork (42 × 42 mm), allowing for the assembly of even smaller graft remnants, much like a puzzle. The cork and the graft are then placed in a cutting machine, which cuts only the graft into 14 stripes of 3 mm width. The cork is rotated 90° and passed again, thus resulting in 196 squares of 3 × 3 mm each. After spraying the epidermal surface with an adhesive dressing spray, the covered cork is transferred to a pre-folded polyamide gauze arranged in 14 × 14 mm square pleats on an aluminium foil backing; the pleat size matches the cuts made in the graft. The cork is then gently lifted, leaving the graft islands adherent to the gauze. The polyamide gauze, along with the aluminium foil, is stretched until the pleats are fully extended. The aluminium backing is removed, and the trimmed polyamide gauze is applied to the wound bed with the graft facing down, secured in place with surgical staples. Staples are left in place for 7 days [3].

RESULTS

Patient demographics and burn characteristics

We identified 10 patients with extensive burns who were treated by the modified Meek skin autografting technique, comprising nine males and one female. Ages ranged from 39 to 89 years, with a mean age of 62.3 years. The mean body surface area affected was 56%, with a range of 30% to 85%. Out of ten patients, one sustained burns by contact with a hot liquid, while the remaining nine were injured by flame exposure. In one case, the injury was self-inflicted. All patients sustained grade III (full-thickness) burn injuries. In addition, seven patients also presented with inhalation injury. ABSI score was calculated upon admission for all patients, varying from 8 to 15. The mean ABSI score in our cohort was 11, reflecting severe injury patterns.

The upper limbs were affected in all patients, followed by the lower limbs and thorax (9/10 cases). Cervico-facial burns were observed in six patients, and five patients had injuries involving the perineum or external genitalia (table 1).

Surgical management and grafting procedures

Initial burn excision and grafting were performed between post-injury days 2 and 14, once patients were hemodynamically and respiratory stable. Seven patients required only a single Meek grafting procedure, while three underwent multiple procedures (two, three, or four grafting sessions). Three patients received additional mesh grafts to cover limited residual defects. In one case, severe lower-limb and forearm burns necessitated amputations.

The modified Meek technique was used predominantly in initial grafting procedures, employing expansion

Table 1

	Patient	Gender	Age	%TBSA	Inhalation Injury	ABSI score	Mechanism of injury
Case 1	I.V.	M	75	55%	Yes	12	Flame
Case 2	I.M.	M	45	55%	No	10	Flame
Case 3	S.E.	F	77	35%	No	10	Hot liquid
Case 4	T.M.	M	48	65%	Yes	12	Flame
Case 5	M.V.	M	39	75%	Yes	12	Flame
Case 6	R.V.	M	55	45%	Yes	10	Flame
Case 7	P.M.	M	89	45%	No	11	Flame
Case 8	P.C.	M	85	70%	Yes	14	Flame
Case 9	S.P.	M	60	30%	Yes	8	Flame
Case 10	P.I	M	50	85%	Yes	14	Flame

ratios from 1:4 to 1:6. The Mean donor area was 3.11% TBSA for first procedures and 2.63% TBSA for subsequent interventions. Detailed operative data, including grafted areas and expansion ratios, are summarised in table 2.

For the five patients who required a second debridement and grafting procedure, the surgery was conducted between days 3 and 9 after the initial intervention. In four of these cases, the modified Meek was again the technique of choice for skin expansion. Among patients treated using the Meek technique, an average of 12.5% of total body surface area (%TBSA) was covered during the first intervention. The %TBSA addressed during the second procedure ranged from 7% to 15%, with an average of 10.75%. None of the grafted areas during the initial intervention required regrafting during the second. Among the nine patients who underwent Meek grafting as the initial procedure, the mean donor area was 3.11% of TBSA. For the four patients undergoing a second Meek procedure, the average donor area was 2.63% TBSA. Operative details of the first skin grafting procedure for each case are presented in table 2.

Surgical outcomes

In our series, only two patients, Case 7 (P.M.) and Case 9 (S.P.), underwent more than two Meek-grafting procedures. In seven cases, the reason for discontinuation was a rapid decline in the patients' general status that ultimately resulted in death. One of the patients was transferred abroad for continuation of treatment at the family's request.

Patient P.M. (Case 7), who suffered burns involving 45 % of total body surface area, underwent initially two excision procedures followed by Meek grafting to the anterior thorax and abdomen, as previously described. On post-injury day 13 (six days after the second procedure), a third grafting procedure was performed, targeting the posterior trunk and left arm, totalling approximately 15% TBSA. A 1:4 expansion

Table 2

	Number of SGP*	Day of First Surgery	Technique	%TBSA grafted	%TBSA donor	Expansion rate	Grafted areas
Case 1	1	3	Meek	10%	3%	1:4	Upper limbs Thorax
Case 2	2	3	Mesh**	8%	-	1:3	Left calf
Case 3	2	14	Meek	8%	2%	1:4	Left forearm Right thigh Right hemithorax
Case 4	2	2	Meek	14%	4%	1:4	Bilateral upper limbs
Case 5	1	5	Meek	17%	5%	1:4	Right lower limb Left Upper limb
Case 6	1	4	Meek	10%	2%	1:6	Bilateral lower limbs-anterior face
Case 7	4	2	Meek	10%	3%	1:4	Anterior Thorax
Case 8	1	12	Meek	18%	3%	1:6	Posterior Thorax Gluteal region
Case 9	4	4	Meek	11%	3%	1:4	Anterior Thorax Bilateral upper limbs
Case 10	1	6	Meek	15%	3%	1:6	Left lower limb

Note: * SGP = skin grafting procedures; ** Case 2 – The initial grafting employed the mesh technique, followed by subsequent grafting using the Meek technique.

ratio was used. On postoperative day 5, after removal of carrier gauzes, local evolution was assessed as favourable, with the grafts adherent to the wound bed, despite stagnation in epithelialization. An isolated area of unsatisfactory evolution, characterised by a non-viable wound bed, was noted at the level of the anterior trunk, involving approximately 1.5 %TBSA.

A last procedure was conducted 6 days later and addressed the right lumbar area, right flank, right arm, and cervical region, with a total grafted surface of 7% TBSA. The same expansion ratio of 1:4 was used. Unfortunately, the patient's general condition deteriorated, leading to death three days following the last grafting session.

Patient S.P. (Case 9) sustained self-inflicted burns involving 30% of total body surface area (%TBSA), affecting primarily the trunk and cervical area. Lower and upper limbs were affected to a lesser extent. The initial two surgeries addressed the thorax, abdomen, arms, and flanks. The grafting technique of choice was Meek, with expansion ratios of 1:4 and 1:6, both of which yielded satisfactory results. On post-injury day 15 (day 6 after the second procedure), a third Meek grafting procedure was performed on 10% TBSA. The procedure involved the thighs, right cervical area, and the right flank, the latter being the only site where regrafting was necessary.

After the removal of polyamide gauzes and staples on post-operative day 7, daily dressings were performed using a non-adherent, sterile gauze. The post-operative course was assessed as satisfactory by the surgical team, with approximately 90% of the skin grafts adherent to the wound bed. A final grafting procedure was conducted 15 days later. Given the limited area addressed (left cervical area) and the low rate of expansion needed, the mesh technique was employed. Despite an initial favourable course, marked by good epithelialization of the wound injuries, the patient's general condition declined, with death occurring on day 37 post-admission. Figures 1–3 demonstrate different stages in the course of treatment.

Fig. 1. Initial presentation of patient S.P. (case 9) with full-thickness burns on the anterior trunk

DISCUSSIONS

In our clinic, the mesh technique remains the most frequently employed method for skin graft expansion in small and moderate burns, due to its simplicity, speed, effective fluid drainage, and adaptability to body contours [8]. Despite these benefits, the mesh technique has notable limitations when treating extensive burns, as the expansion achieved is significantly lower than the theoretical ratios. For example, at a theoretical expansion ratio of 1:3, only 53.1% of the expected expansion rate was obtained in practice [9]. This discrepancy is critical in major procedures, where maximising skin coverage while minimising donor site harvesting is essential.

Consequently, to address this limitation, the Meek technique is preferred for patients presenting with extensive burns and limited donor areas. First described in 1958 by an American surgeon, the method was developed on the principle that skin grafts epithelialize from the periphery, and reducing graft size increases the cumulative perimeter-to-area ratio, thereby accelerating wound closure. In the original method, micrografts were applied onto parachute silk carriers and placed on the wound bed. Although conceptually innovative, the technique was technically demanding: the silk needed soaking, graft separation required two operators, and additional steps were needed for perforation and trimming. Due to its

Fig. 2. Polyamide gauze is applied with the graft facing down onto the wound bed and secured in place with surgical staples

Fig. 3. Skin graft islands in different stages of epithelialization, 5 days after the third grafting procedure

complexity and time-consuming nature, the Meek technique did not gain popularity and was eclipsed by the more expedient technique of mesh grafting [10, 11].

Decades later, with the improved early survival, the lack of suitable donor sites in severely burned patients emerged as a significant limiting factor in wound closure. The renewed interest in the micrografting technique among plastic surgeons led to the development of the Modified Meek technique, which used pre-folded polyamide gauzes with an aluminium foil backing. This new design allowed for faster expansion by a single operator, eliminating the need for bandage perforations. As a result, this innovation reduced operative time [12, 13]. Beyond practicality, the polyamide carrier introduced important functional advantages:

- pleated structure ensuring predictable expansion ratios up to 1:9 [14, 15];
- mechanical stability providing secure fixation, preventing graft shifting, and acting as a first protective layer [13];
- controlled geometry of pleats ensures consistent spacing and layout of skin elements, critical for optimal re-epithelialization [12, 13, 16];
- semi-transparent fabric that enables wound monitoring before removal;
- semi-permeable structure facilitates drainage and gas exchange, preventing desiccation and creating a favourable wound environment [6, 17–22].

In our clinical experience, those properties translated into reliable outcomes. At a 1:6 expansion ratio, an average of 14.33% TBSA was successfully grafted, utilising approximately 2.66% TBSA of donor skin, equivalent to 89% of the expected coverage. Among the patients where an expansion ratio of 1:4 was used, an average of 12% TBSA was grafted from a mean donor area of 3.33% TBSA, corresponding to 90.02% of the predicted surface. Although the expansion rates achieved in our series are slightly lower than those reported by Kamolz et al. [9], they remain remarkably high, reinforcing the Meek technique as the preferred option when treating extensive burns.

In our cohort, the Meek technique demonstrated a high rate of graft take, even in patients with poor general health. Only limited areas were submitted to regrafting, specifically a region of approximately 1.5% on the trunk for patient P.M. (Case 7) and an area of approximately 3% TBSA on the right flank for patient S.P. (Case 9).

Despite favourable local outcomes of burn injuries treated by the Meek technique, the overall prognosis remained poor, with nine of ten patients succumbing to their injuries. This high mortality rate is primarily attributable to the severity of the initial injuries and associated systemic complications. Additionally, old age is a well-established factor of negative prognosis in burn survival. In our cohort, the mean age was 62.3, with two patients aged 85 and 89, respectively, which is higher than in all patient populations included in the systematic review by Quintero et al. [6].

This apparent paradox illustrates a crucial point: while material and textile innovations can ensure reliable local outcomes, they cannot overcome systemic determinants of mortality. From a clinical practice perspective, this highlights the role of textile-based carriers, such as polyamide gauzes, in enabling optimal wound closure, while underscoring the need to integrate aggressive resuscitation, critical care optimisation, infection control, and multidisciplinary support alongside surgical strategies.

Limitations of our study include a small number of cases, the unicentric and retrospective design, and the reliance on subjective assessments documented by the treating clinical team in patients' records.

CONCLUSION

The Meek micrografting technique represents a superior method for achieving wound coverage in extensive full-thickness burn injuries and is commonly used in our centre. This 10-patient case series demonstrated high graft take, with a reduced need for further regrafting in the initially treated areas, even at high expansion rates. Although the overall survival rate remained low, primarily due to inhalation injury, systemic complications, and advanced age, this method is a valuable tool in the surgical management of extensive burns, particularly when donor sites are limited.

ETHICAL APPROVAL

This case series was approved by the Ethics Committee of the Emergency Clinical Hospital for Plastic, Reconstructive, and Burn Surgery (Resolution No. 16/24.07.2025). All procedures were conducted in accordance with the principles outlined in the Declaration of Helsinki.

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