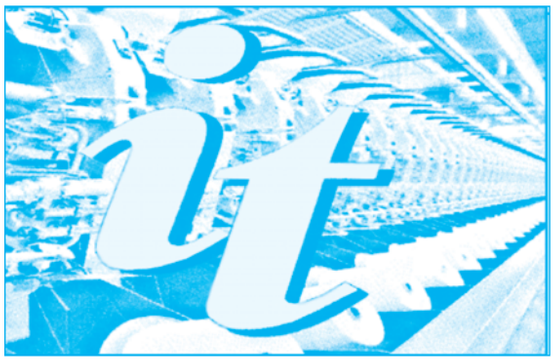


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Best recommended method for washing to disinfect and deodorise waste turkey feathers intended for insulation purposes

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EROL MÜSLÜM

ABSTRACT – REZUMAT

Best recommended method for washing to disinfect and deodorise waste turkey feathers intended for insulation purposes

Waste turkey feathers (TF) must be washed to be used in the production of composite or nonwoven surfaces. Despite cleaning, these fibres can develop strong odours, especially as temperature increases. The gas chromatography-mass spectrometry (GC-MS) method was used to determine the oils and fatty acids that cause odour in clean or dirty TF structure and to see their changes depending on temperature. Fourier transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) images were used to determine whether there was any change in the chemical structure of the feathers after washing. The washing program results were compared, and the W6S program was identified as the most effective method for eliminating volatile substances that may cause odour. According to GC-MS results, the total area of the peaks covered by fatty acids and other substances in the chromatogram decreased by 593 times at 24°C and by 1250 times at 85°C compared to the W1 washing program. This situation provided saponification under the effect of sodium hypochlorite, which is a very strong base. Then, washing with nonionic soap, rinsing with sodium hydroxide and centrifuging were carried out to obtain odourless TF.

Keywords: *turkey feather, disinfection of turkey feathers, bad odours, fibre washing method, gas chromatography-mass spectrometry*

Cea mai recomandată metodă de spălare pentru dezinfectarea și dezodorizarea penelor de curcan uzate, destinate izolării termice

Penele de curcan reziduale (TF) trebuie spălate pentru a putea fi utilizate în producția de suprafețe compozite sau nețesute. În ciuda procesului de curățare, aceste fibre pot emana mirosuri foarte neplăcute, în special odată cu creșterea temperaturii. Metoda cromatografiei de gaze-spectrometriei de masă (GC-MS) a fost utilizată pentru a identifica uleiurile și acizii grași care provoacă mirosul în structura TF curate sau murdare și pentru a observa modificările acestora în funcție de temperatură. Imaginile au fost obținute prin spectroscopie în infraroșu cu transformată Fourier (FTIR) și cu microscopul electronic de baleiaj (SEM) pentru a determina dacă a existat vreo modificare a structurii chimice a penelor după spălare. Rezultatele programelor de spălare au fost comparate și s-a stabilit că cea mai eficientă metodă de curățare pentru eliminarea substanțelor volatile care pot provoca mirosuri neplăcute este programul W6S. Conform rezultatelor GC-MS, aria totală a vârfurilor corespunzătoare acizilor grași și altor substanțe din cromatogramă a scăzut de 593 de ori la 24°C și de 1250 de ori la 85°C, comparativ cu programul de spălare W1. Această situație a permis saponificarea sub efectul hipocloritului de sodiu, care este o bază foarte puternică. Apoi, s-a efectuat spălarea cu săpun neionic, urmată de clătirea cu hidroxid de sodiu și centrifugare, pentru a se obține TF inodore.

Cuvinte-cheie*: pene de curcan, dezinfectarea penelor de curcan, mirosuri neplăcute, metoda de spălare a fibrelor, cromatografie de gaze-spectrometrie de masă*

INTRODUCTION

As a result of turkey meat production, a large amount of TF is released. The statistics show that more than 600 million turkeys are slaughtered every year for meat [1]. It is stated that the total meat production in the 15 countries that produced the most turkey meat worldwide in 2021 was 6.1 million tons [2]. The weight of a TF varies depending on factors such as breed and feeding conditions. Research shows that mature feather weights for different turkey species are around 440 g for female Ross turkeys and 620 g for males [3, 4]. When the number of turkeys slaughtered annually in the world and the average amount of feathers on a turkey are taken into account, it is seen that approximately 0.5 million tons of TF can be released annually. It is predicted that this waste material will increase every year due to increasing turkey meat production.

When the literature is examined, it is seen that a very small portion of these waste feathers are ground and used as feed after boiling at temperatures of 140°C or higher. It is understood that the majority of feathers other than these are disposed of by burning or burying them in the ground. These waste feathers pollute soil, surface water, and groundwater and produce greenhouse gases [5, 6]. Turkey and poultry feathers contain large amounts of nitrogen, which causes high amounts of nitrogen oxides (NOx) to

form during the burning process. This transformation can also lead to the formation of hydrogen cyanide (HCN) [7]. Researchers say burning poultry waste can produce more toxic air emissions than coal-fired power plants [8–10].

There are searches for the use of these wastes in industrial areas or buildings. Turkey and poultry feathers are used in ready-made clothing as filling material, panels for heat and sound insulation, paper production, and in the production of composite materials for insulation purposes by covering them with decorative fabrics. To obtain and use fibre from TF, it must be cleaned of dirt, blood, bacteria, dust, and oil, and it must be ensured that it does not smell or deteriorate over time. Turkeys, like other poultry, have oil that they produce from their bodies. This oil often sticks to the feathers and does not come off unless you clean it well. When feathers are processed at different temperatures, these oils can cause unpleasant odours [11]. Many substances in the feather structure can cause odour or cause the feather to deteriorate and rot. According to Costa and his friends, feathers have approximately 99% volatile solids [12]. About 92% of these are protein and 2.79% are fat [13]. Turkeys regularly oil their feathers throughout their lives. A male Ross turkey accumulates 0.114 grams of oil in his feathers per day [3]. This situation causes heavy oil to accumulate in the feathers over time. When feathers are plucked, there is a breakdown of the oils in the feathers. It is important to remove this broken oil from the feathers. Therefore, the method used to eliminate oil during washing to be performed is very important.

There are no significant studies on the detailed washing and disinfection of TF in the literature. However, there are studies using different methods for washing wool, chicken, and some bird feathers. One group of researchers washed bird feathers in ethanol. The purpose of the ethanol washing process is to clean the feathers and remove any lingering odour [14–17]. Some researchers washed the feathers with detergent and dried them [18]. There are also studies on the effects of washing with different surfactants on the structure of chicken feathers [19]. In another study, fresh feathers taken from chicken bodies were washed in water, aired for a period of time, and then dried in an oven. To eliminate any residual oils, the feathers were treated with petroleum ether utilising a Soxhlet apparatus [20].

There are studies showing that using equipment such as an ultrasound bath and centrifuge positively impacts washing quality and significantly increases cleaning efficiency by removing unwanted substances, bacteria, and moisture from the fibres. Researchers are using ultrasonic cleaning because of its cleansing and antibacterial properties [21–23]. In ultrasonic washing, mechanical actions that help clean fabrics are provided by sound waves [24]. In his research, Ma used ultrasonic energy to clean silk fabrics, aiming to achieve a better appearance after washing. He found that it provided better results than machine washing in removing common stains and maintaining the fabric's appearance and dimensions [25].

Another effective method for cleaning, partial drying, and deodorisation after washing is centrifugation. This process removes dirt, bacteria, and moisture from the fibres, which increases its cleaning efficiency. There are many patented centrifuge cleaning machines with different operating principles available. These machines feature a rotating carousel and a servo-controlled shower nozzle to efficiently wash products. High-speed rotating systems separate the fibres from the liquids, removing surface dirt. During the cleaning process, they utilise a belt, a cleaning device, and an induced draft system to minimise secondary contamination by absorbing water vapour [26–29]. For example, it has been stated that the separation of wool wax becomes easier when fibres that contain a lot of oil in their structure, such as wool, are centrifuged after washing [30, 31]. Centrifuging after yarn dyeing in the package effectively removes 88.2% of solid impurities, resulting in cleaner, smoother fibres. Centrifuging improves friction and electrical properties while reducing spinning dust [32].

Another method used to disinfect bird feathers is the use of ultraviolet (UV) light. Xiaolin and his colleagues have successfully and effectively eliminated bacteria in feathers with the UV device they developed for cleaning and disinfecting bird feathers. The use of UV light is complemented by mechanical systems that ensure the feathers are fully exposed to the disinfecting agents, increasing their overall effectiveness [33, 34]. Yungang has received a patent for cleaning protein fibres with a UV method, removing dust and bacteria. In addition, cleaning efficiency has been increased by designing devices with improved electrostatic, mechanical, and dust collector components and friction mechanisms to increase cleaning efficiency [35].

Another method used in feather processing is ozone disinfection. A new device has been developed to achieve comprehensive sterilisation and odour removal by adding ozone to the ultraviolet disinfection method [34]. Some researchers have developed specialised equipment for cleaning and disinfecting feathers. These devices have been reported to shorten cleaning and disinfection processes and decrease worker workload, resulting in more efficient results [36]. There are studies that subject feathers to an ozonisation process after a conventional wash with surfactants and disinfectants. Ozone's antibacterial properties and odour-eliminating properties were utilised to achieve this cleaning [37, 38].

Fayez and Halıq, in their studies on the disinfection of some bacteria present in poultry hatcheries, stated that disinfectants such as Aquavinol® at a concentration of 5% showed superior effectiveness against pathogens such as E. coli and Salmonella [39]. Paşayev and colleagues found that the most effective cleaning method in terms of removing volatile substances that can cause foul odour from chicken feathers was a short pre-wash with sodium hypochlorite and a finishing treatment with sodium hydroxide

solution, followed by a main wash with a nonionic detergent [40]. It has been stated that ideal cleaning and disinfection are achieved in the washing with sodium hypochlorite in a household washing machine when cleaning the feathers of poultry [41].
When these results from the literature and the data obtained from my applications are examined, it becomes clear that as the time the feathers remain dirty without being washed increases, disinfection becomes more difficult, and removing the odour from the fibres becomes almost impossible. A review of the literature reveals no studies on the disinfection of waste TF. The first step in using waste material for the production of high-value-added products is disinfection and making it smell clean. In this study, different washing methods were used, and after testing the results, the best method was determined and recommended for researchers and manufacturers interested in working in this field.

MATERIAL AND METHOD

Material

The TF used in this study was supplied dirty from a local business and received approximately two days later. To prevent odour and damage to the feathers, a quick, simple wash and rinse with water was performed, then they were dried and prepared for washing. Eleven different recipes, and therefore different chemicals, were used in the washing processes. Chemicals such as soda (Na_2CO_3), nonionic detergent alkyl phenol ethylene oxide (phenyl ethyl alcohol), neutral granular soap, carbon tetrachloride (CCl_4), sodium hypochlorite (NaClO), and sodium hydroxide (NaOH) were used. Equipment such as beakers, heaters, ultrasound devices, and centrifuges was used according to the washing method and program.

Working method

Approach

The fibres need to be disinfected to produce a high-value-added product from TFs and to ensure their long-term use. The feathers must be free from oil, dirt, dust and blood and bodily fluids which accumulate on them during wet removal. The production of TF requires the use of chemicals, hot water, and sometimes a hot press. The oils in the TF can cause odour due to these heat treatments. Various chemicals were used to remove odour because acidic or alkaline washing conditions are required to remove odour. The quantity of chemicals used, the water temperature in the recipes, and the processing times were analysed based on the results of preliminary studies and then applied according to the best wash recipe. The GC-MS device was used to determine the elements that remained in the feather structure after the washings and could cause odour. The feathers subjected to 11 different washing procedures were measured at 24°C and 85°C. The odour produced by the feathers varies depending on the temperature. By comparing the resulting chromatograms, conclusions were drawn about the effects of different temperature regimes on the odour of the feather material, depending on the washing method. Images were taken using a JEOL JSM-6510 scanning electron microscope (SEM) to examine the surface and internal structural morphology of the TFs. Fourier transform infrared spectroscopy (FTIR) analyses were also conducted to assess changes in the chemical structure of the feathers after washing.

SEM image of turkey feathers

One sample was taken from each of 11 washing processes performed using different recipes to examine the structural properties of the fibres. To this end, the fibres were cross-sectioned using a scalpel from the hard part of the feather called the rachis. After the fibres were coated with Pd/Au, they were imaged with an SEM to examine their internal structure.

Preparation of washing methods and washing programs

Detailed information about the washing programs (coded W2, W3, W4, W5, and W6) is provided in table 1, along with washing charts that list the recipes, chemical cleaners, temperatures, and durations for which they are used. The W1 wash is a prewash performed to remove natural and artificial impurities, such as dirt, sweat salts, dyes, etc., from the TF. No washing agents were used in this wash, and the dirty feathers were washed at 30°C for 5 minutes. The goal is to begin the main wash with relatively cleaner fibres. The feather quantity used in these studies is 50 grams, and the liquor ratio is 1:20.
In this study, the TFs coming out of each of the available washing programs were subjected to the spinning and drying process in the centrifuge machine for 15 minutes. The purpose here is to demonstrate the washing effect and odour removal effects of centrifugation. By removing the small amounts of oil, dirt, liquids, and chemicals trapped between the fibres during this process, the result is cleaner, odourless, and drier fibre. The washing processes run through the centrifuge are coded as W2S, W3S, W4S, W5S, and W6S. Figure 1 provides a graphical summary of these washing processes.

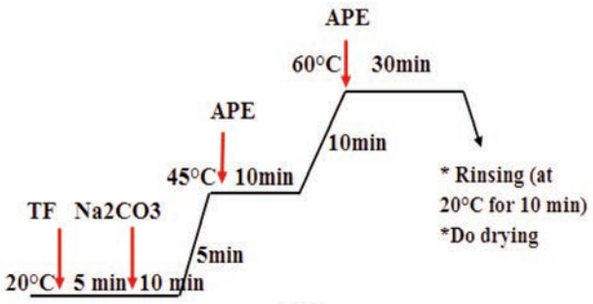
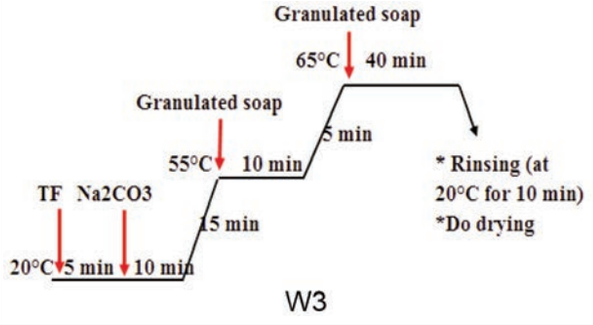
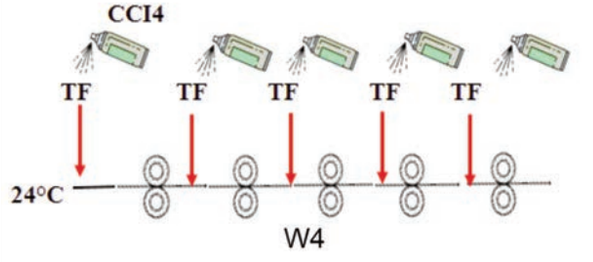
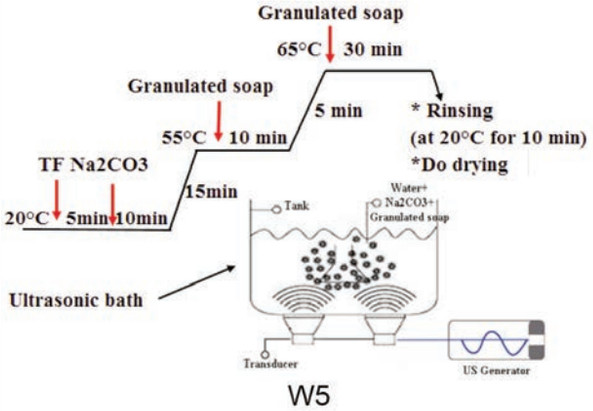
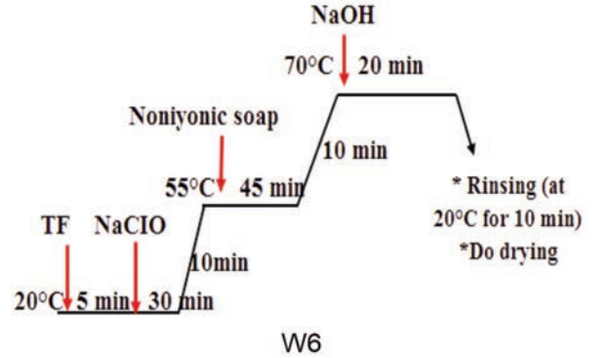
FTIR analysis of feathers washed in different ways

FTIR spectroscopy was used to determine whether there were any changes in the chemical structure of the feathers after washing. For this purpose, measurements were taken from samples of dirty and washed feathers.

Gas chromatography-mass spectrometry (GC-MS)

Steam distillation was used to obtain extracts from feather samples that had been cleaned. An Agilent 7890A GC/5970C model MS detector and an Optima delta-60, 0.25 micrometre (60 m × 0.25 mm ID) column were employed in a GC-MS instrument that used a flame ionisation detector (FID) and MS detectors concurrently for this purpose. The headspace method was used to establish the chromatographic conditions. One gram of TF was weighed on a precision balance and put in a GC vial for this purpose.

WASHİNG PROGRAMMES, CHEMİCALS USED AND PROCESSİNG TİMES

Washing programme chart	Chart explanation
 W2	At a temperature of 20°C, 50 g of TF subjected to the W1 process is soaked in 1 litre of water for 5 minutes. Then, Na_2CO_3 (sodium carbonate) is added to the mixture, and the process is continued for another 10 minutes. The solution temperature is raised to 45°C within 5 minutes. At this stage, 2.5 g of hydrophilic non-ionic detergent Alkyl Phenol Ethylene (APE) is added, and the mixture is processed for 10 minutes. The temperature is then raised to 60°C within 10 minutes, and at this stage, an additional 2.5 g of APE is added, followed by a 30-minute wash. The sample is then removed, rinsed, and dried at 20°C for 10 minutes.
 W3	50 g of TF, which has undergone the W1 wash process, is soaked in 1 litre of water at 20°C for 5 minutes. It is then treated with Na_2CO_3 for 10 minutes. The solution temperature is raised to 55°C within 15 minutes. At this stage, 4 g of granular soap is added, and the process is continued for 10 minutes. The temperature is then raised to 65°C within 5 minutes, and another 4 g of granular soap is added at this stage, and the wash is continued for 40 minutes. The sample is then removed and rinsed at 20°C for 10 minutes. The process is completed by drying.
 W4	In the W4 program, 200 mL of carbon tetrachloride (CCl_4) solvent was used instead of water. CCl□ is a colourless, non-flammable, heavier-than-water liquid with a chloroform-like odour. In this wash, the feathers were laid out on a fibre mat and sprayed with solvent. Then, they were passed between two rollers for squeezing. The process was completed by spraying the solvent five times and passing through the squeezing rollers.
 W5	The W5 program is the same as the W3 washing program, except that the washing process is carried out in an ultrasonic bath. 50 g of TF, previously subjected to the W1 process, is soaked in 1 litre of water at 20°C for 5 minutes. It is then processed in Na_2CO_3 for 10 minutes. The solution temperature is raised to 55°C within 15 minutes. At this stage, 4 g of granular soap is added, and the process continues for 10 minutes. The temperature is raised to 65°C within 5 minutes, and another 4 g of granular soap is added. After washing for 40 minutes, the sample is removed, rinsed at 20°C for 10 minutes, and dried.
 W6	TF was added to 1 litre of water and soaked for 5 minutes, followed by 50 mL of sodium hypochlorite (NaClO) and pre-washed for 30 minutes. Then, the main washing process was carried out using non-ionic soap. Here, 8 mL of soap washing agent was added to 1 litre of water to prepare the solution, and the pre-washed feathers were washed in this solution at 55°C for 45 minutes while being stirred. After this stage, the feathers were bleached and rinsed. The temperature was raised to 70°C within 10 minutes. 5% of the weight of the washed feathers was added to 1 litre of water as NaOH, and bleaching was carried out at 70°C for 20 minutes. Finally, rinsing and drying were carried out at 20°C for 10 minutes to complete the process.

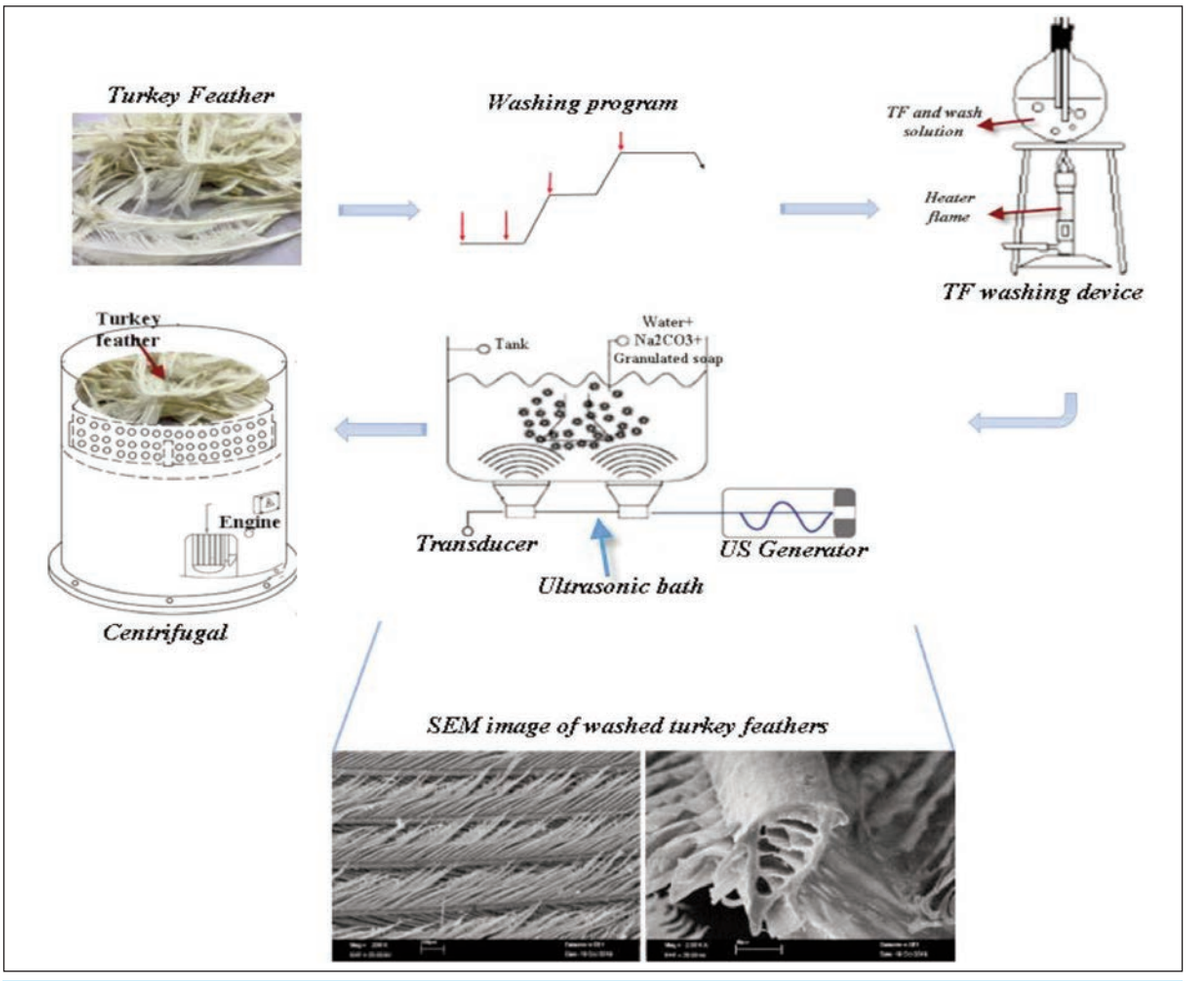


Fig. 1. Graphical summary of the TF washing process

The instrument was filled with the tightly sealed vial. The injector was maintained at 100°C for 30 minutes while the vial was incubated at that temperature. In order to inject 2500 microliters of the final gas into the column, the injector draws gas from the vial three times and then releases it back into the vial.

Conditions for GC-MS: The temperature of the column was maintained at 40°C for 3 minutes, then increased to 190°C at 5°C/min, waited for 3 minutes, then increased to 260°C at 5°C/min, and finally waited for 13 minutes, for a total of 63 minutes. To improve the quality of the separation, a ramped temperature program was chosen. The HS and GC portions of this analysis took 30 and 63 minutes, respectively, for a total analysis time of 93 minutes. The constant gas flow was set at 1 millilitre per minute, and helium was chosen as the carrier gas. The H_2 flow was automatically set to 35 ml/min, the dry air flow to 350 ml/min, and the N_2 to 20–227 ml/min by the instrument software. The Splittles mode was chosen. 290°C was chosen as the ion source, injection temperature, and interface temperature. The m/z (mass/charge) values of the peaks that were obtained and their matches against the Wiley and NIST libraries were used to identify the compound.

RESULT AND DISCUSSION

Morphological properties

After washing, the internal structure of the rachis section of the TF was examined, and its post-washing appearance was examined (figure 2). Accordingly, it was observed that there was no deterioration or deformation in the porous internal structure of the feather.

FTIR results of turkey feathers from different washes

To determine whether the chemical structure of TF was affected by washing and the chemicals used in washing, FTIR analysis was performed on samples taken from dirty and washed feathers. Keratin, which constitutes the majority of cuticle appendages such as hair, nails, animal horns, claws, bird beaks, and bird feathers, is a very common biological material. Insoluble keratin materials, typically composed of proteins with high sulfur content and capable of filament formation, originate from keratin-filled cells and are classified as dead tissue. These biological materials can offer researchers valuable solutions for the production of new structural and functional materials. FTIR analysis of TF samples washed with different washing programs was performed before and after

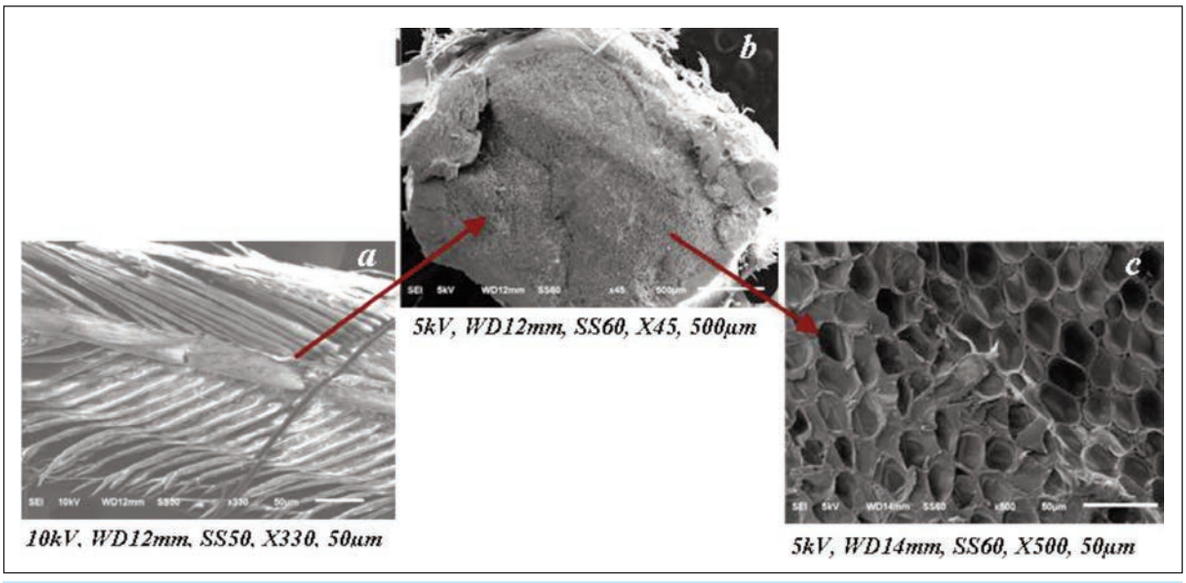


Fig. 2. SEM images of turkey feathers after washing:
a – feather of turkey feather; *b* – rachis section; *c* – hollow internal structure of the feather

washing and cleaning, and TF was analysed in detail. The FTIR spectra of TF in its dirty state (W1) and its washed and disinfected states (W2, W6S, W5) are shown in figure 3. Upon examining the FTIR spectrum obtained from the washed TF samples, the presence of interaction peaks at 3447 (sh broad peak) cm^{-1} from N-H and S-H stretching and possible intramolecular hydrogen bonds formed by –NH bonds is notable. The presence of a characteristic (C=O) peak at around 1705 cm^{-1} (vs very strong), which is found in the main skeleton of the keratin protein, in the FTIR spectrum of the obtained material is an important parameter confirming the keratin structure. The presence of (C1-N), (C3-N), (C1-C1), and ip (C=O) at 1286 cm^{-1}, which are stress peaks originating from C1-N, C3-N, and C1-C1 bonds and planar deformation peaks of the C=O group, also indicates the presence of keratin structure. The peak values of 1535 cm^{-1} and 1521 cm^{-1}, 1635 cm^{-1}, and 1614 cm^{-1} confirm the presence of keratin extract in the obtained material compared with the literature data [42, 43]. The keratin content in the structure was not adversely affected by the washing and disinfection processes, and the resonance peak in the spectrum showed a high degree of similarity to the washed stem sample.

Gas chromatography-mass spectrometry (GC-MS) results

Samples taken from feathers washed and dried using different methods were analysed using a GC-MS device at temperatures of 24°C and 85°C. The peak areas of volatile compounds exceeding 1% in the chromatograms were taken into consideration.

During the GC-MS analysis performed on the extracts obtained at 24°C and 85°C from feathers that underwent only a simple rinsing process with clean water, the retention times (RT), peak areas (PA), and concentrations (% peak area or % PA) of

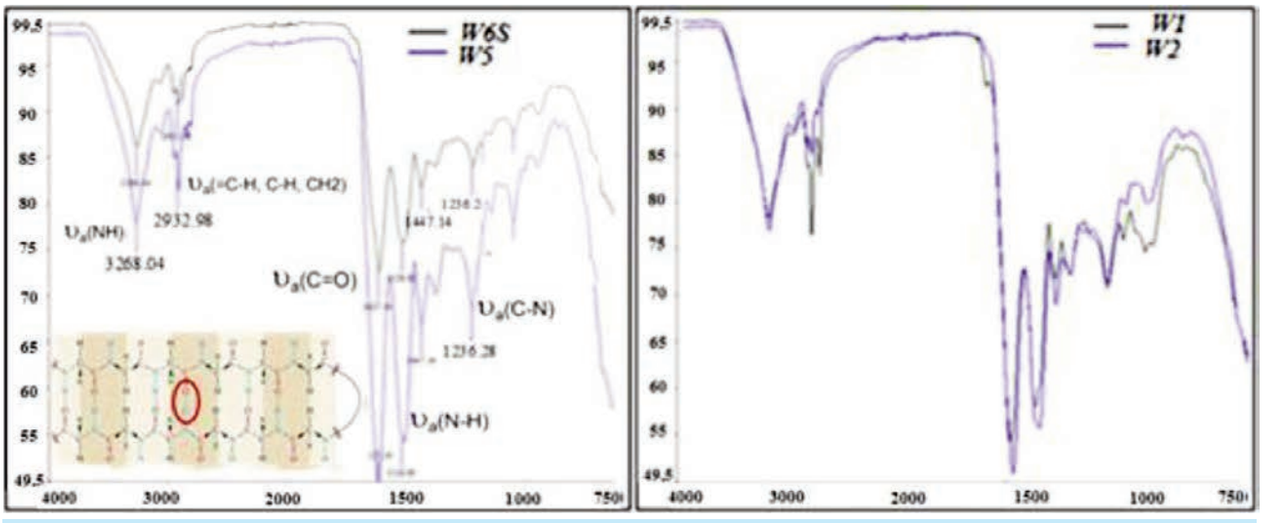


Fig. 3. FTIR spectra of TFs washed according to different washing methods

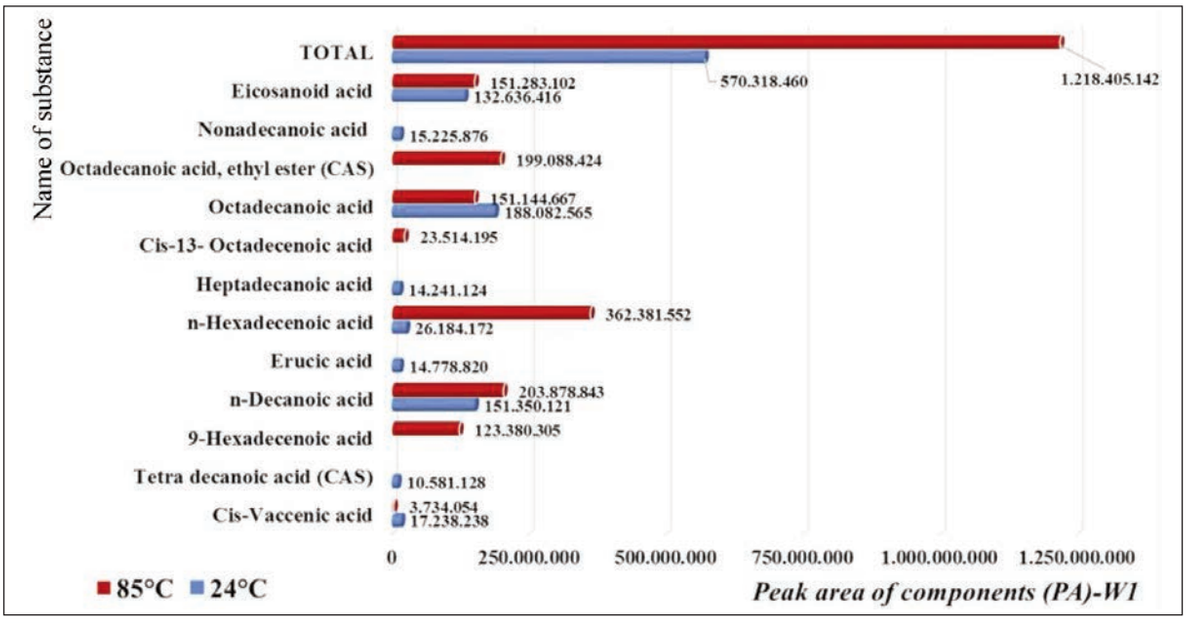


Fig. 4. GC-MS results of W1-coded TF rinsed in pure water

the active components recorded were calculated. The PA, which is the most important data guiding analyses, was considered and reflected in the graphs. The GC-MS results prepared using the PA data of sample W1 at 24°C and 85°C are shown in figure 4.

The presence of volatile substances in the structure of W1-coded turkey feathers rinsed in pure water at different temperatures, and fatty acids released mainly due to hydrolytic changes in the fats in the structure of the feathers, can be observed. When the data in figure 4 is examined, the PA value of the fatty acids in the structure of the W1-coded sample has increased by approximately 2.5 times as the temperature increases. This increase indicates that the odour of the material increases with temperature.

Figure 5 shows the GC-MS analysis results of extracts obtained from feathers washed under washing conditions coded W2 and kept at temperatures of 24°C and 85°C.

When the results in figure 5 are examined, it can be seen that a certain portion of foreign substances and fatty acids in the feathers decreased under the effect of nonionic detergent and sodium carbonate (Na_2CO_3). The overall area of the peaks in the chromatogram covered by fatty acids and other compounds has dropped by 86% at room temperature when comparing the PA data in figure 5 with the data in figure 4. This is a result of the removal of fatty acids due to the effect of the detergent and sodium carbonate used. It is clearly observed that a portion of the fatty acids changes depending on temperature

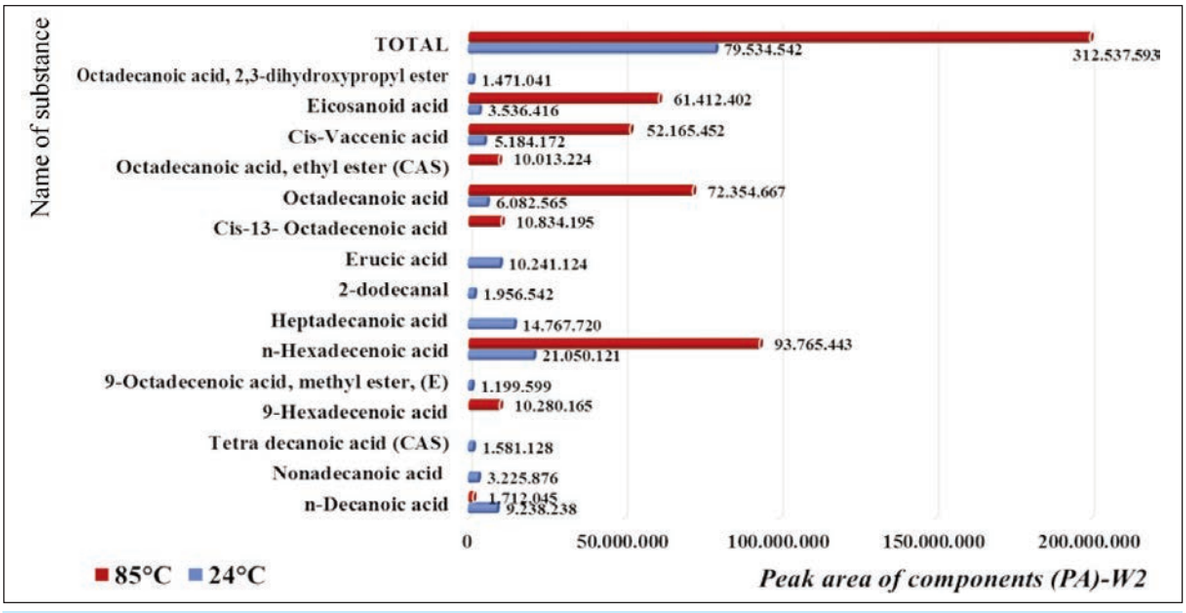


Fig. 5. GC-MS results of TF washed according to prescription code W2

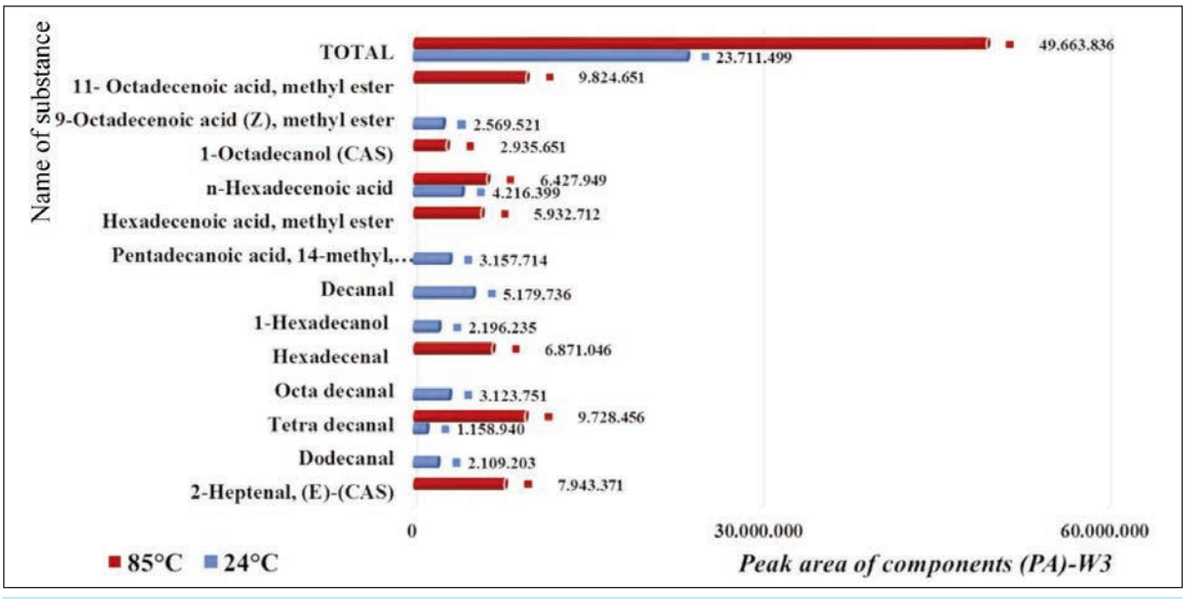


Fig. 6. GC-MS results of TF washed according to W3-coded prescription

variations. Figure 6 shows the GC-MS analysis results of extracts obtained from feathers washed under washing conditions coded W3 and kept at temperatures of 24°C and 85°C.

Looking at the results in figure 6, it can be seen that a significant portion of foreign substances and fatty acids in feathers are reduced by the effect of granular soap and sodium carbonate (Na_2CO_3). When comparing the PA data in figure 6 with the data in figure 4, it is observed that the total area of the peaks covered by fatty acids and other substances in the chromatogram has decreased by 96% at normal temperature. Where the type of fatty acids changes due to the effect of temperature, the detergents used, and the washing method has been identified. However, it was observed that the difference in odour between normal and high temperatures is still very high. The GC-MS analysis results of extracts obtained from feathers washed under washing conditions coded W4 and kept at temperatures of 24°C and 85°C are shown in figure 7.

Examining the results of the W4 washing program, which substitutes a carbon tetrachloride (CCl_4) solvent for water (figure 7), revealed that while the washing result was less successful than W3, it greatly reduced the amount of odour when compared to W1. Overall, though, it appears that the chromatogram's volatile chemical content did not decrease to the intended degree. The fatty acids creating the odour did not reduce to the appropriate level, as seen by the increase in PA brought on by the temperature increase. The GC-MS analysis results of extracts

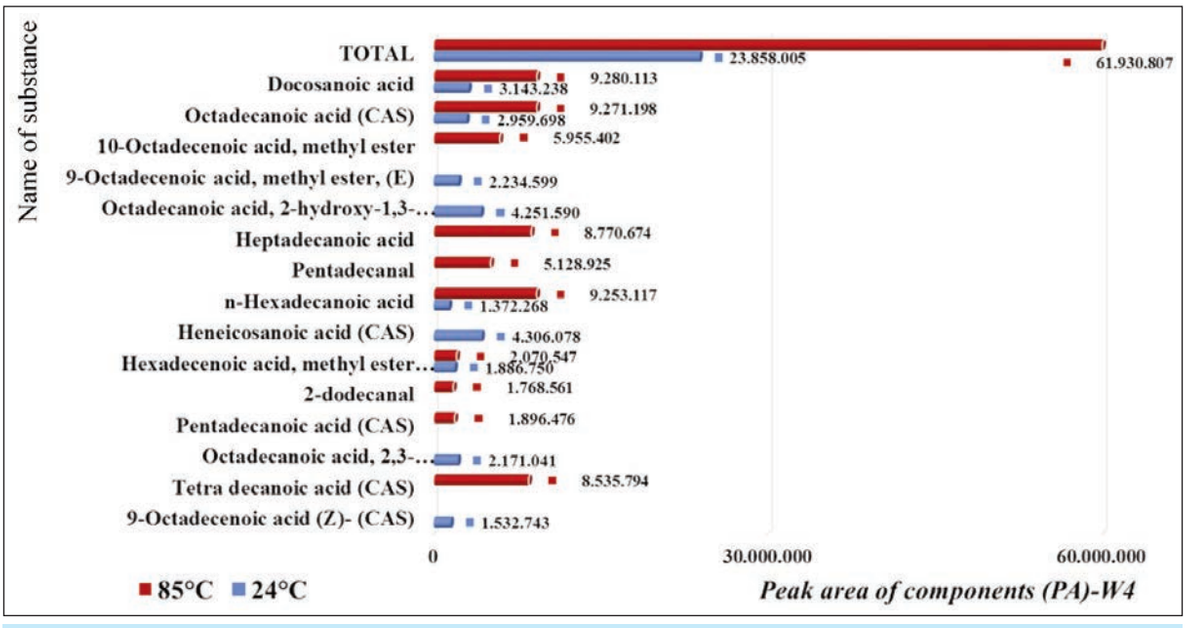


Fig. 7. GC-MS results of TF washed according to prescription code W4

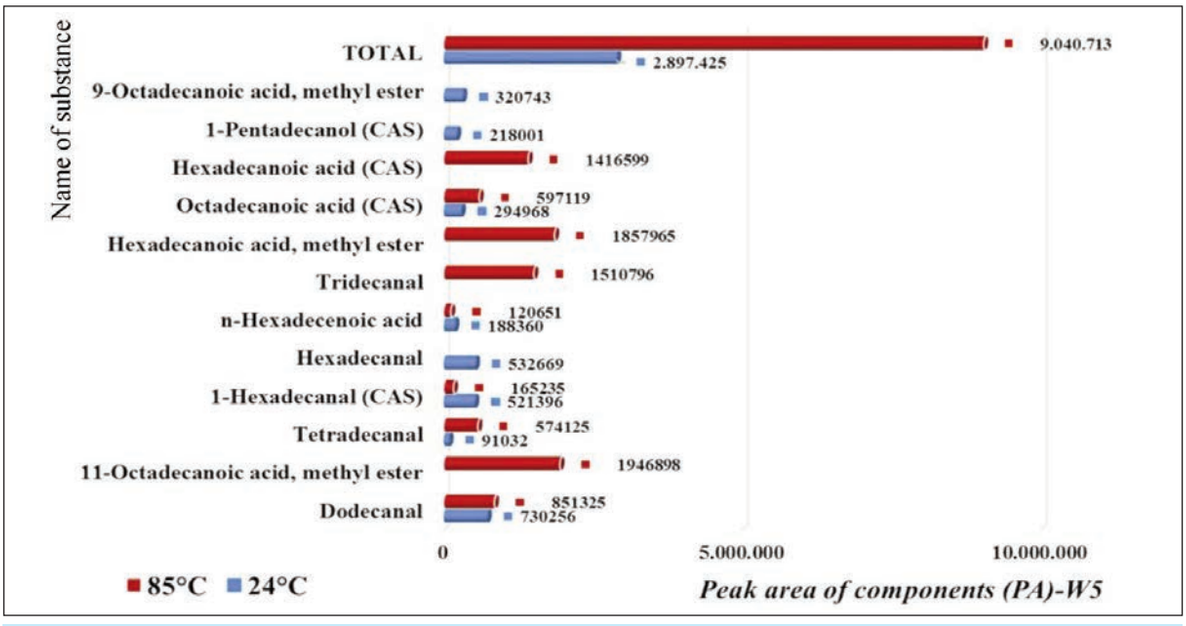


Fig. 8. GC-MS results of TF washed according to prescription code W5

obtained from feathers washed under W5 washing conditions and kept at temperatures of 24°C and 85°C are shown in figure 8.

The main distinction between the W5 and W3 washing programs is that the former uses an ultrasonic bath for the washing procedure. In comparison to the W3 washing process, the chromatograms of the extracts produced at 24°C and 85°C from the samples taken after the W5 washing process demonstrate a considerable decrease in the overall peak areas of the volatiles. This suggests that ultrasonic washing improves the feathers' cleaning capabilities. It is evident from looking at figures 6 and 8 that ultrasonic washing significantly lowers the overall PA. It hasn't yet produced the intended cleaning result, though. Figure 9 displays the GC-MS analysis findings of extracts taken from feathers that were cleaned using washing conditions coded W6 and stored at 24°C and 85°C.

When examining the GC-MS results of extracts obtained from washed feathers at temperatures of 24°C and 85°C, it is evident that the odour remaining in the feathers is primarily caused by fatty acids formed as a result of the hydrolysis of fats and fat residues. For this reason, in the W6 washing method, after the main washing process was carried out with sodium hypochlorite (NaClO) and non-ionic soap, the feathers were subjected to bleaching and rinsing with NaOH to neutralise the fatty acids and residues (table 1 with the detailed recipe).

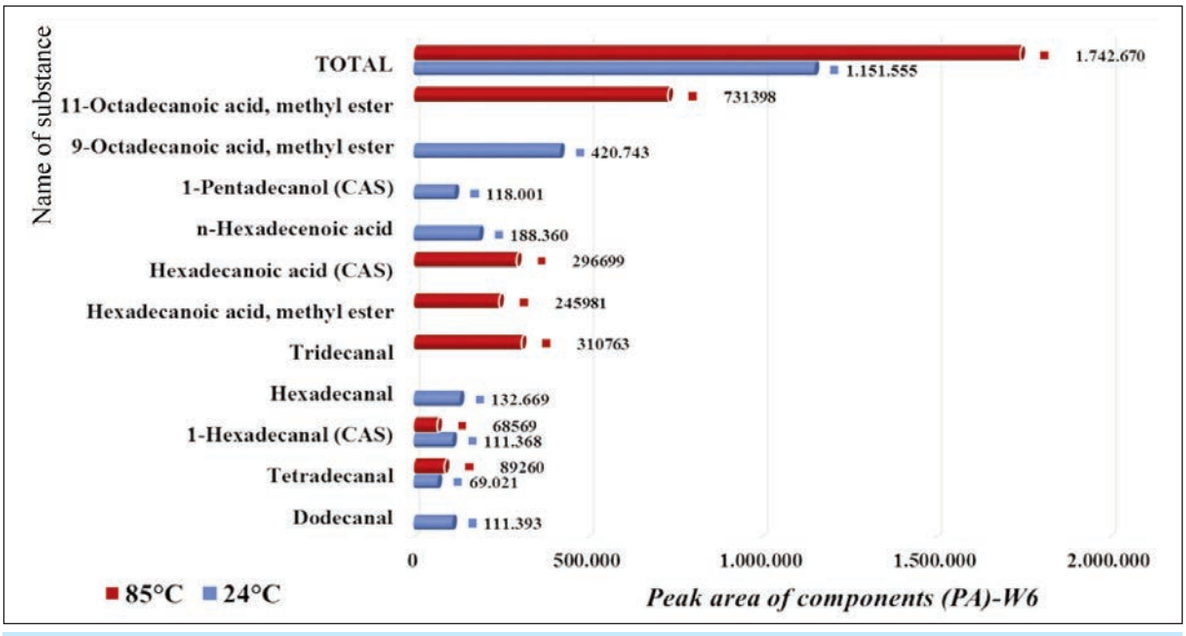


Fig. 9. GC-MS results of TF washed according to prescription code W6

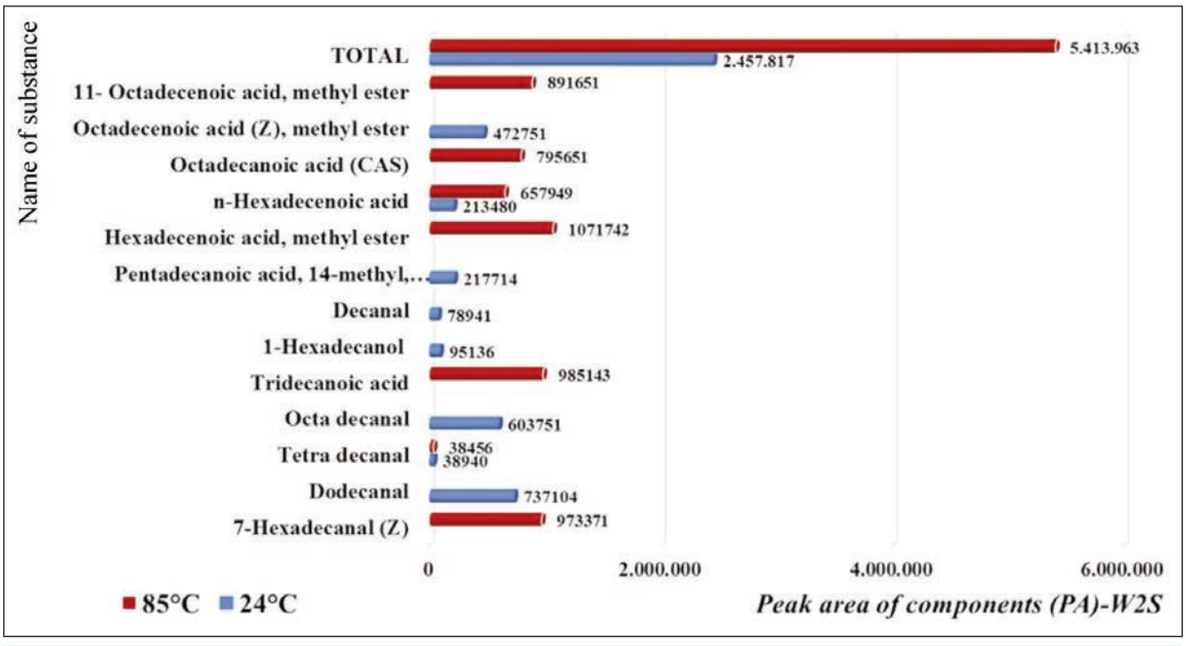


Fig. 10. GC-MS results of TFs washed according to the W2S-coded prescription

When the chromatograms of the samples obtained at low and high temperatures in figure 9 are compared with the chromatograms of the feathers in other washes, it is seen that the total peak areas of the volatile substances formed are minimised.

According to the data in figure 9, it is observed that the total peak area of the volatile compounds released with increasing temperature approaches the total peak area of the volatile compounds released at normal temperature. This suggests that TF's smell won't get stronger as the temperature rises. It has been determined that it is among the best outcomes. Figure 10 shows the GC-MS analysis results of extracts obtained from feathers washed under washing conditions coded W7 and kept at temperatures of 24°C and 85°C. The W2S program is a wash, as determined by processing the feathers washed after the W2 program in a centrifuge machine. To analyse the results of this program, it is possible to compare them with the W2 wash results in figure 5.

The W2S washing programme using a centrifuge machine has been shown to significantly reduce foreign matter and fatty acids in feathers. When compared with the PA data in figure 5, it is observed that the total area of the peaks covered by fatty acids and other substances in the chromatogram decreased by approximately 32 times at 24°C and approximately 58 times at 85°C. This has been evaluated as a result of the centrifuge process used. This result, consistent with the literature, has been confirmed once again by our studies. Another finding is that the types of volatile fatty acids change significantly depending on changes in washing methods. Figure 11 shows the GC-MS analysis results of extracts obtained from feathers washed under W3S washing conditions and kept at temperatures of 24°C and 85°C. The W3S program is a wash, as determined by processing the feathers washed after the W3 program in a centrifuge machine. It is possible to compare the results of this program with the W3 wash results in figure 6.

After W3 washing, it is observed that foreign substances and fatty acids in the feathers are significantly reduced by processing in a centrifuge machine. When compared with the PA data in figure 6, it is observed that the total area of the peaks covered by fatty acids and other substances in the chromatogram decreases by approximately 18 times at 24°C and approximately 15 times at 85°C. This is considered to be a result of the centrifugation process used. Figure 12 shows the GC-MS analysis results of extracts obtained from feathers washed under W4S washing conditions and kept at temperatures of 24°C and 85°C. The W4S program is a washing process determined by subjecting the feathers washed after the W4 program to treatment in a centrifuge machine. The results of this program can be compared with the W4 washing results in figure 7 for analysis.

After W4 washing, it is observed that foreign substances and fatty acids in the feathers are significantly reduced by processing in a centrifuge machine. When compared with the PA data in figure 7, it is observed that the total area of the peaks covered by fatty acids and other substances in the chromatogram decreases by approximately 8 times at 24°C and approximately 5 times at 85°C. This is considered to be a result of the centrifugation process used. While the effect of centrifugation on certain types of washing is more limited, it has been observed to enhance the performance of the washing process. The more limited effect of centrifugation is likely due to the fact that the solvent cleaning process

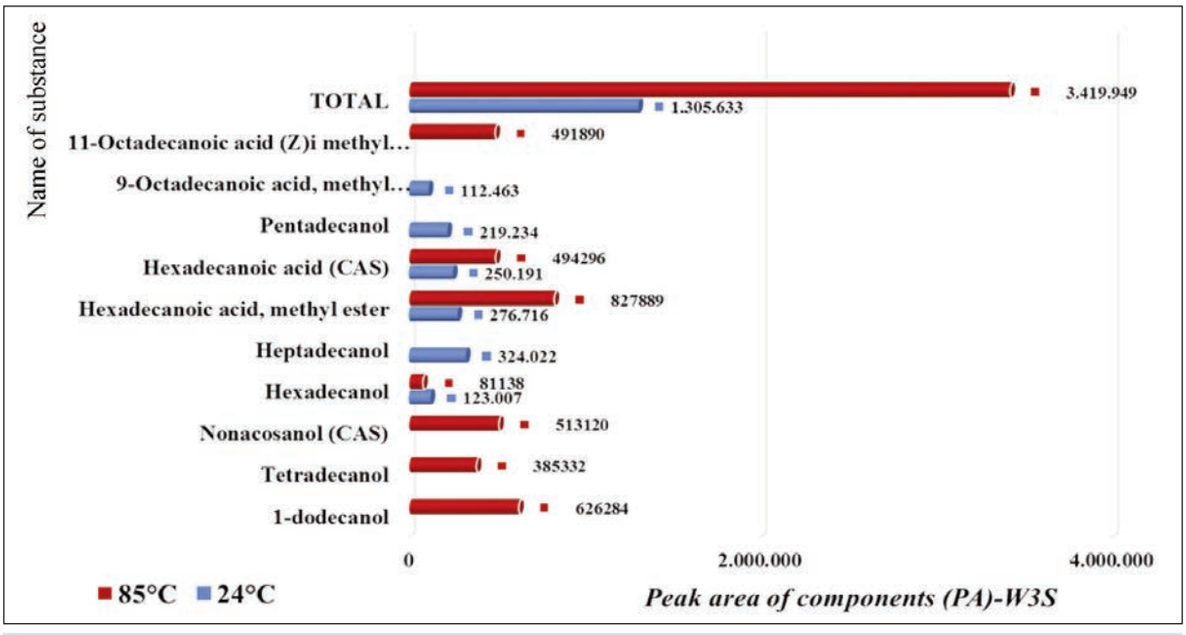


Fig. 11. GC-MS results of TFs washed according to the W3S-coded prescription

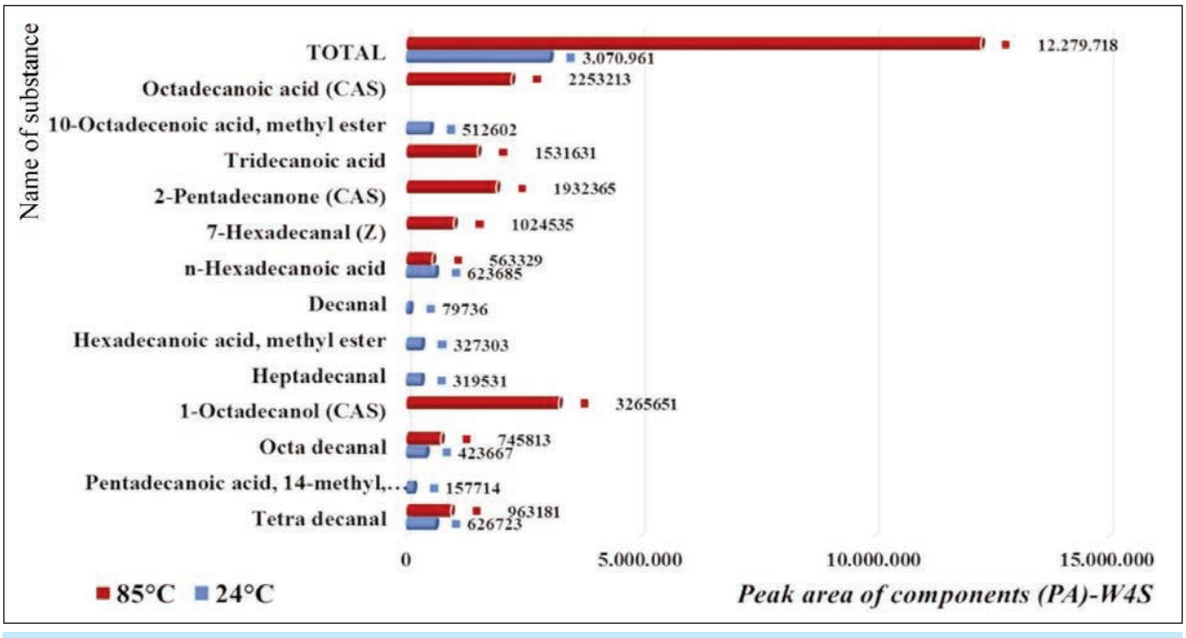


Fig. 12. GC-MS results of TFs washed according to the W4S code prescription

was performed, and no fatty acids that could be separated from the material by centrifugation and cause odour were detected.

Figure 13 shows the GC-MS analysis results of extracts obtained from feathers washed under W5S washing conditions and kept at temperatures of 24°C and 85°C. The W5S program is a wash determined by processing the feathers washed after the W5 program in a centrifuge machine. The results of this program can be compared with the W5 wash results in figure 8 for analysis.

After the W5 washing process, it can be seen that foreign substances and fatty acids in the feathers are significantly reduced by processing in a centrifuge machine. When compared with the PA data in figure 8, it is observed that the total area of the peaks covered by fatty acids and other substances in the chromatogram decreased by approximately 68% at 24°C and by approximately 88% at 85°C.

Additionally, it is observed that the total PA values at 24°C and 85°C are very close to each other. This indicates that the odour caused by the temperature difference has been reduced to minimum levels. The fact that W5S yields better results than the W5 washing program is attributed to the centrifugal processing method used.

Figure 14 shows the GC-MS analysis results of extracts obtained from feathers washed under W6S washing conditions and kept at temperatures of 24°C and 85°C. The W6S program is a wash determined

by processing the feathers washed under the W6 program in a centrifuge machine. The results of this program can be compared with the W6 wash results in figure 9 for analysis.

After the W6 washing process, it can be said that the foreign substances and fatty acids in the feathers are almost completely removed by processing them in a centrifuge machine. When compared with the total PA data in figure 9, it can be seen that the total area of the peaks covered by fatty acids and other substances in the chromatogram decreased by approximately 16% at 24°C and by approximately 66% at 85°C. Additionally, it is observed that the total PA values at 24°C and 85°C are very close to each other. This indicates that the odour caused by the temperature difference has been eliminated. The fact that W6S yielded better results than the W6 washing program is attributed to the centrifugal processing used. The W6S program was applied to remove the residues remaining on the feathers after the W6 washing process, despite the neutralisation of the fatty acids, and to obtain an odourless and clean result. When the chromatograms of the samples obtained at 24°C and 85°C in figure 14 are compared with the chromatograms of the feathers from other washes, it is observed that the total peak areas of the volatile compounds formed are minimised. Based on these data, it is observed that as temperature

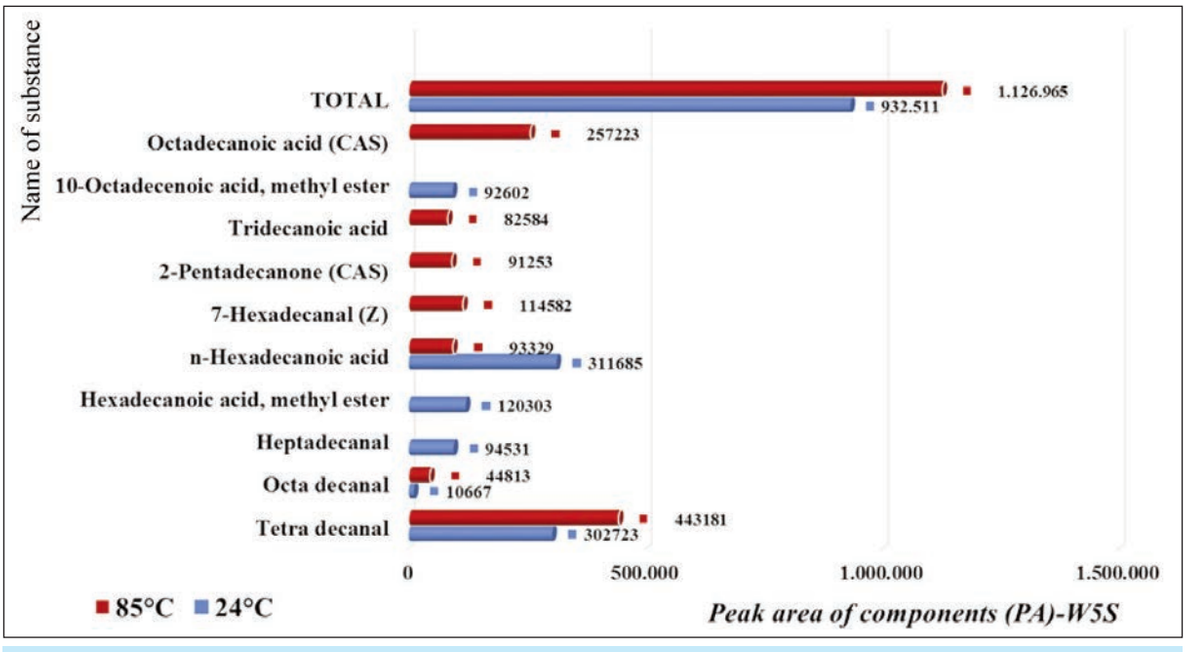


Fig. 13. GC-MS results of TFs washed according to the W5S-coded prescription

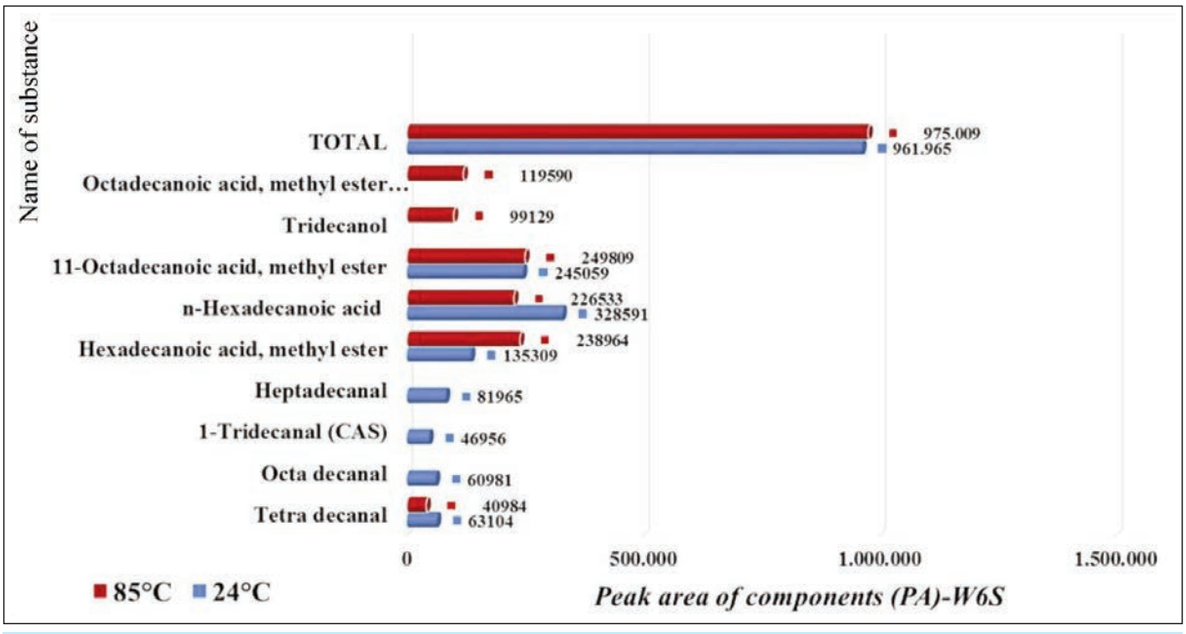


Fig. 14. GC-MS results of TFs washed according to the W6S code prescription

increases, the total peak area of the volatile compounds released appears to overlap with the total peak area of the volatile compounds released at normal temperature. This clearly indicates that the odour of TF will not increase with temperature. This has been identified as the best washing result.

CONCLUSION

Basically, animal fibres, and more specifically turkey, chicken, goose, and other bird feathers, must be washed before use. These feathers are highly susceptible to environmental influences. It is particularly important to avoid environments with high temperatures and humidity, which can damage their structure and cause them to smell. This research revealed that when cleaned feathers were stored in hot conditions or used to make materials at high temperatures, they released an unpleasant smell. Since turkey feathers are especially sensitive to environmental factors like temperature changes, 11 distinct washing techniques and programs were created to get rid of their odour. The feathers were heated to temperatures of 24°C and 85°C to extract volatile oils and fatty acids that cause the odour. Analyses were performed using a GC-MS device to identify and remove substances in the structure of feathers that cause bad odours. The analysis revealed that the primary substances responsible for the unpleasant odour are oils, fatty acids, and residues in the feathers.

- The results show that dirty feathers contain high levels of fatty acids and volatile compounds.
- It has been proven that these volatile compounds, which cause odours, can be removed depending on the type and method of washing. Some types of washing eliminate volatile compounds, while other washing methods are ineffective.
- SEM images were taken to determine the surface and internal structure of the turkey feathers after washing. The internal structure in the SEM images was observed to be intact after washing. The fact that the feathers remain intact is of great importance, especially when they are used in the manufacture of insulation materials.
- The most effective washing method was found to be the W6S program. This program consists of four stages. After washing, the amount of odour remaining on the hair has been reduced to a level that is imperceptible to humans. After washing, the total PA amount at temperatures of 24°C and 85°C is seen to be almost the same.
- According to the FTIR analyses and SEM results, no changes in the internal and external structure of the fibres were observed as a result of the washing process.

Finally, if I need to give a few basic headlines to the results of the study, I can state the following:

- The use of centrifuges for washing and disinfecting turkey feathers yields good results.
- Possible delays in the washing of protein-based animal fibres can cause odours and damage the structure.
- It is possible to remove the odour from turkey feathers by using different chemicals and washing methods.
- The best cleaning can be achieved by neutralising the fats and fatty acids in the structure of protein fibres.
- The best cleaning method for turkey feathers is pre-washing with NACIO + main washing with non-ionic soap + bleaching with NAOH + centrifuging.

I recommend this washing method to my colleagues working in the production of similar feathers and to industry professionals.

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A generalizable high-fidelity fabric simulation system optimised for e-commerce and design workflows

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ABSTRACT – REZUMAT

A generalizable high-fidelity fabric simulation system optimised for e-commerce and design workflows

Achieving high-fidelity, real-time garment simulation is a central challenge in virtual try-on systems. This difficulty stems from the need to balance accurate fabric-body interaction with strict computational constraints. This study presents a data-driven fabric simulation framework that integrates deformation learning with geometric refinement to enable precise fitting and photorealistic detail at interactive speeds. Compared with conventional physics-based solvers and simplified learning pipelines, the proposed approach achieves improved wrinkle fidelity, more stable fabric body correspondence, and higher computational efficiency without sacrificing visual quality. These results demonstrate the framework's practical viability for large-scale deployment in virtual try-on platforms, intelligent apparel design workflows, and digital retail visualisation applications. By unifying data-driven deformation learning with principled refinement strategies under a scalable computational paradigm, this work advances high-fidelity fabric simulation and provides a technical foundation for next-generation digital fitting, e-commerce platforms, and design workflows.

Keywords: *fabric simulation, learning model, virtual reality, wrinkle preservation, dataset*

Un sistem de simulare a materialelor textile de înaltă precizie, generalizabil, optimizat pentru comerțul electronic și fluxurile de lucru din domeniul proiectării

Obținerea unei simulări a articolelor vestimentare cu înaltă precizie și în timp real reprezintă o provocare centrală în sistemele de probare virtuală. Această dificultate decurge din necesitatea de a găsi un echilibru între interacțiunea fidelă dintre material textil și corp și constrângerile computaționale stricte. Prezentul studiu descrie un cadru de simulare a materialelor textile bazat pe date, care integrează învățarea deformărilor cu rafinarea geometrică pentru a permite o ajustare precisă și detalii fotorealiste la viteze interactive. În comparație cu soluțiile convenționale bazate pe fizică și cu fluxurile de învățare simplificate, abordarea propusă obține o fidelitate îmbunătățită a rezistenței la șifonare, o corespondență mai stabilă între materialul textil și corp și o eficiență computațională mai mare, fără a sacrifica calitatea vizuală. Aceste rezultate demonstrează viabilitatea practică a cadrului pentru implementarea la scară largă în platforme de probare virtuală, fluxuri de lucru inteligente de proiectare a îmbrăcămintei și aplicații de vizualizare digitală pentru comerțul cu amănuntul. Prin unificarea învățării bazate pe date a deformării cu strategiile de rafinare fundamentate, în cadrul unei paradigme computaționale scalabile, această lucrare aduce progrese în simularea materialelor textile de înaltă precizie și oferă o bază tehnică pentru probarea digitală de ultimă generație, platformele de comerț electronic și fluxurile de lucru de proiectare.

Cuvinte-cheie: *simularea materialelor textile, model de învățare, realitate virtuală, păstrarea rezistenței la șifonare, set de date*

INTRODUCTION

Accurate and efficient simulation of fabric behaviour remains a fundamental challenge for scalable virtual try-on systems. Existing approaches have achieved progress in either visual realism or physical accuracy, yet few methods simultaneously preserve fine fabric details, maintain robustness across diverse fabrics and body shapes, and meet real-time performance requirements. The objective of this study is to develop a unified learning-driven framework for fabric deformation. This framework aims to achieve high fidelity while maintaining interactive computational efficiency, enabling practical deployment in next-generation digital fitting systems. Early research relied on image-based techniques or handcrafted physical models to approximate fabric appearance. Recent deep learning approaches improved automation and adaptability. For example, convolutional networks have extracted geometric features from RGB-D data to guide fabric smoothing and flattening, but these methods require large-scale training data and show limited generalisation to diverse fabric properties [1]. Comprehensive reviews have documented the progression from two-dimensional image manipulation to three-dimensional-aware deep networks while emphasising persistent challenges in scalability and system robustness [2, 3]. Reinforcement learning has also been applied to robotic cloth manipulation with encouraging sim-to-real transfer, yet it depends on

extensive physical simulation and complex training pipelines [4]. From a complementary perspective, physics-informed approaches have focused on accurate material modelling. Mesoscale frameworks based on inverse parameter estimation capture yarn-scale interactions in UHMWPE fabrics [5], while unified hyperelastic models address nonlinear deformation behaviour to reduce wrinkling in woven prepregs [6]. Despite their accuracy, such methods remain computationally intensive and are generally unsuitable for interactive applications requiring real-time response. In addition, perceptual studies demonstrate ongoing difficulties in achieving visually natural fabric appearance under varying body shapes, motions, and lighting conditions [7]. Surveys of clothing simulation research further highlight fragmented methodologies and the absence of unified evaluation benchmarks, which continue to impede consistent assessment of fabric realism [8].

Building on these limitations, this study proposes a machine learning-driven virtual simulation framework that integrates data-driven mesh deformation with perceptually guided geometric refinement to achieve accurate fitting, realistic wrinkle reconstruction, and stable real-time performance. The proposed approach avoids simplified fabric geometry and handcrafted parameter tuning, offering a scalable solution for high-fidelity virtual fabric depiction across diverse application scenarios.

DATASET

A robust foundation for virtual fabric display and simulation was established using a structured dataset containing 38,913 2D and 6,350 3D samples. A graphic segmentation algorithm constructed temporal sequences, represented as a discrete time series. This time-conscious representation captures dynamic postures and supports 3D shape reconstruction while preserving realistic folds, providing the necessary foundation for modelling plausible draping (figure 1).



Fig. 1. Example of fabric dataset

An object's spatial pose requires six degrees of freedom: three translational variables (x, y, z) for position and three rotational variables (roll, pitch, yaw) for orientation. For rigid objects, pose is defined as a fixed transformation relative to a canonical origin. This definition fails for deformable objects like cloth. Their surface geometry varies continuously, making the rigid pose definition inapplicable [9]. This annotation scheme provides consistent spatial representation and precise geometry for learning tasks. Coupling fabric appearance with pose matrices enables supervised training, supporting generalisation across fabric types. If multiple instances (N) are present, N corresponding 4×4 matrices are generated to describe their spatial poses (figure 2).

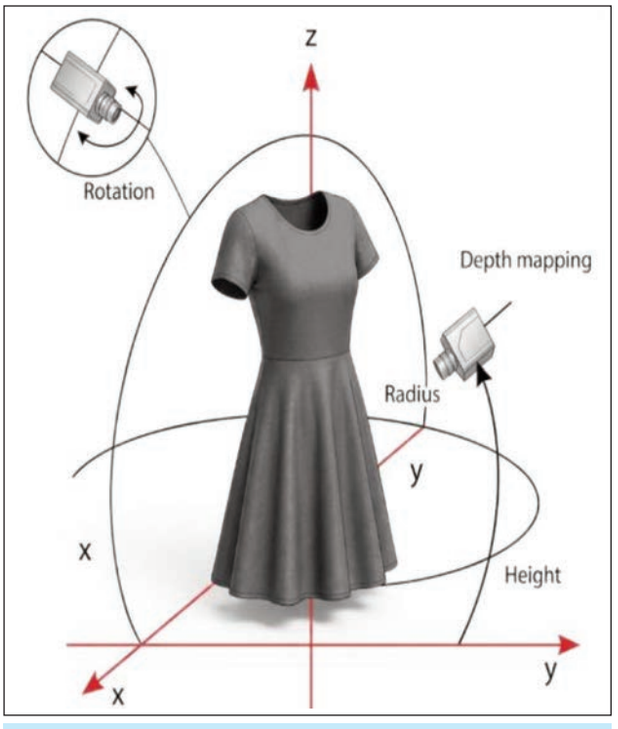


Fig. 2. Fabric depth mapping configuration

CLOTHING VIRTUAL DISPLAY NETWORK BASED ON DEEP LEARNING

By integrating human body and fabric datasets with a mathematical model for body reconstruction and a spatial perception-based fabric prediction scheme, this method achieves rapid generation of high-fidelity virtual fabric renderings [10]. The proposed framework, detailed in figure 3, utilises an encoder-decoder generator architecture. This system effectively captures depth maps and sequential data. It extracts distinct features from both the body and fabric inputs. Principal Component Analysis (PCA) then compresses these features into a shared latent space. Within this space, a fabric fitting regressor predicts vertex displacements. This prediction generates natural fabric deformations. To ensure structural coherence and preserve wrinkle dynamics, the skinning matrix is optimised. This optimization utilizes the reconstructed body geometry [11]. Using a data-driven pipeline,

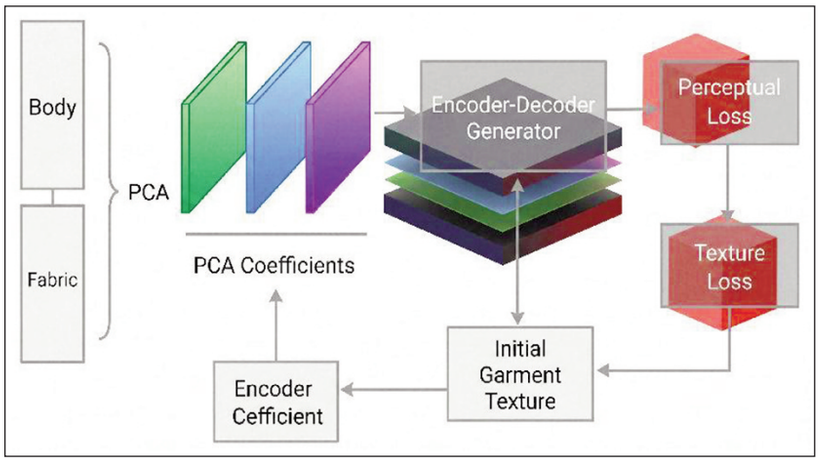


Fig. 3. Network framework of fabric virtual display

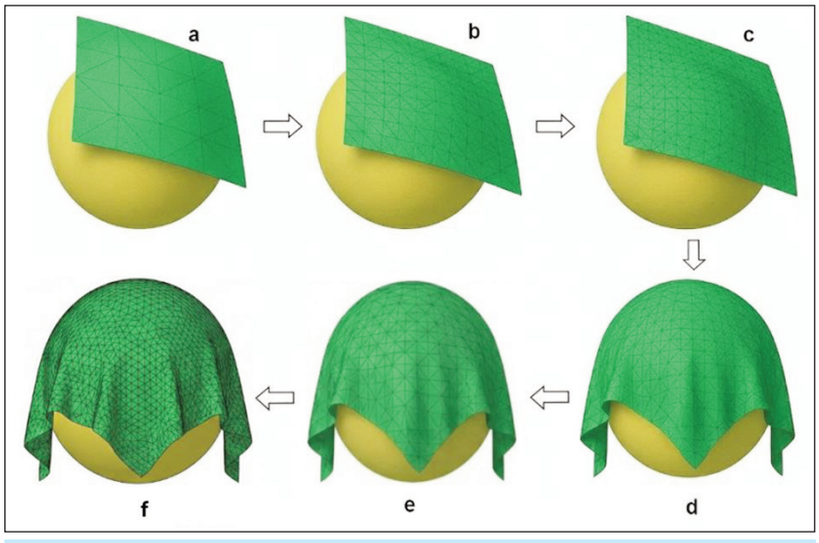


Fig. 4. Simulation of collision between fabric and spherical body approximations

the regressor couples body and fabric models by simulating collisions between the fabric mesh and spherical body approximations (figure 4), progressively displacing vertices from initial separation to full conformity. This process yields realistic wrinkle formation and a faithful virtual fabric display.

Specifically, a fabric virtual display network based on deep learning is composed of shape parameters θ. The deformable human mesh G_h and the deformable fabric mesh G_c on the human model are composed. Based on physical mechanics, $N_c(\theta)$ is the mechanical feedback result of the human fabric model in the virtual display of fabrics. Therefore, the equation of the human body model is as follows:

$$G_h(\theta) = S\{U_b(\theta),\theta,s_b\} \quad (1)$$

where $S(\cdot)$ is a skinning equation, $U_b(\theta) \in R^{3\times V_h}$ is a human body mesh template containing V_h vertices, and S_b is the skinning weight matrix. Similar to the human body model equation, the fabric model equation is as follows:

$$U_G(\theta) = U'_G + R_G(\theta) \quad (2)$$

Among them, $U'_G \in R^{3\times V_G}$ is a fabric mesh template containing V_G vertices, and R_G is a nonlinear regressor input as human shape parameters. The equation for generating fabric mesh deformation through skin equations is as follows:

$$G_c(\theta) = S\{U_c(\theta),\theta,s_c\} \quad (3)$$

Map the vertices of the fabric mesh template onto adjacent triangles, and combine them with S_b to obtain the skin weight matrix S_c.

Therefore, the virtual display of fabrics is achieved by learning the fabric fitting regression of the template, and the key to this process is to calculate the displacement of the fabric mesh. The working principle of the fabric fitting regression device is as follows:

$$R_G(\theta): R^{|\theta|} \rightarrow R^{3\times V_G} \quad (4)$$

By inputting body shape parameters θ, the displacement $\Delta D' \in R^{3\times V_G}$ of each vertex is generated, and the formula for fabric fitting regression is as follows:

$$\Delta D = \Psi(N_c(\theta)) - U_G \quad (5)$$

$\Psi(\cdot)$ is a clothing fitting tool, which maintains smooth deformation of the fabric and uses a multi-layer neural network to minimise the loss function as follows:

$$L = \sum_{i=1}^{k} \left\| [\Psi(N_c(\theta)) - U_G] - R_G(\theta) \right\|_2^2 \quad (6)$$

The fabric mesh exhibits stretching and draping deformations in response to body changes. This behaviour is regulated by a fabric fitting regressor that optimises vertex fields subject to global similarity constraints [12]. By optimising mesh displacements, the proposed framework generates realistic fabric wrinkles with adaptive subdivision for surface refinement. The model is trained end-to-end using a convolutional neural network (CNN) that maps a template mesh to deformed fabric vertices. Supervision combines loss terms on vertex positions and surface normals, together with an energy constraint to prevent interpenetration while preserving wrinkle details. Boundary artefacts are mitigated using a Gaussian mixture prior and Graph Cuts on a uniformly segmented template. The network takes 64×64×3 depth maps as input and outputs fabric meshes in either full or PCA-compressed form. Convolutional blocks with ReLU activations and dropout efficiently predict vertex displacements, enabling a fast and high-quality virtual fitting pipeline.

EVALUATION OF CLOTHING VIRTUAL DISPLAY BASED ON DEEP LEARNING

The network balances visual quality and efficiency. A multilayer model predicts fabric shape and pose using a fit regressor with up to 1,200 hidden neurons. A 15% dropout rate mitigates overfitting with an initial learning rate of 0.0001. Training uses 300 sequences and 50 test sequences covering 16 body shapes. Truncated BPTT with a 100-step limit reduces computation, while shape interpolation and vertex displacement yield realistic deformations.

QUANTITATIVE EVALUATION

The non-linear clothing vertex regressor increases per-frame mesh deformation time from 6.31 milliseconds for 4710 meshes to 10.91 milliseconds for 15210 meshes, demonstrating low computational complexity and suitability for interactive use, as shown in table 1.

Memory usage remains compact, with clothing fit regression requiring about 1.1 megabytes and wrinkle regression about 108.1 megabytes, supporting efficient fabric simulation in real-time environments.

Table 1

FABRIC DEFORMATION TREATMENT TIME		
Triangle count	**Mean (ms)**	**Standard deviation**
4710	6.31	0.28
7710	8.23	0.30
15210	10.91	0.31

Multiple linear regression models are evaluated during training to assess fitting performance. A linear skinning algorithm aligns the clothing mesh with the human body model. Iterative optimisation allows the Multi-Layer Perceptron (MLP) network to produce smooth hierarchical simulation results. These accurately represent diverse body shapes and fabric forms. To quantify strain constraints, the average vertex error is computed for each body vertex. The proposed MLP achieves accurate and stable fitting performance. Low-level displacement constraints guide the regressor during deformation. This ensures natural fit and realistic wrinkles. Implicitly learning body fabric contact reduces physical simulation limitations. Vertex position error provides a reliable generalisation metric for evaluation.

QUALITATIVE EVALUATION

The fabric achieves smooth chest-to-abdomen fitting with natural hem drape, and fine wrinkles are generated from 128 × 128 px inputs through a CNN regressor trained on collision-free datasets with displacement constraints, as shown in figure 5, *a*. Wrinkle transitions progress from slight mesh deformation to pronounced waist creases while maintaining hem curvature and precise alignment to spine and shoulders, as shown in figure 5, *b*. The hem shifts dynamically from an initial ~90° suspension to a thigh-conforming bend, preserving drape stability under motion, as shown in figure 5, *c*.

The two level regression separates body shape fitting from nonlinear dynamic responses, enabling over 200 fps real-time virtual try-on, as shown in figure 5. Enhanced Lagrangian strain constraints maintain stability on irregular meshes exceeding 50 k vertices, delivering physically plausible, high-detail deformation without the computational cost of full physics-based solvers. Fabric adapts naturally to motion with physical realism. Enhanced Lagrangian strain constraints keep large irregular meshes stable and ensure great detail in fabric motion under complex movements.

DISCUSSION

The proposed method was subjected to a rigorous evaluation protocol, incorporating five-fold cross-validation and leave-one-shape-out experiments to ensure robust generalisation. Across diverse fabric categories, the model demonstrated highly stable generalisation, achieving a consistent mean vertex error of 8.25 mm. This geometric accuracy is competitive with methods such as TailorNet, which typically exhibits an error range of 10–12 mm. Crucially, the approach achieves real-time performance, operating at 6–11 ms per frame, exceeding 200 fps.

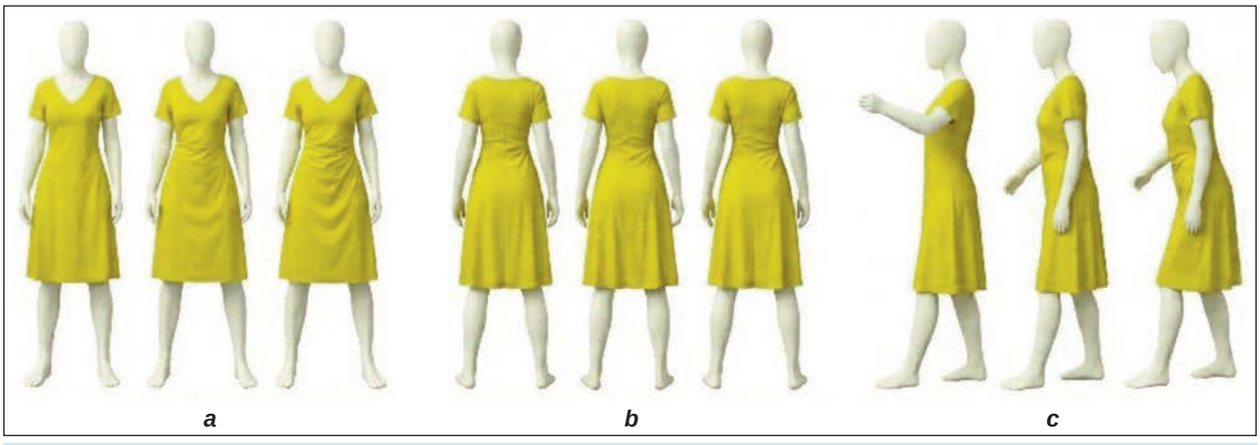


Fig. 5. Virtual display of clothing on the *a* – front, *b* – back, and *c* – sides

Table 2

COMPARISON OF FABRIC SIMULATION METHODS			
Method	**Mean Vertex Error (mm)**	**Wrinkle fidelity**	**Runtime**
Proposed method	8.25	High	6–11 ms
DeepWrinkles	9–11	High	13 ms
TailorNet	10–12	High	1–2 ms
GarNet	9–10	Moderate–High	100× faster than PBS

While TailorNet offers lower latency of 1–2 ms, the proposed method provides superior performance compared to DeepWrinkles 13 ms [13,14].

Furthermore, the method was qualitatively confirmed to offer superior wrinkle preservation, rated as high fidelity. This high fidelity result is significant because the method maintains efficiency without sacrificing visual quality, unlike GarNet, which offers only 'Moderate-High' fidelity [15]. Direct numerical comparisons must be interpreted cautiously due to known variations in experimental protocols across different studies. Future work will focus on establishing standardised benchmarking protocols and incorporating a broader spectrum of fabric properties to enhance physical realism.

CONCLUSIONS

The high-fidelity framework achieves accurate fabric interaction. It ensures fine wrinkle preservation and sustains real-time performance over 200 FPS. Quantitative results show lower vertex errors and improved efficiency compared with other methods. This confirms robust generalisation across diverse body shapes. The framework offers significant industrial relevance for e-commerce platforms and design workflows. It provides a photorealistic virtual try-on experience. This strategy significantly curbs product return rates while simultaneously advancing global sustainability goals. Limitations remain in generalising to unseen fabric properties. Temporal coherence under complex motion must be ensured. Future work focuses on unified benchmarking protocols. Training will extend to a broader range of fabric properties.

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How does corporate financialization affect operational risk in textile firms? Evidence from China

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ABSTRACT – REZUMAT

How does corporate financialization affect operational risk in textile firms? Evidence from China

Against the backdrop of a widening divergence between the virtual and real economies, coupled with the increasingly pronounced trend of financialization among traditional manufacturing enterprises, China's textile industry, a vital pillar of the national economy and a core export-oriented sector, has witnessed a significant shift in resources toward financial activities. This trend may reshape the landscape of its operational risks. This study examines the impact of financialization on operational risk in China's textile industry using listed firms from 2007 to 2024 as the sample. We find a significant positive correlation between corporate financialization and operational risk, which becomes more pronounced when the level of managerial myopia is higher. A series of robustness tests, such as using instrumental variables and propensity score matching, consistently support the baseline findings. Further analysis indicates that financialization affects operational risk through two channels: crowding out physical capital investment and increasing corporate opacity. Finally, we find that internal control quality and media coverage help mitigate the positive impact of financialization on operational risk. This study enriches the existing literature on the risk drivers and operational mechanisms in traditional manufacturing. It provides empirical support for textile enterprises to balance financial activities with core business development, and for regulatory bodies to optimise corporate governance and industrial policies.

Keywords: *textile industry firms, corporate financialization, operational risk, managerial myopia, corporate governance*

Cum influențează financiarizarea corporativă riscul operațional în cadrul întreprinderilor din sectorul textil? Date din China

Pe fondul unei divergențe tot mai mari între economia virtuală și cea reală, coroborată cu tendința din ce în ce mai pronunțată de financiarizare în rândul întreprinderilor tradiționale din sectorul de producție, industria textilă din China, un pilon vital al economiei naționale și un sector cheie orientat către export, a înregistrat o reorientare semnificativă a resurselor către activități financiare. Această tendință ar putea remodela peisajul riscurilor operaționale din acest sector. Prezentul studiu examinează impactul financiarizării asupra riscului operațional în industria textilă din China, utilizând ca eșantion întreprinderile cotate la bursă din perioada 2007–2024. S-a constatat o corelație pozitivă semnificativă între financiarizarea corporativă și riscul operațional, care devine mai pronunțată atunci când nivelul de miopie managerială este mai ridicat. O serie de teste de robustețe, precum utilizarea variabilelor instrumentale și potrivirea scorului de propensiune, susține în mod consecvent concluziile de bază. Analiza suplimentară indică faptul că financiarizarea afectează riscul operațional prin două canale: înlocuirea investițiilor în capital fizic și creșterea opacității corporative. În final, se constată contribuția calității controlului intern și a acoperirii mediatice la atenuarea impactului pozitiv al financiarizării asupra riscului operațional. Acest studiu îmbogățește literatura de specialitate existentă privind factorii de risc și mecanismele operaționale din sectorul de producție tradițional. Acesta oferă dovezi empirice care ajută întreprinderile din sectorul textil să găsească un echilibru între activitățile financiare și dezvoltarea activității principale, iar organismele de reglementare să optimizeze guvernanța corporativă și politicile industriale.

Cuvinte-cheie*: întreprinderi din industria textilă, financiarizare corporativă, risc operational, miopie managerială, guvernanță corporativă*

INTRODUCTION

As a traditional pillar industry and vital civilian sector of China's national economy, the textile industry plays an irreplaceable strategic role in securing employment, stabilising exports, and meeting consumer demand. Since the reform and opening-up, leveraging its labour cost advantages and comprehensive industrial chain capabilities, China's textile sector has gradually emerged as the world's largest producer, consumer, and exporter of textiles. Data from the China National Textile and Apparel Council indicates that in recent years, China's textile industry output has consistently accounted for over 30% of the global total, while its exports represent more than 25% of the world's textile and apparel trade. As the only country with a complete textile industrial chain, China occupies a central position within the global textile industry chain and supply chain system. However, in recent years, the internal and external development environment for China's textile industry

has undergone profound changes, with bottlenecks in traditional development models becoming increasingly apparent. Internationally, the rise of trade protectionism and unilateralism, coupled with factors such as Sino-US trade friction and the restructuring of regional trade agreements, has significantly increased uncertainties in textile export markets [1]. Since 2020, the global COVID-19 pandemic has further exacerbated risks of global supply chain disruptions and pressures from shrinking demand, leaving textile exporters confronting multiple challenges including order losses, rising logistics costs, and heightened exchange rate volatility. Internally, China's fading demographic dividend and persistently rising labour costs have gradually eroded the textile industry's traditional low-cost competitive advantage. Furthermore, domestic environmental policies have intensified pressure on energy-intensive and high-pollution textile enterprises to reduce energy consumption and emissions [2, 3], making industrial restructuring and upgrading increasingly urgent.

Against this backdrop, Chinese textile firms have undergone significant shifts in their business strategies and resource allocation approaches. One notable phenomenon is the continuous rise in corporate financialization. Corporate financialization is generally defined as the economic behaviour where firms allocate more of their funds, assets, and other resources to the financial sector rather than investing them in physical capital or core business development [4–7]. From a macro perspective, China's financial markets have experienced rapid development in recent years, with an expanding array of financial products and services. The average profit margin in the financial sector has significantly outpaced that of traditional manufacturing industries like textiles. This divergence in profitability between the financial and real sectors has created a strong "siphoning effect" on textile firms, incentivising them to redirect capital toward high-margin financial activities for short-term gains [8, 9]. At the micro level, textile firms face increasing operational pressures in their core businesses. Some firms, experiencing sluggish growth and declining profitability in their main operations, attempt to compensate for insufficient core business profits through financial investment returns to meet shareholders' short-term return demands. This ultimately fosters a tendency toward "decoupling from the real economy", significantly impacting corporate performance. As shown in figure 1, among ten representative manufacturing sectors in China from 2007 to 2024, the average financialization levels of firms in the three textile-related industries (textiles, garments, and chemical fibres) are significantly higher than those in other sectors. This demonstrates that corporate financialization has become an undeniable economic phenomenon.

In fact, the impact of corporate financialization on the development of the real economy remains a core concern for both academia and policymakers. Previous studies have shown that corporate financialization undermines productive investment and slows capital accumulation. For instance, several studies [10–12] utilised data from the United States, Europe, and China to find that corporate financialization significantly inhibits real investment.

Furthermore, scholars have demonstrated that corporate financialization weakens the incentive for manufacturing firms to invest in R&D [13] and harms firm long-term performance [7, 8]. Notably, as a vital component of China's real economy, the financialization of the textile industry poses critical implications for industrial security and economic stability, particularly in terms of its effects on corporate operational risks. Operational risk, one of the core risks firms

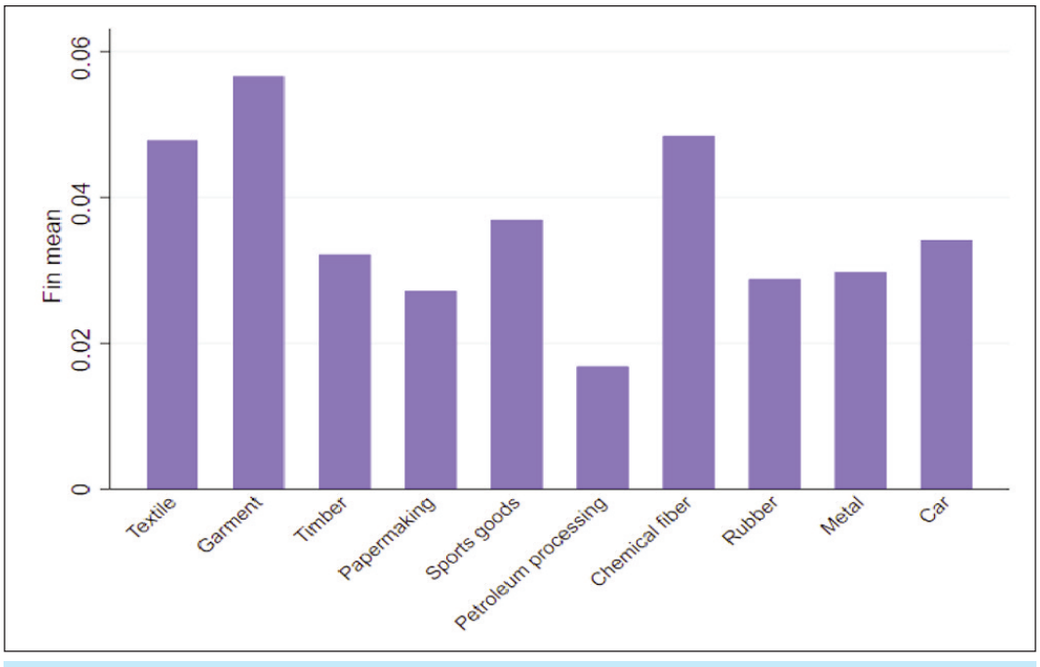


Fig. 1. Financialization levels across ten typical manufacturing industries

face, primarily refers to the possibility of instability or even financial distress arising from uncertainties in internal and external environments during daily production and operations [9]. Against the backdrop of structural imbalances between the real and virtual economies, corporate financialization may generate a "crowding-out effect". By diverting resources from physical capital investment [11], it increases the uncertainty of corporate returns, thereby amplifying operational risks. Furthermore, firms may use financial investments to embellish financial statements, exacerbating internal and external information opacity. This heightens the levels of "adverse selection" and "moral hazard", ultimately elevating the firm's operational risk profile.

To investigate how financialization affects operational risk in textile firms, we follow recent research [14–16] in measuring financialization levels using the proportion of financial assets relative to total assets. Concurrently, following Deng et al. [9], we use return volatility to gauge operational risk. Using data from Chinese textile industry listed firms from 2007 to 2024, we find that corporate financialization significantly and positively affects operational risk. This impact is also economically meaningful, as a one-standard-deviation increase in corporate financialization is associated with a 1.48% rise in operational risk. Subsequently, we conduct a cross-sectional analysis to examine conditions under which financialization may exert a greater influence. We find that when managers exhibit higher levels of myopia, corporate financialization exerts a greater impact on operational risk. This result confirms that financialization is driven by managerial myopia.

Second, we conduct a series of robustness tests to ensure the reliability of our baseline findings. To address potential reverse causality, we employ a two-stage least squares regression using the average financialization level of peer firms in the previous year as an instrumental variable. To address sample selection bias, we perform propensity score matching. We further consider industry cyclicality, test nonlinear relationships, and consider alternative explanations. None of these modifications altered our baseline findings.

Next, we seek to validate the underlying channels through which financialization affects operational risk in textile firms. Specifically, can financialization impact operational risk by crowding out physical capital investment and increasing corporate opacity? Following the recent research [17, 18], we construct a two-stage model. We find that corporate financialization negatively correlates with physical capital investment, while the portion of physical capital investment explained by corporate financialization negatively correlates with operational risk. This indicates physical capital investment serves as an intermediary channel. Furthermore, we find that corporate financialization positively correlates with corporate opacity, and the opacity induced by financialization positively correlates with operational risk, indicating that opacity also serves as an intermediary channel.

Finally, we aim to verify whether certain corporate governance mechanisms can generate supervisory effects that mitigate the positive impact of corporate financialization on operational risk. In this regard, we use internal controls as a proxy for internal governance mechanisms and media coverage as a proxy for external governance mechanisms. Empirical results indicate that when internal control quality is higher, or media coverage is more extensive, the positive effect of corporate financialization on operational risk is weakened. These findings provide empirical evidence supporting accelerated improvements in corporate governance systems to curb managerial myopia.

This study contributes to the literature in several ways. First, we expand research on the economic consequences of corporate financialization within specific industries. Previous studies have predominantly focused on listed companies as a whole, lacking targeted research on specific sectors, particularly traditional labour-intensive industries like textiles. The textile industry possesses unique characteristics, including a long industrial chain, high sensitivity to macroeconomic cycles, strong export orientation, and narrow profit margins. Consequently, the outcomes of financialization in this sector may differ significantly from other industries. By focusing on the textile industry, a traditional pillar industry, this study addresses the shortcomings of existing research that overlooks sector-specific features, providing an in-depth analysis of the unique impact of financialization on operational risk. Second, we provide new evidence regarding the drivers of corporate financialization. As the core decision-makers in resource allocation, management's tendency toward myopia may influence the degree of financialization, thereby moderating the relationship between financialization and operational risk. By examining this relationship through the lens of managerial myopia, an internal decision-making characteristic, this study helps reveal the micro-level motivations behind corporate financialization decisions and the boundary conditions of their consequences. Third, this study reveals the specific pathways through which financialization impacts operational risk in textile firms. By examining two channels, physical capital investment and corporate opacity, it clarifies the underlying mechanisms of financialization's influence on operational risk, providing theoretical foundations for targeted policy formulation. Fourth, existing research has insufficiently addressed how to mitigate the negative impact of corporate financialization on operational risk. This study examines the moderating effects of internal control quality and external media attention on the relationship between financialization and operational risk. It provides practical governance pathways to alleviate operational risks stemming from financialization in the textile industry and promote the sector's shift from virtual to real economy, offering significant policy implications.

The subsequent arrangement of this paper is as follows. The second section presents the hypothesis development; 3rd section outlines the research

design; 4th section reports the empirical findings; and 5th section concludes the study.

HYPOTHESIS DEVELOPMENT

Financialization and operational risk in textile firms

Corporate financialization signifies a significant shift in a firm's resource allocation, thereby exerting a substantial impact on the competitiveness of its core business and the transparency of its information. For textile firms, the effects of financialization on operational risk are primarily mediated through the following two mechanisms:

First, financialization in textile firms weakens core business competitiveness through a "crowding-out effect", thereby increasing operational risk. As a quintessential traditional manufacturing sector, the textile industry relies on tangible capital investments (such as upgrading advanced production equipment and expanding production lines) and enhancing supply chain efficiency for its core competitiveness. These require sustained, substantial capital and resource allocation from firms. However, when textile firms allocate more capital to financial activities, resources intended for physical capital investment are inevitably displaced. This leads to slower improvements in core business production capacity and delayed technological innovation, thereby weakening the firm's competitiveness in areas such as product quality and production costs [12, 13]. Against the backdrop of intensifying market competition and evolving consumer demands in the current textile industry, diminished core business competitiveness leaves enterprises more vulnerable to external shocks such as market demand fluctuations, rising raw material prices, and competitor pressures. This undermines the stability of core business revenue and profits while significantly elevating operational risks. For instance, if textile enterprises reduce investment in new spinning equipment, their production efficiency will struggle to improve. With rising labour costs, unit production costs will increase significantly. When market price competition arises, enterprises will lack room for price reductions, thereby facing risks of order loss and declining market share.

Second, financialization in textile firms elevates operational risk by increasing corporate opacity. Corporate transparency, defined as the adequacy, accuracy, and timeliness of financial, operational, and risk disclosures to external stakeholders, is crucial for mitigating information asymmetry and ensuring capital market efficiency [19–21]. For textile firms, financialization creates opportunities for management to engage in earnings management, masking underlying operational issues. When core business growth stagnates and profitability declines, companies may resort to financialization to manipulate earnings, embellishing financial statements to maintain short-term performance stability [16]. However, such earnings management distorts the firm's true profit structure. External stakeholders struggle to accurately discern the extent and motives of earnings management through disclosed information, potentially misinterpreting "financialization-supported short-term performance" as "long-term gains from enhanced core business competitiveness", leading to resource misallocation. When financial market conditions deteriorate, causing financial investment gains to vanish or even turn into losses, the company's true core business difficulties are exposed. At this point, investor confidence collapses, creditors tighten credit, and the company faces risks such as intensified financing constraints and plummeting stock prices, triggering an operational crisis. Furthermore, financialization exacerbates "adverse selection" and "moral hazard" under conditions of information asymmetry. Regarding adverse selection, reduced transparency makes it difficult for external stakeholders to assess the operational quality of textile enterprises. This prevents investors from accurately screening investment targets. High-quality firms may curb investments in their core business due to rising financing costs, while low-quality firms may secure financing based on false performance, further exacerbating resource misallocation within the industry. Regarding moral hazard, diminished transparency weakens external oversight's constraints on management. When external stakeholders cannot clearly monitor the efficiency and risk profile of financialised capital, management may divert such funds into high-risk speculative activities or use financialised operations to transfer corporate resources.

These behaviours significantly increase operational uncertainty and ultimately elevate business risk. Based on the above analysis, we propose the following hypothesis:

H1: Holding other variables constant, financialization positively impacts operational risk in textile firms.

Financialization of textile firms, managerial myopia, and operational risk

As the core decision-makers in corporate resource allocation, management's decision orientation and behavioural characteristics exert a critical influence on the degree of corporate financialization and its economic consequences. Against the backdrop of an increasingly inflated virtual economy, management's vision has become further short-term oriented, leading to managerial myopia [10]. Management myopia is typically defined as a decision-making tendency where executives excessively focus on short-term corporate performance while neglecting long-term developmental interests [22]. Within textile companies, management myopia significantly mediates the relationship between financialization and operational risk through the following mechanisms:

First, managerial myopia intensifies the degree of financialization within textile firms, thereby amplifying the positive impact of financialization on operational risk. Management with myopic tendencies prioritises achieving short-term performance gains during their tenure to satisfy shareholder demands for immediate returns, secure higher compensation incentives, or

avoid job threats stemming from poor short-term results [23]. For textile firms, core business development is characterised by long cycles and slow returns. In contrast, financial investments can generate short-term gains, rapidly boosting corporate profits and stock performance. Thus, when facing immediate market pressures, managers' investment horizons narrow further, leading them to prioritise short-term financial targets over activities that create long-term value [24, 25]. This excessive financialization driven by managerial myopia further intensifies the "crowding-out effect" on physical capital investment and R&D spending, undermining the stability of core operations and amplifying financialization's positive impact on operational risks.

Second, managerial myopia intensifies corporate opacity, thereby reinforcing the positive correlation between financialization and operational risk. Myopic management is more likely to conceal financialization-related losses through accounting manoeuvres, specifically, adjusting accounting policies or booking asset impairment provisions to hide losses when financial investments underperform [26]. This diminishes the transparency of corporate financial information. External stakeholders such as investors and creditors are unable to accurately identify the firm's true operational risks, thereby failing to take timely measures to help the firm address these risks. This ultimately leads to the further accumulation and amplification of operational risks. Based on the above analysis, we propose the second hypothesis:

H2: Holding other factors constant, the higher the degree of management myopia, the more significant the positive impact of financialization on operational risk for textile firms.

RESEARCH DESIGN

Sample selection

We select company data from China's A-share textile, apparel, and chemical fibre industries for the period 2007–2024 as our primary sample, as these three sectors are most closely linked to the textile industry. We select the A-share market because it constitutes the main body of China's capital market, featuring substantial market capitalisation and high liquidity, ensuring data richness and stability. Subsequently, we exclude samples subject to special exclusion due to losses and those with missing key variables. Ultimately, we obtain 1,205 observations.

The required data for this study are sourced from the China Stock Market and Accounting Research Database. To mitigate the interference of extreme values on our findings, we apply trimmed tailing to firm-level continuous variables at the upper and lower 1% percentiles.

Variables

Operational risk

Operational risk can essentially be attributed to the possibility of returns deviating from expectations. Following Deng et al. [9], we use the volatility of returns to measure operational risk. The calculation formula is as follows:

$$Risk_{i,t} = \sqrt{\frac{1}{T-1}\sum_{t=1}^{T}(E_{i,t} - \frac{1}{T-1}\sum_{t=1}^{T}E_{i,t})^2} \quad |T = 4 \quad (1)$$

$$E_{i,t} = \frac{EBITDA_{i,t}}{A_{i,t-1}} \quad (2)$$

where $Risk_{i,t}$ denotes the operational risk of firm i in year t; $E_{i,t}$ represents the *EBITDA* margin of firm i in year t; and $A_{i,t-1}$ indicates the total assets of company i in year t–1. We calculate $Risk_{i,t}$ using the standard deviation of the rolling values of $E_{i,t}$ over the past four years (–4 years to –1 year). A higher $Risk_{i,t}$ indicates a greater level of operational risk for the company.

Corporate financialization

Following the majority of existing studies [27], we measure corporate financialization from an investment activity perspective by calculating the ratio of financial assets to total assets. This metric reasonably reflects the extent to which a company engages in financial activities [28]. In accordance with Chinese Accounting Standards and relevant literature practices, financial assets encompass: trading financial assets, available-for-sale financial assets, held-to-maturity investments, derivative financial assets, and loans and advances. Due to adjustments in the classification of financial assets under Chinese accounting standards in 2018, for the sample period from 2018 to 2024, financial assets comprise: trading financial assets, derivative financial assets, loans and advances, debt investments, other debt investments, other equity investments, and other non-current financial assets. Some studies also argue that corporate financialization is reflected in the increased contribution of financial investment returns to a firm's overall profitability [4]. Therefore, in our robustness checks, we also use the proportion of financial returns as another proxy for corporate financialization.

Moreover, some studies measure financialization from an asset–liability correlation perspective [29, 30]; however, this measurement approach primarily targets lending-like activities (such as entrusted loans and shadow banking operations), but mainstream forms of financialization, such as passive allocations to stocks, funds, and wealth management products, are not included, so we excluded this measure.

Baseline model

Following recent research [31, 32], we construct the following multiple regression model to validate the impact of financialization on operational risk in textile firms:

$$Risk_{i,t} = \alpha_0 + \alpha_1 Fin_{i,t} + \alpha_2 Size_{i,t} + \alpha_3 Age_{i,t} + \alpha_4 Roa_{i,t} + \\ + \alpha_5 Lev_{i,t} + \alpha_6 Growth_{i,t} + \alpha_7 Insiti_{i,t} + \alpha_8 Manage_{i,t} + \\ + \alpha_9 Board_{i,t} + \alpha_{10} Indep_{i,t} + Firm + Year + \varepsilon_{i,t} \quad (3)$$

where *Risk* represents the firm's operational risk, while *Fin* indicates the level of corporate financialization. Subsequent variables are operational and corporate governance-level controls, including: Firm

size (*Size*) typically influences resource reserve capacity, risk resilience, and information disclosure quality. In the textile industry, larger enterprises often possess more comprehensive industrial chain layouts and stronger cash flow, granting them greater buffering capacity against market volatility and rising raw material prices. This may mitigate operational risks, leading us to anticipate a negative coefficient. Following Deng et al. [9], firm size is measured using the natural logarithm of total assets. Firm age (*Age*) reflects operational experience, industry accumulation, and institutional maturity. Longer-established textile firms typically cultivate stable customer bases, supply chain systems, and internal management models, enhancing core business stability. However, they may also face challenges like equipment obsolescence and slow technological iteration, potentially elevating operational risk levels. Therefore, its coefficient remains uncertain. Following established research conventions, we measure firm age using the natural logarithm of the difference between the observation year and the year of establishment. Profitability (*ROA*) directly reflects the health of a firm's core business operations. Higher profitability in textile enterprises indicates more robust cash flow from core operations, potentially reducing reliance on financial investments and making operational risks more manageable. Conversely, enterprises with weaker profitability may be more inclined to compensate for profit gaps through financialization, thereby amplifying risks. Profitability is represented by *ROA*. Debt-to-Asset Ratio (*Lev*): This ratio reflects a firm's financial leverage and debt burden. As a traditional manufacturing sector with extended capital turnover cycles, excessive debt ratios in the textile industry may increase interest expenses and repayment pressures. When significant funds are tied up in financial activities, this can easily trigger liquidity risks, thereby amplifying operational risks. The debt ratio is measured by dividing total liabilities by total assets. Growth capacity (*Growth*) reflects a firm's market expansion potential and core business development trajectory. Textile enterprises with strong growth capacity typically focus on core activities like capacity expansion and market development, exhibiting relatively lower financialization and more controllable operational risks. Conversely, high-growth enterprises may face greater agency issues, making their coefficients uncertain. Following Su and Liu [13], growth is measured by the revenue growth rate. Institutional ownership (*Insiti*). As professional external shareholders, institutional investors possess stronger oversight capabilities and information interpretation skills. For textile enterprises, higher institutional ownership strengthens oversight constraints on management, potentially curbing excessive financialization driven by short-term interests and thereby influencing operational risk. We anticipate a negative coefficient for this factor. Management ownership (*Manage*). Management ownership constitutes a vital component of incentive mechanisms, directly influencing managerial decision-making orientation. Higher management ownership aligns interests with long-term corporate development, potentially reducing short-term financialization speculation. Thus, we anticipate a negative coefficient. Board size (*Board*) reflects a firm's decision-making efficiency and oversight capacity. For textile enterprises, a moderate board size facilitates integration of diverse perspectives, enhances decision-making rationality, and curbs irrational financialization. However, excessive size may lead to inefficient decision-making and weakened oversight, potentially exacerbating risks. Therefore, its coefficient remains uncertain.

Following Fang and Ju [27], board size is measured by the natural logarithm of the number of board members. Independent director ratio (*Indep*). As a core force in external governance, independent directors possess professional oversight capabilities and independence, effectively constraining managerial opportunistic behaviour. We expect its coefficient to be negative. Following Xu and Xuan [8], the independent director ratio is measured by the number of independent directors divided by the total number of board members.

EMPIRICAL RESULTS

Descriptive statistics

We report the descriptive statistics for the variables in table 1. The maximum value of *Risk* at 2.547 indicates that some firms exhibit relatively high levels of operational risk. The mean and median of *Fin* are 0.053 and 0.006, respectively, suggesting a right-skewed distribution of financialization levels among firms. The maximum value of *Fin* is 0.685, indicating that some companies have a relatively high proportion of financial assets. The mean values of *Insiti*, *Manage*, *Board*, and *Indep* are 0.415, 0.093, 2.251, and 0.372, respectively, suggesting that institutional investors, management, the board of directors, and independent directors hold significant positions in listed textile firms. The values of other variables all fall within reasonable ranges.

Financialization and operational risk in textile firms

We report the results of baseline regression tests in table 2. Following Ju et al., we employ a stepwise approach to add control variables and find that the coefficient for Fin remains consistently and significantly positive, indicating that corporate financialization elevates operational risk levels. This coefficient also holds economic significance, as we find that each standard deviation increase in corporate financialization correlates with a 1.48% rise (0.151×0.098) in operational risk levels. This result provides empirical evidence that resource allocation changes driven by financialization translate into heightened risk exposure.

Regarding control variables, we find that the coefficients for *Size*, *Roa*, *Manage*, *Board*, and *Indep* are negative, while the coefficients for *Age*, *Lev*, *Growth*, and *Insiti* are positive. Notably, the coefficient for

Table 1

DESCRIPTIVE STATISTICS FOR VARIABLES						
Variable	**N**	**Mean**	**Sd**	**Min**	**Median**	**Max**
Risk	1205	0.059	0.158	0.003	0.031	2.547
Fin	1205	0.053	0.098	0	0.006	0.685
Size	1205	21.99	1.112	19.406	21.927	26.422
Age	1205	2.963	0.293	1.946	2.996	3.638
Roa	1205	0.023	0.069	–0.627	0.025	0.218
Lev	1205	0.431	0.190	0.047	0.414	0.930
Growth	1205	0.210	0.808	–0.937	0.090	9.880
Insiti	1205	0.415	0.212	0.001	0.422	0.933
Manage	1205	0.093	0.164	0	0.001	0.695
Board	1205	2.251	0.163	1.792	2.303	2.773
Indep	1205	0.372	0.054	0.250	0.333	0.600

Insiti indicates that institutional ownership increases a firm's operational risk. This may stem from the fact that institutional investors in China are typically short-term in nature, preferring short-term trading. Consequently, they may lack the willingness and capacity for oversight [33], thereby failing to mitigate operational risks arising from financialization.

Table 2

THE BASELINE REGRESSION RESULTS			
Coefficient	**(1)**	**(2)**	**(3)**
	Risk	***Risk***	***Risk***
Fin	0.121***	0.151***	0.151***
	(3.529)	(3.696)	(3.704)
Size	–0.021	–0.036**	–0.047**
	(–1.545)	(–2.188)	(–2.290)
Age	0.219*	0.197	0.272*
	(1.663)	(1.560)	(1.715)
Roa	–0.032	0.025	–0.008
	(–0.667)	(0.505)	(–0.164)
Lev		0.102***	0.104***
		(2.744)	(2.793)
Growth		0.008**	0.008*
		(2.071)	(1.901)
Insiti			0.165**
			(2.428)
Manage			–0.010
			(–0.240)
Board			–0.029
			(–0.477)
Indep			–0.076
			(–0.577)
Constant	–0.139	0.220	0.249
	(–0.617)	(1.128)	(1.031)
Firm effects	Yes	Yes	Yes
Year effects	Yes	Yes	Yes
N	1205	1205	1205
Adj.R2	0.205	0.208	0.214

Note: ***, ** and * represent t-value significance at the 1%, 5% and 10% statistical levels, respectively.

Financialization of textile firms, managerial myopia, and operational risk

To investigate how managerial myopia mediates the relationship between corporate financialization and operational risk, we divide the sample into two groups based on the median level of managerial myopia and conduct separate regressions. Generally, the "Management Discussion and Analysis" (MD&A) can largely reflect managers' perceptions and efforts toward the firm [34]. To this end, following Yu et al. [25], we measure managerial myopia by identifying a set of words indicative of myopia and calculating the proportion of their frequency relative to the total word frequency in the "Management Discussion and Analysis".

Table 3 reports the test results. We find that when managerial myopia is high, the coefficient for Fin is significantly positive; however, this phenomenon is not observed when managerial myopia is low. More importantly, the coefficients for the two groups pass the difference test. This result indicates that managerial myopia is a key factor driving corporate financialization.

Table 3

THE RESULTS OF THE MANAGERIAL MYOPIA EXAMINATION		
Managerial myopia	**(1)**	**(2)**
	High	**Low**
	Risk	*Risk*
Fin	0.279**	0.073
	(2.403)	(2.090)
Controls & Constant	Yes	Yes
Firm effects	Yes	Yes
Year effects	Yes	Yes
N	752	453
Adj. R2	0.401	0.134
Difference test (1) = (2)	0.206** (P-value = 0.020)	

Note: ***, ** and * represent t-value significance at the 1%, 5% and 10% statistical levels, respectively.

Robustness tests

Instrumental variable test

To overcome the issue of reverse causality between corporate financialization and operational risk, we employ an instrumental variable approach. We select the average financialization level (L.*IV*) of other firms in the same industry during the previous year as the instrumental variable for two primary reasons: First, strong evidence indicates that a firm's financial investment decisions are significantly influenced by the behaviour of other firms in the same industry [35]. Management may follow industry trends to avoid falling behind competitors or to gain short-term market recognition. Consequently, the previous year's average financialization level within the industry is highly correlated with a firm's financialization level in the current year. Furthermore, regarding exogeneity, no evidence has yet been found indicating a clear relationship between the previous year's average industry financialization level and a specific firm's operational risk in the current year. Therefore, this instrumental variable is reasonable.

Column (1) of table 4 shows that L.*IV* is significantly positively correlated with *Fin*, indicating that the instrument satisfies the correlation requirement. Column (2) reveals that when L.*IV* is included in the baseline regression, its coefficient is insignificant, thus meeting the exogeneity requirement. More importantly, as shown in Column (3), when we perform two-stage least squares (2SLS) based on this instrumental variable, the coefficient for *Fin* remains significantly positive. This result indicates that the baseline findings possess a degree of robustness.

Propensity score matching

Firms with differing levels of financialization may exhibit fundamental differences, suggesting that factors driving operational risk could stem from characteristics other than financialization levels. To mitigate this sample selection bias, we performed propensity score matching. Specifically, we divided companies into two groups based on the median financialization level, defining those above the median as the treatment group (*Treat* = 1). Subsequently, using the control variables specified earlier, we employed one-to-one nearest neighbour matching to identify control groups within the remaining sample that were characteristic-wise similar to the treatment group. Finally, we incorporated the matched samples into the baseline model. As shown in column (1) of table 5, the coefficient for *Fin* is significantly positive, indicating that the baseline conclusion remains unchanged after accounting for sample selection bias.

Consideration of the industry cyclicality

Research indicates that industry development is significantly influenced by macroeconomic cycles, as monetary and industrial policies vary across different periods [36]. For the textile industry, macroeconomic indicators such as China's economic growth rate and changes in household disposable income directly impact domestic demand for textiles. During economic upturns, robust consumer demand leads to increased textile orders; conversely, during downturns, weak domestic demand may push the industry into an adjustment phase. Furthermore, prices of textile raw materials (e.g., cotton, polyester) may exhibit cyclical fluctuations influenced by factors such as planting area, weather, oil prices, and policy interventions. Concurrently, firms adjust raw material inventories based on price expectations, creating a "restocking-deleveraging" cycle that amplifies the impact of price volatility on production.

To control for these macro factors, we further incorporated an "industry × year" fixed effect into the baseline model. As shown in Column (2) of table 5, our conclusions remain largely unchanged.

Test nonlinear relationships

The relationship between corporate financialization and operational risk may not be purely linear. To verify this, we added a quadratic term for financialization (*Fin_s*) to the baseline regression. As shown in column (3) of table 5, the quadratic term is significantly negative. However, upon examining the financialization levels at extreme points, we find only 20 samples

Table 4

ROBUSTNESS TESTS 1			
Coefficient	**(1)**	**(2)**	**(3)**
	Fin	***Risk***	***Risk***
Fin		0.201***	0.407***
		(4.092)	(5.420)
L.*IV*	0.516***	–0.106	
	(2.877)	(–0.275)	
Constant & Controls	Yes	Yes	Yes
Firm effects	Yes	Yes	Yes
Year effects	Yes	Yes	Yes
N	1205	1205	1205
Adj.R2	0.205	0.208	/
LM statistic	9.030		
Wald F statistic	12.191		

Note: ***, ** and * represent t-value significance at the 1%, 5% and 10% statistical levels, respectively.

Table 5

ROBUSTNESS TESTS 2			
Coefficient	**(1)**	**(2)**	**(3)**
	Risk	***Risk***	***Risk***
Fin	0.170**	0.164***	0.316***
	(2.437)	(3.345)	(2.975)
Fin_s			–0.380*
			(–1.943)
Constant & Controls	Yes	Yes	Yes
Firm effects	Yes	Yes	Yes
Year effects	Yes	Yes	Yes
N	620	1205	1205
Adj.R2	0.146	0.222	0.214

Note: ***, ** and * represent t-value significance at the 1%, 5% and 10% statistical levels, respectively.

exceed this threshold. Additionally, the Utest command yields a P-value significantly greater than 0.1. Consequently, this result does not effectively support the existence of a nonlinear relationship.

Consider alternative interpretations

Our findings may also be subject to an alternative interpretation: firms with higher operational risks in their core businesses may allocate more financial assets to diversify related risks. In other words, elevated operational risk levels may be the cause rather than the consequence of financialization. Following this logic, when operational risk levels are low, we would not observe a positive correlation between financialization and operational risk. Conversely, when operational risk levels are high, we would observe such a positive correlation.

To test this, we divided the sample into two groups based on the median level of operating risk and conducted separate regressions. As shown in table 6, we find that financialization increases operating risk levels in both samples. This result rejects the alternative explanation.

Table 6

ROBUSTNESS TESTS 3		
Operational risk	**(1)**	**(2)**
	High	**Low**
	Risk	***Risk***
Fin	0.125**	0.006**
	(1.999)	(2.038)
Controls & Constant	Yes	Yes
Firm effects	Yes	Yes
Year effects	Yes	Yes
N	602	603
Adj. R2	0.499	0.177

Note: ***, ** and * represent t-value significance at the 1%, 5% and 10% statistical levels, respectively.

Replace core variables

We further ensure the robustness of our conclusions by replacing key variables. Previous research indicates that the proportion of corporate finance channel returns also serves as a crucial metric for measuring corporate financialization. This is because corporate financialization reveals the contribution of financial investment returns to a firm's overall profitability [4]. To address this, we calculated the proportion of corporate financial returns and defined it as *Fin_Profit*, computed as: (Investment income + Fair value change income – Income from investments in associates and joint ventures) / Operating profit. As shown in table 7, column (1), we find *Fin_Profit* to be significantly positive, indicating that our conclusions remain robust when considering the proportion of financial returns as a proxy variable.

Additionally, for operating risk, we calculated the difference between the maximum and minimum rolling-period tax-adjusted EBITDA as another proxy, defined as *Risk*2. As shown in table 7, column (2), *Fin* remains significantly positive.

Table 7

ROBUSTNESS TESTS 4		
Coefficient	**(1)**	**(2)**
	Risk	***Risk2***
Fin_Profit		0.569***
		(2.887)
Fin	0.001*	
	(1.892)	
Controls & Constant	Yes	Yes
Firm effects	Yes	Yes
Year effects	Yes	Yes
N	1205	1205
Adj. R2	0.210	0.127

Note: ***, ** and * represent t-value significance at the 1%, 5% and 10% statistical levels, respectively.

Impact channels

The preceding discussion has confirmed that financialization in the textile industry exerts a positive influence on operational risk. However, the specific channels through which this impact occurs remain unclear. The hypothesis section suggests that, on one hand, when textile firms allocate more resources to financial investments, this inevitably crowds out real investments, ultimately weakening core business competitiveness and increasing operational risk. On the other hand, financialization also heightens corporate opacity, leading to resource misallocation and increased levels of adverse selection and moral hazard, factors that similarly elevate operational risk. To test whether financialization affects operational risk through these two channels, "crowding out real capital investment" and "increasing corporate opacity", we follow Ju et al. [16] in constructing the following two-stage model:

$$Capital(Opacity)_{l,t} = \beta_0 + \beta_1 Fin_{l,t} + \beta_3 Controls + \\ + Firm + Year + \varepsilon_{l,t} \quad (4)$$

$$Risk_{l,t} = \gamma_0 + \gamma_1 Capital(Opacity)_hat_{l,t} + \gamma_3 Controls + \\ + Firm + Year + \varepsilon_{l,t} \quad (5)$$

In formula 4, *Capital* represents physical capital investment, calculated as: (Net fixed assets + Net construction in progress + Construction materials) / Total assets. *Opacity* denotes corporate opacity, measured by the modified Jones Index. In equation 5, *Capital* (*Opacity*)*_hat* is a predicted value representing the portion of *Capital*(*Opacity*) explained by *Fin*. If physical capital investment (corporate opacity) serves as a channel through which corporate financialization affects operational risk, we should observe statistically significant coefficients for both *Fin* and *Capital*(*Opacity*)*_hat*.

Table 8 reports the test results for the physical capital investment channel. Column (2) shows that the

Table 8

CHANNELS FOR PHYSICAL CAPITAL INVESTMENT			
Coefficient	**(1)**	**(2)**	**(3)**
	Baseline	**The first step**	**The second step**
	Fin	***Capital***	***Risk***
Fin	0.151***	–0.216***	
	(3.704)	(–5.416)	
Capital_hat			–0.699***
			(–3.704)
Constant & Controls	Yes	Yes	Yes
Firm effects	Yes	Yes	Yes
Year effects	Yes	Yes	Yes
N	1205	1205	1205
Adj.R2	0.214	0.819	0.214

Note: ***, ** and * represent t-value significance at the 1%, 5% and 10% statistical levels, respectively.

Table 9

CHANNELS FOR CORPORATE OPACITY			
Coefficient	**(1)**	**(2)**	**(3)**
	Baseline	**The first step**	**The second step**
	Fin	***Opacity***	***Risk***
Fin	0.151***	–0.025***	
	(3.704)	(–2.929)	
Opacity_hat			–6.109***
			(–3.704)
Constant & Controls	Yes	Yes	Yes
Firm effects	Yes	Yes	Yes
Year effects	Yes	Yes	Yes
N	1205	1205	1205
Adj.R2	0.214	0.121	0.214

Note: ***, ** and * represent t-value significance at the 1%, 5% and 10% statistical levels, respectively.

coefficient for *Fin* is significantly negative in the first stage, indicating that corporate financialization indeed crowds out physical capital investment. Column (3) reveals that the coefficient for *Capital*(*Opacity*)*_hat* is significantly negative in the second stage, suggesting that the portion of physical capital investment explained by corporate financialization is negatively correlated with operational risk. Following Chen et al. [18], we also test the regression coefficients. We find that the product of the coefficients from the first stage (0.216 × 0.699) aligns with the baseline regression (0.151). This result confirms that physical capital investment is indeed a channel through which corporate financialization influences operational risk.

Similarly, we report the results of testing the channel of corporate opacity in table 9. Column (2) shows that the coefficient for *Fin* is significantly positive in the first stage, indicating that corporate financialization indeed increases corporate opacity. Column (3) reveals that the coefficient for *Opacity_hat* is significantly positive in the second stage, suggesting that the portion of corporate opacity attributable to financialization is positively correlated with operational risk. We also observe that the product of the coefficients from the first and second stages (0.025 × 6.109) aligns with the baseline regression (0.151). This result indicates that corporate opacity constitutes an additional channel through which financialization influences operational risk.

Further discussion: consider internal and external governance mechanisms

The preceding discussion confirms that financialization in textile firms elevates operational risk levels, achieved by crowding out physical capital investment and increasing corporate opacity. Does any governance mechanism exist to mitigate the adverse effects of financialization? This section examines how internal controls and media coverage function as internal and external governance mechanisms to counteract the negative consequences of financialization.

Consider internal control

Since the enactment of the Sarbanes-Oxley Act, the importance of internal controls in corporate governance has garnered increasing attention and become a hot topic in academia. Internal control refers to a firm's establishment of systems and norms to ensure effective risk management and control, primarily encompassing elements such as internal environment, risk assessment, control activities, information and communication, and internal monitoring [37]. As a core institutional arrangement within textile firms' internal governance, high-quality internal control directly addresses the two primary transmission channels of financialization risk, resource misallocation and information failure, through multidimensional effects, thereby mitigating their positive influence on operational risk. From a decision-constraint perspective, internal controls enhance oversight of management by optimising governance structures (e.g., increasing independent director representation, establishing risk management committees). Coupled with a "core business-oriented" compensation system, this effectively curbs management incentives to divert funds excessively into financial sectors due to short-termism [38]. Particularly for the textile industry, characterised by "long tangible investment cycles and less obvious short-term returns", internal controls prevent management from diverting funds intended for raw material procurement or equipment upgrades to meet short-term profit targets. This approach curtails irrational decisions to "decouple from the real economy" at the source [39]. From a resource allocation perspective, internal controls establish the priority of physical capital investments through rigid budgetary controls and standardise financial investment decisions via multi-tiered approval processes. This safeguards funding for critical core investments such as production line upgrades and environmental

equipment retrofits. Regarding information rectification, internal controls strictly regulate classification standards and measurement methods for financial assets, preventing management from concealing financialization risks through accounting manipulation. while requiring detailed disclosure of financialization funding sources, uses, and risk exposures. This mitigates information asymmetry stemming from financial business complexity, enabling external stakeholders to accurately assess textile firms' core operations and financial asset risks. It prevents chain reactions like intensified financing constraints and market confidence collapse triggered by misjudged information [40]. Therefore, we argue that when a company possesses high-quality internal controls, the positive impact of financialization on operational risks is mitigated.

To validate the governance effect of internal controls, we divided the sample into two groups based on the median internal control score of listed companies and conducted grouped regression analysis. In this regard, we employ the Dibo Listed Company Internal Control Index to measure internal control quality. This index is based on the achievement level of the five major objectives of internal control and incorporates adjustments for internal control deficiencies, comprehensively reflecting the internal control quality of listed companies. As shown in table 10, we find that when internal control quality is high, corporate financialization no longer exerts a positive influence on operational risk, thereby demonstrating the robust governance effect of strong internal controls.

Table 10

RESULTS FOR INTERNAL CONTROL		
Internal control	**(1)**	**(2)**
	High	**Low**
	Risk	***Risk***
Fin	0.069	0.218***
	(1.180)	(3.103)
Controls & Constant	Yes	Yes
Firm effects	Yes	Yes
Year effects	Yes	Yes
N	677	528
Adj. R2	0.239	0.184
Difference test (1) = (2)	–0.149** (P-value = 0.020)	

Note: ***, ** and * represent t-value significance at the 1%, 5% and 10% statistical levels, respectively.

Consider media coverage

In Western societies, the media is regarded as the "fourth estate", independent of the legislative, judicial, and executive branches [41]. It plays a crucial role in promoting public information dissemination, shaping public opinion, influencing capital market pricing, and constraining the actions of governments and regulatory bodies [42]. As a key force in corporate external governance, media reporting leverages its dual functions of information intermediation and oversight to mitigate risks arising from corporate financialization. At the information disclosure level, media professionals uncover hidden financialization practices within textile companies through investigative reporting and bridge information gaps for external stakeholders by interpreting financial data. Addressing common issues in textile financialization such as ambiguous fair value measurements and opaque hedge accounting, media can compare disclosure standards across industries and interview financial experts to compel companies to improve transparency. This reduces misjudgments stemming from information failures, such as helping banks accurately assess textile firms' debt-repayment capabilities and avoid misallocation of credit resources due to hidden financialization risks [43]. At the behavioural constraint level, media reporting creates effective checks on management through "reputational pressure". For instance, if a textile company faces cash shortages in its core business and employee layoffs due to financial investment losses, media exposure could trigger investor sell-offs, bank credit tightening, and erode overseas clients' confidence. As an export-dependent industry, the loss of international orders would directly exacerbate the core business crisis. This consequence would compel management to reallocate resources, reduce speculative financial investments, and redirect capital back to the main operations. Therefore, we argue that when a company receives high levels of media coverage, the positive impact of financialization on operational risk is diminished.

We measure media coverage using the total number of online and print media reports on the company during the year and perform grouped regression based on the median. As shown in table 11, we find that the positive impact of corporate financialization on operational risk is significantly weakened in samples with higher media coverage, thereby demonstrating the information effect of media coverage in constraining firms' short-term behaviour.

Table 11

RESULTS FOR INTERNAL CONTROL		
Media report	**(1)**	**(2)**
	High	**Low**
	Risk	***Risk***
Fin	0.070	0.219**
	(0.938)	(2.572)
Controls & Constant	Yes	Yes
Firm effects	Yes	Yes
Year effects	Yes	Yes
N	602	603
Adj. R2	0.499	0.177
Difference test (1) = (2)	–0.149** (P-value = 0.010)	

Note: ***, ** and * represent t-value significance at the 1%, 5% and 10% statistical levels, respectively.

CONCLUSIONS

This paper examines the impact mechanism and governance pathways of financialization on operational risk in China's textile industry, using a sample of three categories of textile-related listed firms on the A-share market from 2007 to 2024. We primarily draw the following conclusions:

First, we find a significant positive correlation between financialization and operational risk in textile firms. That is, when textile enterprises allocate more resources to financial activities, their operational risk levels increase significantly. This finding aligns closely with the industry's characteristics. As a traditional labour-intensive and export-oriented sector, the textile industry's core competitiveness relies on physical capital investment and the stability of its main business operations. Financialization not only diverts funds needed for core business development but also exacerbates earnings uncertainty and information asymmetry due to financial asset price volatility and increased disclosure complexity, ultimately translating into heightened risk exposure.

Second, when managers exhibit higher levels of myopia, management is more inclined to pursue short-term gains through financial investments, leading to elevated risk levels. This finding reveals the micro-level decision-making drivers of financialization risks in textile firms, indicating that managerial characteristics constitute critical boundary conditions influencing the economic consequences of financialization.

Third, financialization in textile companies impacts operational risk through two channels: crowding out physical capital investment and increasing corporate opacity. On one hand, financialization significantly reduces textile firms' allocation to physical capital domains such as fixed assets and R&D investment, weakening core business competitiveness and directly elevating operational risk. On the other hand, the complexity of financial operations and potential earnings management by management increase the opacity of information disclosure in textile companies. External stakeholders struggle to accurately discern financial asset risks and the true state of core operations. Information asymmetry triggers financing constraints and resource misallocation, further amplifying operational risk.

Finally, both the quality of internal controls and external media coverage significantly mitigate the positive impact of financialization on operational risks in textile companies. From an internal governance perspective, high-quality internal controls curb excessive financialization at its source and block risk transmission by constraining management's short-term decision-making and standardising financial information disclosure. From an external governance perspective, media coverage mitigates risks arising from irrational management decisions by uncovering hidden financialization information, exerting reputational pressure, and guiding financialization back to serving the core business, thereby forming external oversight and checks and balances.

This study carries the following policy implications. First, at the regulatory level. Regulatory authorities need to establish clear "red line standards" for financial investments by textile companies and prohibit firms from diverting operational funds, such as those allocated for raw material procurement or employee compensation, into high-risk financial sectors. Regulators should also establish a dynamic monitoring mechanism for financialization risks, requiring listed textile companies to disclose quarterly information on financial asset allocations and market value fluctuations. Firms exceeding financialization thresholds should face inquiries and corrective oversight to prevent the exacerbation of "decoupling from the real economy". Additionally, at the institutional level, regulators must strengthen mandatory requirements for internal control systems. The completeness and effectiveness of financial risk management within internal control evaluation reports of listed textile firms should be incorporated into regulatory rating metrics. Firms with weak internal controls and frequent financial risks should be ordered to rectify them within a specified timeframe. Simultaneously, the independence and professionalism of media oversight must be safeguarded by establishing rapid response mechanisms for media exposure leads, prioritising investigations into reported financial irregularities by textile companies. Simultaneously, media reporting boundaries should be standardised to ensure objectivity.

Second, at the listed firms' level. Textile firms should adopt a clear business strategy prioritising their core operations over financial activities. Firms must develop more rational resource allocation rules, prioritising funding for critical areas like production line upgrades and supply chain optimisation. Strict limits should be imposed on capital allocated to non-core financial investments to prevent financialization from deviating from its essential purpose of serving the core business. Additionally, companies need to strengthen internal controls to block the transmission of financialization risks. For example, multi-tiered approval and risk threshold control mechanisms should be established, requiring financial investment decisions to undergo triple review by the finance department, risk management department, and board of directors. Second, to address reduced transparency caused by financialization, listed textile companies should enhance the content and format of information disclosure. This includes standardising accounting treatment and disclosure for financial operations, clarifying financial asset classification criteria, and detailing fair value measurement methods and risk exposures. Such measures help investors accurately assess the rationality and risks of financialization, preventing market misjudgments stemming from ambiguous information. Finally, this study identifies management myopia as a key driver of corporate financialization. Listed companies must therefore refine executive incentive structures to curb short-termism. Examples

include adjusting compensation frameworks to link executive pay with long-term metrics like tangible investment returns and R&D conversion rates. Firms may also implement term-based performance evaluations to prevent irrational financialization decisions driven by short-term pressure. Simultaneously, firms should establish accountability mechanisms for financialization risks, holding management responsible for significantly increased operational risks stemming from excessive financialization. This dual approach of incentives and constraints effectively curbs myopic behaviour.

This study deepens the understanding of the mechanisms through which financialization impacts operational risk and enriches research on the adaptability of corporate governance in traditional manufacturing firms. Nevertheless, this study has certain limitations. First, this paper uses A-share-listed textile, apparel, and chemical fibre enterprises as its sample, failing to include non-listed companies and small-to-medium textile enterprises. As a labour-intensive industry, the textile sector features a high proportion of small, medium, and micro enterprises. The resource constraints and financialization motivations of these firms may differ significantly from those of listed companies, potentially making the impact mechanisms of financialization on operational risk more complex. Therefore, the generalizability of the findings requires further validation. Future research could expand the sample to include non-listed textile enterprises and cross-border textile enterprises, conducting comparative analyses of financialization behaviours and their risk effects across enterprises of different scales, ownership structures, and export dependency levels. Second, while this paper validates the moderating roles of internal governance (internal controls) and external governance (media coverage), it does not delve into the impact of macro-environmental heterogeneity. For instance, institutional environments across regions with varying degrees of marketisation, textile industry "green transition" policies, and external shocks like Sino-US trade friction may alter the relationship between financialization and operational risk. Future research could integrate macro-environmental factors and more industry-specific governance measures for further discussion.

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Novel zinc carbonate synthesis using olive wood ash extract: a sustainable approach for enhancing cotton flame retardancy

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ABSTRACT – REZUMAT

Novel zinc carbonate synthesis using olive wood ash extract: a sustainable approach for enhancing cotton flame retardancy

This study presents a novel, sustainable, and cost-effective method for synthesising zinc carbonate ($ZnCO_3$) via the precipitation of zinc acetate using an alkaline extract derived from olive wood charcoal ash, which stabilises at approximately pH 13.0. The formation of the desired ($ZnCO_3$) flame retardant was confirmed using XRD and Fourier-transform infrared (FTIR) spectroscopy.
The synthesised ($ZnCO_3$) was applied to cotton fabric via a pad-dry-cure process at two concentrations (0.5 wt. % and 1.4 wt. %), resulting in final add-on percentages of 6.0% ± 0.3% and 8.0% ± 0.4%. Flammability tests demonstrated significant fire resistance improvement: the burning rate of the fabric was reduced by up to 63%, decreasing from 0.62 cm/s (untreated) to 0.23 cm/s for the 8.0% treated sample, increasing total burning time from 48 s to 126 s. Mechanical characterisation revealed that the 8.0% treated fabric exhibited an enhanced tensile strength, increasing by an average of over 22% without significant fabric shrinkage. These findings highlight olive charcoal ash as a promising, sustainable, zero-cost alkali source and ($ZnCO_3$) as an effective, eco-friendly flame-retardant coating for reinforced cotton textiles.

Keywords: *zinc carbonate, sustainable synthesis, ash water, flame-retardant cotton*

O nouă metodă de sinteză a carbonatului de zinc cu ajutorul extractului de cenușă din lemn de măslin: o abordare sustenabilă pentru îmbunătățirea proprietăților ignifuge ale bumbacului

Acest studiu prezintă o metodă inovatoare, sustenabilă și rentabilă de sintetizare a carbonatului de zinc ($ZnCO_3$) prin precipitarea acetatului de zinc cu ajutorul unui extract alcalin obținut din cenușa de lemn de măslin, care se stabilizează la o valoare a pH-ului de aproximativ 13,0. Formarea substanței ignifuge dorite ($ZnCO_3$) a fost confirmată prin spectroscopie XRD și spectroscopie în infraroșu cu transformată Fourier (FTIR).
Carbonatul de zinc ($ZnCO_3$) sintetizat a fost aplicat pe țesătura de bumbac printr-un proces de fulardare-uscare-condensare la două concentrații (0,5% în greutate și 1,4% în greutate), rezultând procente finale de adăugare de 6,0% ± 0,3% și 8,0% ± 0,4%. Testele de inflamabilitate au demonstrat o îmbunătățire semnificativă a rezistenței la foc: viteza de ardere a țesăturii a fost redusă cu până la 63%, scăzând de la 0,62 cm/s (netratată) la 0,23 cm/s pentru proba tratată cu 8,0%, ceea ce a dus la creșterea timpului total de ardere de la 48 s la 126 s. Caracterizarea mecanică a relevat că țesătura tratată cu 8,0% a prezentat o rezistență la tracțiune îmbunătățită, crescând în medie cu peste 22%, fără o contracție semnificativă a țesăturii. Aceste rezultate evidențiază cenușa de lemn de măslin ca o sursă de alcalii promițătoare, durabilă și fără costuri, precum și ($ZnCO_3$) ca un strat ignifug eficient și ecologic pentru țesăturile din bumbac consolidate.

Cuvinte-cheie: *carbonat de zinc, sinteză durabilă, apă de cenușă, bumbac ignifug*

INTRODUCTION

Textiles with multifunctional properties, especially flame resistance, play a crucial role in safety-oriented applications such as protective workwear, medical fabrics, and home furnishings, where reducing flammability can help prevent injuries and property damage [1–8]. The textile industry has increasingly shifted toward safer and more sustainable alternatives to traditional flame retardants, with carbonate-based compounds, such as zinc carbonate ($ZnCO_3$), emerging as promising eco-friendly options. This compound functions by releasing non-flammable gases, such as carbon dioxide (CO_2), upon heating, which dilutes flammable gases and suppresses combustion [9]. Additionally, they promote char formation, creating a protective barrier that limits heat and oxygen transfer to the material. Known for their low toxicity, environmental compatibility, and cost-effectiveness, carbonate-based flame retardants offer a significant advantage over conventional halogenated systems, making them a viable solution for sustainable textile applications.

The use of Zinc Carbonate $ZnCO_3$ specifically its basic form, hydrozincite, as a textile flame retardant has been explored extensively through conventional chemical precipitation methods [9, 10]. These established routes typically involve dissolving a soluble zinc precursor (like zinc acetate or zinc sulfate) in water and introducing a commercially sourced alkaline agent, such as Sodium Hydroxide (NaOH) or Potassium Carbonate (K_2CO_3), under controlled pH and temperature conditions to induce the precipitation of $ZnCO_3$ [11, 12]. This chemical approach yields nanoparticles with good control over morphology and size, enabling uniform application to fabrics [13]. Studies have demonstrated that $ZnCO_3$ synthesised this way provides effective flame inhibition via its endothermic decomposition, leading to reduced heat release and enhanced char formation [14, 15].

However, the economic feasibility and environmental profile of these methods are often hampered by the reliance on high-purity, expensive commercial chemical reagents, which directly contributes to the overall material cost and chemical waste burden of the finishing process.

Consequently, contemporary research has decisively shifted toward developing non-toxic, eco-friendly alternatives. This strategic shift emphasises the valorisation of waste materials and the use of sustainable inorganic compounds. Research into environmentally friendly bio-based flame retardants has attracted considerable interest to address these environmental safety issues, such as using pumpkin extract (Cucurbita maxima) [16], Banana (Musa Cavendish) Pseudostem Sap extract [17], spinach leaf juice [18], and chicken eggshell powder [19]. Harnessing agricultural waste as a chemical precursor represents a vital strategy in this context, directly supporting the transition to a sustainable circular economy, which aims to convert liabilities (waste) into high-value assets.

Olive wood charcoal ash (OWCA) is a sustainable by-product of charcoal combustion which contains alkaline compounds such as calcite and calcium oxide (CaO), along with trace minerals like potassium, magnesium, and phosphorus. These components make OWCA valuable for soil enhancement, pest control, and composting in agriculture [20]. Moreover, ash water has been employed in green synthesis methods, such as the production of zinc oxide (ZnO) catalysts [21].

The choice to utilise olive wood charcoal ash extract instead of conventional alkaline reagents (like NaOH or K_2CO_3) is primarily justified by principles of sustainability and long-term economic advantage, despite the initial requirement for filtering and leaching [22]. This method employs a zero-cost agricultural waste product as the primary chemical precursor, which strategically eliminates the need to purchase the most expensive component of the synthesis: high-purity commercial alkaline chemicals. This waste valorisation not only drastically lowers the material cost footprint, making the $ZnCO_3$ synthesis more competitive and scalable, but also minimises environmental pollution by converting a high-volume waste liability into a valuable resource, aligning the entire process with the fundamental goals of the circular economy and Green Chemistry.

The critical research gap addressed by this study is the development of a fully circular and cost-effective synthesis route. This work is the first to utilise Olive Wood Charcoal Ash Extract, a zero-cost agricultural waste, as a sustainable and eco-friendly alkali source with the aim of applying it as a flame retardant coating for cotton cloth. This novel approach demonstrates a superior, economical, and environmentally sustainable pathway to provide a sustainable, cost-effective solution for enhancing the safety and functionality of textiles, while promoting the use of biomass-derived materials in advanced applications.

METHODS AND MATERIALS

Preparation of OWCA water extract and characterisation

Olive Wood Charcoal is commonly used in rural Tunisian families for cooking. The ash of this Charcoal was collected for this study and was mixed with distilled water at varying concentrations (10%, 20%, and 40% w/v) to prepare the ash water extract. Each mixture was stirred continuously for 100 minutes at room temperature, 40 and 70°C to facilitate the dissolution of soluble minerals. The solutions were filtered by centrifugation at 3500 rpm for 5 minutes, followed by filtration through (Whatman No.1) filter paper to remove impurities. The pH of each extract was measured using a calibrated pH meter (S-610H), and the extracts were stored in sealed containers at room temperature for further use. This approach was intentionally chosen to demonstrate a sustainable, waste-to-value synthesis route. While requiring initial steps for extraction and filtration, the use of this zero-cost agricultural waste eliminates the need for expensive, commercially purchased alkaline reagents (such as NaOH), thereby enhancing the environmental and economic viability of the overall finishing process.

Synthesis of zinc carbonate

Zinc carbonate was synthesised via a precipitation method using zinc acetate dehydrate and water extracts of olive wood ash. In a typical procedure, 0.1 g of zinc acetate dihydrate was dissolved in 200 mL of olive wood ash water extract (prepared at a concentration of 10% w/v). Immediately after the addition of the zinc acetate solution, the reaction started, and the solution became white and cloudy. The reaction continued for 2 h, and then the suspension produced was kept still overnight to precipitate. After the reaction, the resultant precipitate was allowed to settle for 48 hours at room temperature. The precipitate was then separated from the reaction solution by centrifugation at 4000 rpm for 10 minutes and repeatedly washed with deionised water to

remove any soluble impurities. Finally, the purified product was dried in an oven at 80°C for 24 hours to yield zinc carbonate as a fine powder (figure 1).

All chemicals, including zinc acetate dihydrate (99.99%) and non-toxic polyacrylate-based blinder solution with 20% solid content (acrylamide/Acrylic Acid copolymer), were sourced from ALDRICH and used as received.

The alkaline agent for the precipitation was derived from the olive charcoal ash extract (providing OH^- and CO_3^{2-} ions). The synthesis involves the precipitation of the basic form of zinc carbonate, Hydrozincite, rather than pure $ZnCO_3$, which is typical under the high pH conditions established by the extract. The balanced chemical reaction for the primary synthesis is as follows:

$$5Zn^{2+} + 2CO_3^{2-} + 6OH^- \xrightarrow{\text{Precipitation}} Zn_5(CO3)_2(OH)_6$$

Textile cotton fabric modification

A 100% cotton fabric with a plain weave structure and density of (118 g/m^2) cut along the chain direction has been used for the entire study.

The treatment bath for fabric impregnation consisted of 10 mL of water and 20 mL of acrylic binder. The cotton fabric was padded with the prepared solution using double impregnation method to apply the prepared solution, followed by double squeezing with a lab padder at a fixed rate. The fabric was then dried in an oven at 80°C for 3 min (figure 2). To quantify the effective mass absorption after coating, the percentage of addition was calculated using equation 1.

$$Add\text{-}on\ (\%) = \frac{W_{after\ treatment} - W_{before\ treatment}}{W_{before\ treatment}} \times 100 \quad (1)$$

The amount of liquid solution retained by the fabric was controlled and quantified using the Wet Pickup (WPU) measurement. *WPU* was determined by weighing three replicate samples ($n = 3$) before (dry) and immediately after (wet) passing them through the padder, using the following equation:

$$WPU\ (\%) = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100 \quad (2)$$

The padder speed and pressure were carefully calibrated to maintain consistency across all treatment groups (both $ZnCO_3$ concentrations and both additive levels). Across all samples, the coating process achieved a mean WPU of 57% ± 1%, demonstrating the high reproducibility of the liquid transfer step.

Characterization techniques

X-ray diffraction (XRD) spectra were obtained using an X'Pert Pro Panalytical X-ray diffractometer and a D8 ADVANCE system from Bruker, USA. The diffractograms were processed with X'Pert HighScore Plus software and were performed with a resolution of 0.02° and 30 scans. The functional groups of the samples were identified using the ATR-FTIR spectroscopy technique within the range of 400–4000 cm^{-1}.

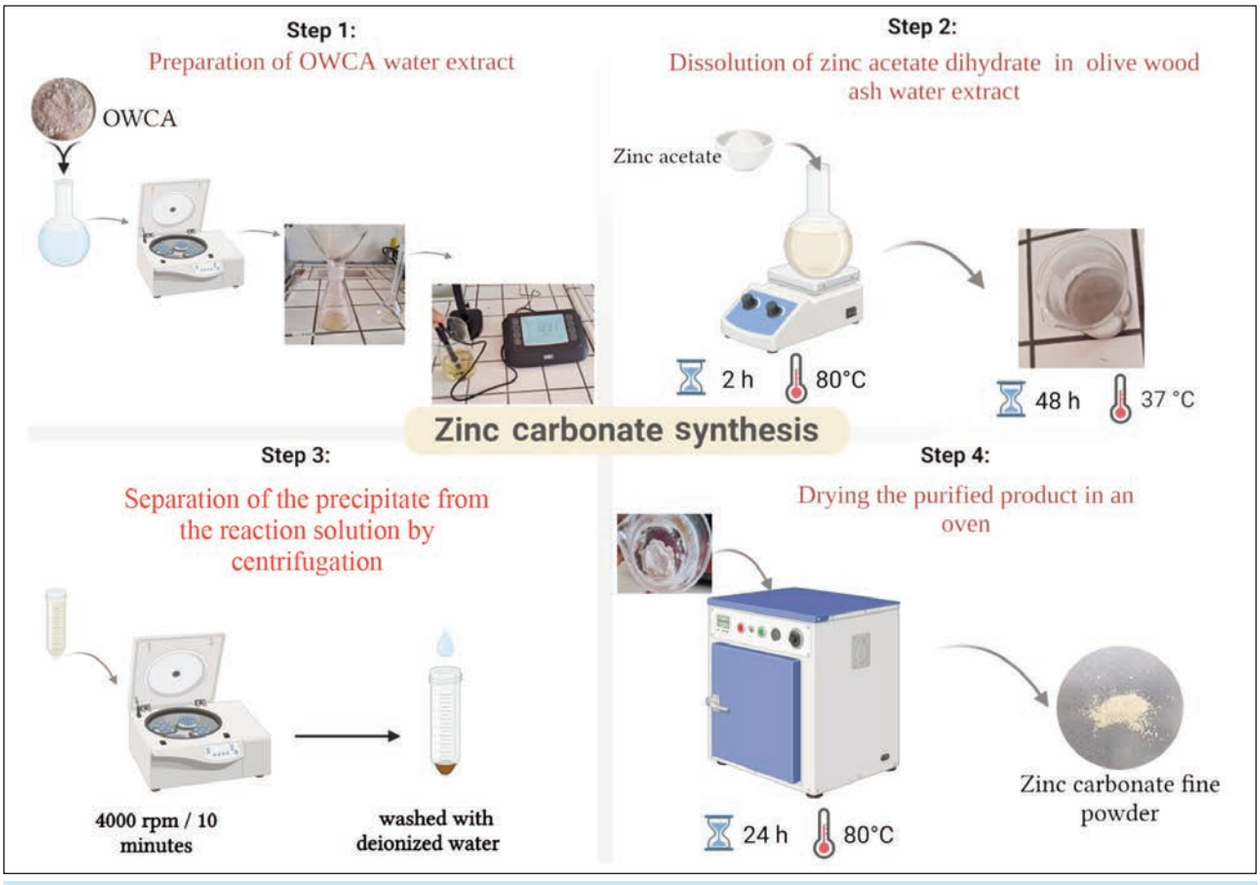


Fig. 1. Illustration of the green process of the synthesis of zinc carbonate

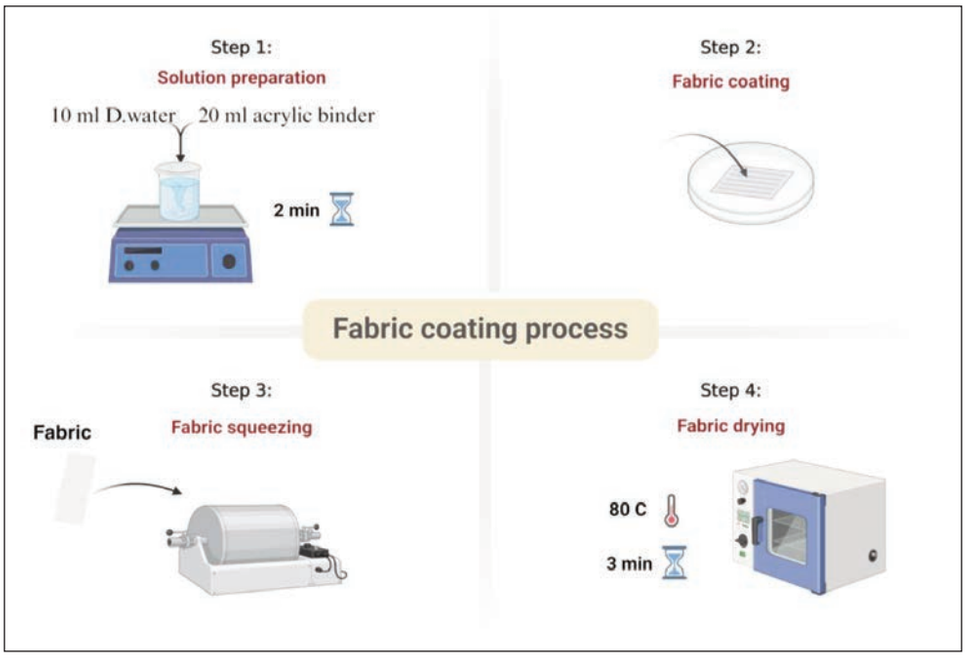


Fig. 2. Fabric coating process

Scanning Electron Microscopy (SEM) images of the selected samples were captured. The flame retardancy of untreated and treated fabrics was evaluated in accordance with ASTM D6413 (Standard Test Method for Flame Resistance of Textiles, Vertical Test). Fabric samples (300 mm × 75 mm) were vertically mounted and exposed to a flame with a calibrated length of 38 mm for 12 seconds to measure ignition resistance and burning behaviour. Five replicate samples ($n = 5$) were tested for each treatment condition. In parallel, the tensile strength and elongation of both control and treated fabrics were assessed following ASTM D5034 (Standard Test Method for Breaking Strength and Elongation of Textile Fabrics, Grab Test), using a universal testing machine to apply uniaxial force until rupture. Five replicate strips ($n = 5$) were tested in both the warp and weft directions for each sample.

RESULTS AND DISCUSSION

XRD

The X-ray diffraction patterns of zinc carbonate, untreated cotton, and cotton treated with zinc carbonate are shown in figure 3. The resulting diffraction pattern corresponds reasonably well to that of Zinc carbonate in its basic form (zinc carbonate hydroxide or hydrozincite [14–15]. The XRD analysis revealed characteristic reflection peaks at (200), (201), (310), (020), (311), (401), (510), (112), (330), (512), (332), and (313), which are consistent with the monoclinic crystal structure of hydrozincite (reference pattern: JC-PDF: 00-019-1458) [14]. Untreated cotton shows two dominant peaks around 2θ = 15.3, 17° and 23.4° and 32.4°, which correspond to crystalline planes of cellulose in cotton fabric [15]. Upon treatment with zinc carbonate, the treated cotton retains the characteristic cellulose peaks, suggesting that the fundamental crystalline structure of the cotton fibres remains intact after treatment. However, the treated cotton pattern also exhibits additional peaks at 2θ = 21.4° and 22.6°, which correspond to the reflections of zinc carbonate, confirming its successful incorporation onto the textile surface. The presence of these $ZnCO_3$ peaks, albeit with lower intensity compared to the pure sample, indicates that zinc carbonate is present in a dispersed form rather than large, well-ordered crystals.

FTIR

The FTIR spectra of untreated cotton, Zinc carbonate and Zinc carbonate-treated cotton (figure 4) provide valuable insights into their chemical compositions

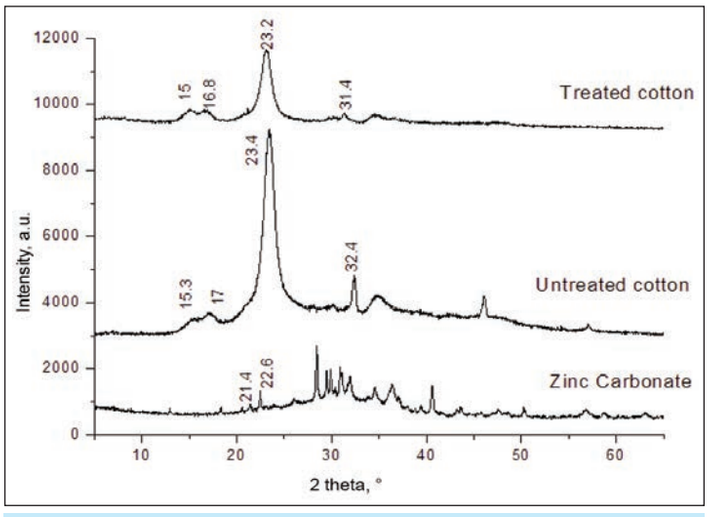


Fig. 3. XRD of zinc carbonate, untreated and treated cotton textile

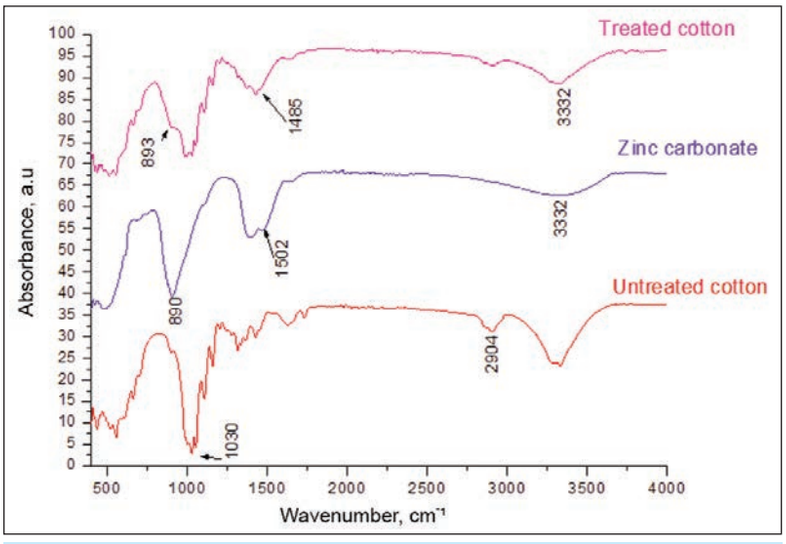


Fig. 4. FTIR Analysis of untreated cotton (red), zinc carbonate (blue) and zinc carbonate-treated cotton (purple)

and interactions. The spectrum of zinc carbonate exhibits characteristic peaks associated with carbonate functional groups, including a strong asymmetric stretching band at 1502 cm^{-1} and an out-of-plane bending mode at 889 cm^{-1}, confirming the presence of CO_3^{2-} ions. Additionally, a broad absorption band around 3332 cm^{-1} corresponds to O-H stretching, indicating surface hydroxyl groups or water molecules in the structure. In contrast, untreated cotton shows a distinct cellulose fingerprint, with a broad O-H stretching peak around 3300–3400 cm^{-1}, highlighting its hydrophilic nature, and a C-H stretching band near 2900 cm^{-1} from aliphatic groups in the cellulose backbone. The characteristic C-O-C and C-O stretching vibrations between 1050 cm^{-1} and 1160 cm^{-1} represent the glycosidic bonds within cellulose, while a peak at 1635 cm^{-1} is attributed to bound water molecules [13].

Upon modification with zinc carbonate, the treated cotton spectrum reveals a combination of both materials, confirming successful deposition. The carbonate peaks at ~870 cm^{-1} and 1430 cm^{-1}, which are prominent in pure zinc carbonate, appear clearly in the treated cotton, indicating its presence on the textile surface. Meanwhile, the cellulose peaks, including C-H (~2904 cm^{-1}) and C-O (1030 cm^{-1}) stretching, remain visible, suggesting that the fundamental structure of cotton is preserved. However, slight shifts in peak positions and intensity variations suggest possible interactions between zinc carbonate and the cotton groups**,** likely through hydrogen bonding or surface attachment mechanisms**.**

SEM

As shown in figure 5, the treated cotton fibres appear as elongated, cylindrical structures, with the zinc carbonate deposits visible as irregularly shaped clusters adhering to their surfaces. It is observed that some agglomeration of the zinc carbonate particles has occurred, leading to a somewhat uneven distribution across the fibre surfaces. This phenomenon can likely be attributed to the high concentration of the precursor solution, which increased the frequency of particle-particle collisions during the deposition process. While this agglomeration represents a degree of unevenness, the coating is still sufficiently distributed to impart a significant flame-retardant effect. This successful surface modification acts as a protective barrier, as evidenced by the substantial improvement in flame resistance observed in our combustion tests. Therefore, despite the visible particle aggregation, the coating effectively inhibits flame spread and provides the intended protection to the textile.

Mechanical strength of the treated fabric

The mechanical properties of the fabric were evaluated by measuring the tensile strength in both the warp and weft directions, with the full data presented in table 1. The untreated cotton fabric showed base tensile strengths of 189 N (warp) and 168 (weft). Upon treatment with 1.4 additive levels ($ZnCO_3$), the tensile strength increased significantly in both axes, reaching 235 N in the warp direction and 205 N in the weft direction. This represents an average increase of 24.3%in the warp and 22.0% in the weft direction. This finding aligns with the results reported by Sharma et al., who observed a 12 % increase in tensile strength upon treatment of cotton with zinc carbonate nanoparticles [13]. The observed increase is attributed to the reinforcing effect of the nanoparticles and the presence of the polymeric binder, which enhances fibre-to-fibre bonding and load distribution within the textile structure, thereby confirming that the zinc carbonate treatment did not negatively impact the fabric's intrinsic strength. It is also important to note that no significant fabric shrinkage was observed through macroscopic inspection following the pad-dry-cure process. Therefore, the observed increase in tensile strength is attributed to the reinforcing action of the $ZnCO_3$ nanoparticles and the polymeric binder promoting enhanced load distribution and fibre-to-fibre adhesion, rather than an artefact of dimensional stabilisation.

Table 1

MEAN TENSILE STRENGTH (N) AND PERCENTAGE INCREASE IN WARP AND WEFT DIRECTIONS

Sample	Direction	Tensile Strength (N)	Tensile increase (%)
Untreated	Warp	189 ± 5	N/A
Untreated	Weft	168 ± 3	N/A
Treated	Warp	235 ± 4	24.3
Treated	Weft	205 ± 5	22

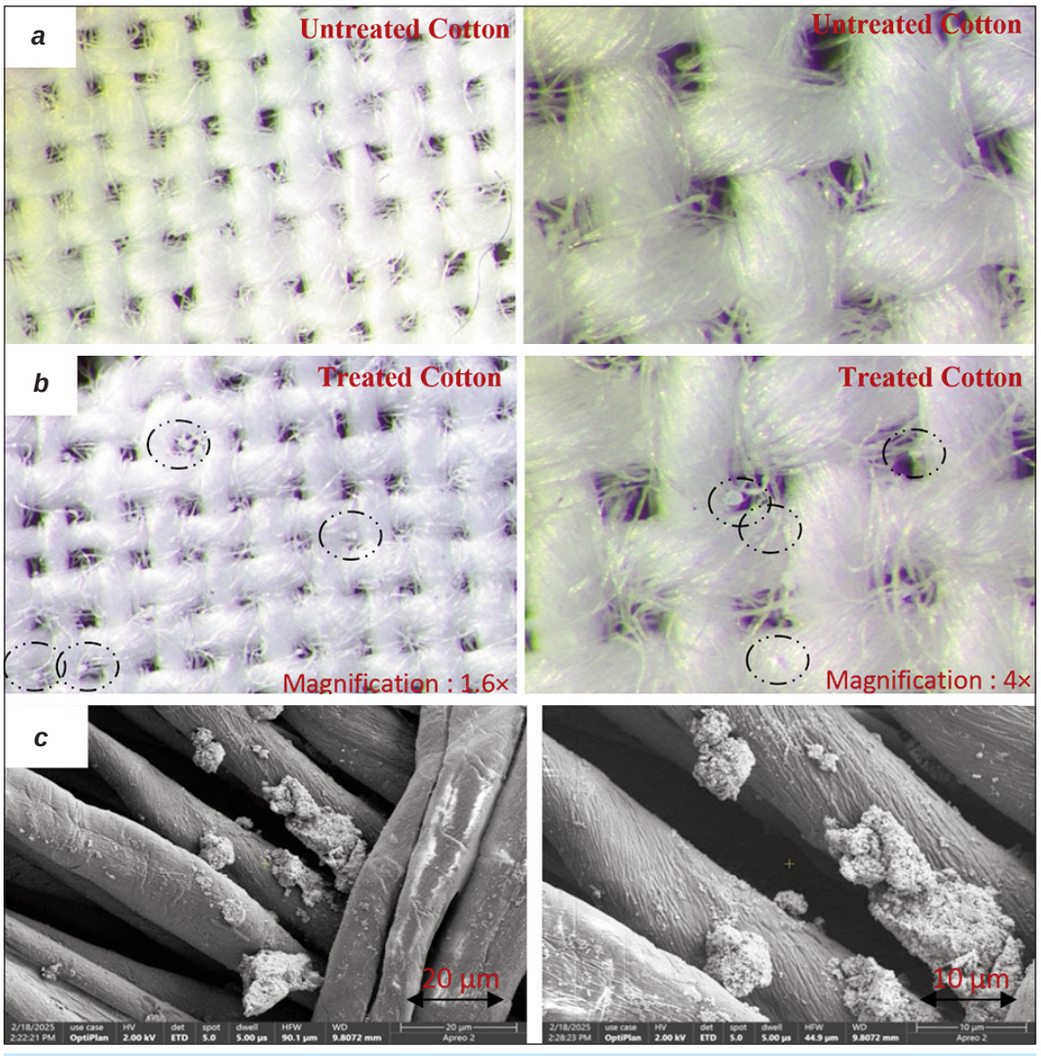


Fig. 5. Microscopic analysis comparing untreated and treated cotton fabric: *a* – optical micrograph of untreated fabric; *b* – optical micrograph of treated fabric; *c* – SEM images of treated fabric

Flammability analysis of the treated fabric

Cotton fabric was treated with synthesised zinc carbonate. Subsequently, the treated fabric and control fabric were evaluated for fire retardant properties.

It was observed that the untreated cotton fabric burned quickly, with flashes and flames, within a minute. After it finished burning, a light, fragile, whitish ash remained. However, while the control fabric exhibited an afterglow after burning, the zinc carbonate-treated cotton fabric showed no such afterglow. The key results of this study are summarised in the following table. Burning rates were calculated by dividing the sample length (30 cm) by the burning time.

The fire-retardant mechanism of zinc carbonate ($ZnCO_3$) is based on various synergistic effects. When exposed to heat, $ZnCO_3$ decomposes endothermically according to the following reaction:

$$ZnCO_3 \longrightarrow ZnO + CO_2$$

As shown in studies involving thermal decomposition, transformation of basic zinc carbonates to ZnO begins at relatively low temperatures (noticeable decomposition at 150–200 °C) and leads to ZnO as a solid product [15]. Then, the formed ZnO in the condensed phase enhances substrate protection by

Table 2

ADD-ON PERCENTAGE AND VERTICAL FLAMMABILITY PERFORMANCE OF UNTREATED AND $ZnCO_3$ TREATED COTTON FABRIC

Sample	Additive (%)	Add-On (%)	Burning time (s)	Burning rate (cm/s)
A	untreated	-	48 ± 1.0	0.62 ± 0.05
B	0.5	6 ± 0.3	81 ± 3.5	0.37 ± 0.02
C	1.4	8 ± 0.4	126 ± 4.2	0.23 ± 0.01

favouring char formation, which is denser and more cohesive, acting as a thermal shell providing a heat barrier and mass transfer inhibitor. Experimentally, $ZnCO_3$ treatments on cotton have shown a significant improvement in LOI and high char mass retention (LOI value of 30 and a specific char length of 40 mm with more than 40% char mass retention at 600°C) [13].

Lastly, the effects can be seen in the more general terms of metallic additives, with many publications noting that metal oxides (including ZnO) encourage catalytic carbonisation and formation of a dense char layer that significantly decreases the polymer area exposed to air, thereby improving condensed-phase protection and smoke removal [23].

This study demonstrates that the incorporation of zinc carbonate is an effective flame retardant for cotton fabric. At a 1.4% additive level, our treated fabric showed a significant increase in burning time of 162.5% and a decrease in burning rate of 63% compared to the untreated cotton. To contextualise these results, we compared our findings with similar studies in the literature. Sharma et al. synthesised zinc carbonate nanoneedles using a conventional direct precipitation method with zinc sulfate and sodium carbonate [13]. Their study reported a burning rate of 0.05 cm/s, but this was achieved with a significantly higher additive level of 4% under alkaline conditions. Although their burning rate was lower, our findings are highly competitive, achieving a comparable flame-retardant effect with a much lower additive level (1.4%), which is beneficial for maintaining fabric properties and reducing cost. Conversely, our results showed superior performance compared to the work of Tseghai et al., who utilised chicken eggshell powder as an additive. Their fabric, with a 0.3% additive level, had a burning rate of 1.4 cm/s, which is significantly higher than the 0.23 cm/s achieved in our study [19]. These comparisons highlight the effectiveness of our green-synthesised zinc carbonate in imparting a strong flame-retardant property to cotton fabrics, while also showcasing the advantages of our eco-friendly approach. Notably, our study demonstrates that our green synthesis of zinc carbonate, applied via the dip-coating method, achieves optimal flame retardancy with a relatively low additive level of 1.4%. This constitutes a significant contribution to the field. Furthermore, an important practical advantage is the low add-on percentage of our treatment, which is 0.6% for a 0.5% additive level and 8% for a 1.4% additive level, indicating uniform deposition of the $ZnCO_3$/acrylic binder preparation for all replicates. This parameter allows for comparability of flammability results by confirming an identical coating weight was applied to all samples. This is considerably lower than the typical 20–30% required for many commercial flame-retardant treatments [13]. The use of a lower add-on percentage not only reduces costs but also helps to better preserve the natural properties and hand-feel of the cotton fabric.

From a sustainability and economic perspective, the synthesised $ZnCO_3$ finishing offers distinct advantages over conventional systems. The method adheres strongly to the principles of the circular economy by utilising Olive Wood Charcoal Ash extract, a zero-cost agricultural waste, to successfully replace costly, high-purity commercial alkaline precursors (e.g., NaOH) needed for precipitation. This waste valorisation significantly reduces the material cost footprint and the need for fresh raw chemical resources. Furthermore, by providing an effective, non-toxic $ZnCO_3$ coating, the technology offers a viable alternative to widely used toxic or persistent flame retardants (such as halogenated or formaldehyde-based systems), thereby mitigating environmental pollution and health risks.

CONCLUSION

In this study, we successfully developed and validated a novel, sustainable route for synthesising an effective textile flame retardant by using an alkaline extract derived from olive wood charcoal ash. This methodology effectively performs waste valorisation by utilising a zero-cost agricultural byproduct to replace expensive, purchased commercial alkaline reagents, thereby establishing a proof-of-concept for a truly circular economy approach to chemical synthesis. The alkaline extract exhibited pH values near 13 under varying conditions, enabling efficient precipitation of zinc carbonate. XRD analysis confirmed the formation of the basic form of Zinc carbonate, as evidenced by characteristic diffraction peaks corresponding to its crystalline structure. However, the presence of non-indexed peaks suggests compositional complexity, likely arising from residual components in the ash-derived alkaline agent used during synthesis. The resulting $ZnCO_3$ coating offers significant improvements in textile properties: the 8.0% ± 0.4% treated fabric exhibited substantial FR performance, reducing the burning rate by up to 63% and increasing tensile strength by over 22% across both the warp and weft directions, without inducing significant fabric shrinkage. These findings position the $ZnCO_3$ coating as a highly viable, eco-friendly, and economically sound alternative to conventional, resource-intensive FR textile finishes.

However, a primary limitation identified was the durability of the coating to standard laundering. Future research will therefore focus strategically on process optimisation through techniques like sonication to improve particle uniformity, and the investigation of alternative, environmentally benign cross-linking agents to significantly enhance the adhesion and wash durability of the $ZnCO_3$ coating, thereby validating the long-term commercial potential of this sustainable textile finish.

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Research on the collar-placket shape of modern vests and the inheritance of digital fashion matching

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ABSTRACT – REZUMAT

Research on the collar-placket shape of modern vests and the inheritance of digital fashion matching

The vest is a traditional clothing item in China that has been continuously used to the present day. It is highly practical, diverse in form, lightweight, flexible, and suitable for a wide range of occasions. Based on 81 physical objects and 76 historical image materials of modern vests collected by the Jiangnan University Folk Costume Museum as research samples, the study compares the evolution of vests, collar-placket shapes, and the evolution of wearing and matching through a triple-evidence methodology: physical surveying, historical imagery, and archival documentation. The study reveals that during the late Qing Dynasty and early Republic of China periods, popular stand-up collar styles of modern vests included single-breasted placket, pipa placket, front-opening placket, pair placket, and herringbone placket. The traditional continuation of the round-collar placket includes the single-breasted placket, pipa placket, front-opening placket, wavy single-breasted placket, pair placket, eight-character front placket, shoulder-opening placket, and no front placket. Additionally, special collar forms that reflect a blend of Chinese and Western styles include a square-collar front-opening placket, a boat-shaped collar with a shoulder-opening placket, a heart-shaped open collar with a slanting front, and a pullover collar. The research clarifies that vest wearing and matching evolved from the late Qing Dynasty combinations, such as vests worn with Manchu-style clothing, traditional long gowns and skirts, and traditional Chinese jackets and trousers, to the Republic of China era, where vests were commonly paired with cheongsams and inverted big sleeve suits. The AHP fuzzy comprehensive evaluation method has proven effective in assessing the digital display of modern vest-wearing forms, offering new insights into the preservation and inheritance of modern vest culture.

Keywords: *modern vest, vest evolution, collar-placket shape, digital wearing matching, fuzzy comprehensive evaluation method*

Studiu privind forma gulerului și a fentei de închidere a vestelor moderne și transmiterea tradiției potrivirii digitale în domeniul modei

Vesta este o piesă vestimentară tradițională din China, care a fost folosită în mod continuu până în prezent. Este extrem de practică, are forme variate, este ușoară, flexibilă și potrivită pentru o gamă largă de ocazii. Bazat pe 81 de obiecte fizice și 76 de materiale imagistice istorice reprezentând veste moderne, colectate de Muzeul Costumelor Populare al Universității Jiangnan ca eșantioane de cercetare, studiul compară evoluția vestelor, a formelor gulerului și a modului de purtare și asortare prin intermediul unei metodologii bazate pe trei tipuri de dovezi: studii fizice, imagini istorice și documentație de arhivă. Studiul relevă faptul că, în perioada de la sfârșitul dinastiei Qing și începutul Republicii Chineze, stilurile populare de guler ridicat ale vestelor moderne includeau gulerul cu fentă simplă, fenta „pipa”, fenta cu deschidere frontală, fenta dublă și fenta în zig-zag. Printre variantele tradiționale ale gulerului rotund care s-au păstrat se numără gulerul cu fenta simplă, fenta „pipa”, fenta cu deschidere frontală, fenta ondulată simplă, fenta dublă, fenta frontală în formă de opt, fenta cu deschidere la umăr și fenta fără deschidere frontală. În plus, formele speciale de guler care reflectă o îmbinare a stilurilor chinezesc și occidental includ gulerul pătrat cu fentă cu deschidere frontală, gulerul în formă de barcă cu fentă cu deschidere la umăr, gulerul deschis în formă de inimă cu partea frontală înclinată și gulerul tip pulover. Cercetarea arată că modul de purtare și asortare a vestelor a evoluat de la combinațiile din perioada târzie a dinastiei Qing, precum vestele purtate cu ținute în stil manciurian, rochiile lungi și fustele tradiționale, precum și jacheta și pantalonii tradiționali chinezești, până în epoca Republicii Chineze, când vestele erau asortate în mod obișnuit cu cheongsam-urile și costumele cu mâneci largi răsucite. Metoda de evaluare cuprinzătoare fuzzy AHP s-a dovedit eficientă în evaluarea reprezentării digitale a formelor moderne de purtare a vestelor, oferind perspective noi asupra conservării și moștenirii culturii moderne a vestelor.

Cuvinte-cheie: *vestă modernă, evoluția vestei, forma gulerului și a fentei, asortarea digitală a ținutelor, metodă cuprinzătoare de evaluare de tip fuzzy*

INTRODUCTION

Vest, also known as “Kanjian” or “close-fitting”, evolved from military uniforms and serves as a general term for multi-button sleeveless shirts. During the Qing Dynasty, the vest was referred to as “Junjikan”, and among the Manchu people, it was called “Batu Lu Kanjian”. According to the “Qing Bei Lei Cao·Clothing”, it was recorded: “In the capital, the Batu Lu jacket was highly popular. When officials from various ministries met court officials, they often

wore this garment" [1]. The Batulu Kanjian was originally worn by important officials of the imperial court, and later became a semi-ceremonial dress. The modern vest is a type of clothing with high popularity and frequency of wear for both men and women. Its collar and front placket, as key components of the vest, play an important role in accentuating the beauty of the face and neck, and the shape of the collar and front placket also reflects the aesthetic tendency and artistic style of clothing in that era [2].

At present, academic discussion on vests mostly focuses on the design and shape [3, 4], decorative art [5] and manufacturing techniques [6]. However, there remains a lack of specialised studies on the collars and front plackets structures and wearing form of modern vests. In terms of digital display of clothing, examples include the spring outing painting of Lady Guo [7], Beauties Wearing Flowers [8] and the plain unlined silk gauze gown of the Mawangdui Han Dynasty Tomb [9]. The purpose of this paper is to measure and analyse the modern vest heirloom objects, explore their collar and front structure, and systematically sort out their dressing collocation. By integrating digital simulation technology with the visual display of modern vest wear, this study seeks to provide a new perspective for the design innovation and promotion of traditional Chinese vest styles.

METHOD

General scheme

This paper primarily examines the collar-placket shape of modern vests and the inheritance of digital fashion matching from three perspectives, as shown in figure 1. First, it traces the origin and development of the vest form and sorts out its development trajectory and evolution rules. Next, it delves into the collar-placket shape of modern vests; stand-up collars were prevalent during the late Qing Dynasty and early Republic of China periods, reflecting the characteristics of the era. The round collar shape continued the tradition, showcasing the inheritance of culture. Additionally, there were unique collar-placket shapes that blended Chinese and Western styles, reflecting cultural integration. In terms of digital fashion pairing and simulation effect evaluation for modern vests, the study examines the evolution of wearing matching, covering various combinations with garments such as Manchu-style clothing, traditional long gowns and skirts, traditional Chinese jackets and trousers, cheongsams and inverted big-sleeve suits, showcasing a wide variety of styles.

Furthermore, the simulation effect evaluation of digital matching is carried out, utilising three-dimensional simulation technology to present the matching effect of modern vests. The multi-level fuzzy comprehensive evaluation theory is introduced to construct a digital matching simulation effect evaluation system for modern vests. Through fuzzy comprehensive evaluation, the simulation effect of different matching forms is quantitatively analysed, providing a scientific basis for the research on the fashion matching of modern vests.

The origin and development of the form of the vest

Throughout multiple dynasties, the vest design primarily featured sleeveless, collarless, or short-sleeved, collarless upper garments [4]. Changes

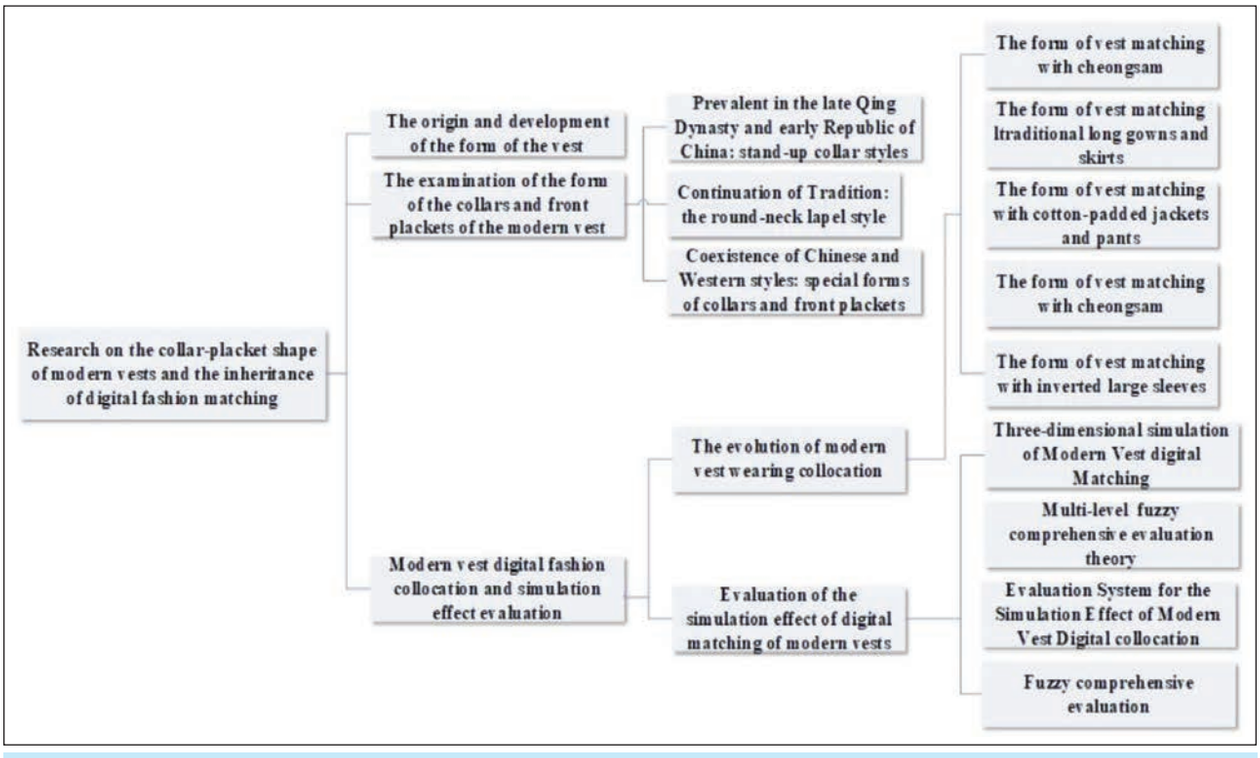


Fig. 1. Research on the collar-placket shape of modern vests and the technical route of digital fashion matching inheritance

occurred in the shape of the collar, the length of the sleeves, and the closure method of the vest. As shown in table 1, the earliest shape of the vest can be traced back to the military armour of the Qin Dynasty, establishing the basic shape of the sleeveless vest [10]. Based on sleeve length, the armour of the Qin Dynasty, the Qin-Han Dynasty's Liangdang, the Ming Dynasty's bijia, and the Qing Dynasty's vests all featured the modern sleeveless vest shape; From the shape of the collar, from the pre-Qin period to the Ming Dynasty, the mainstream collar styles included collarless, straight collar, vertical collar, crossed collar, and square collar, etc. By the Qing Dynasty, round collars and stand-up collars gradually became dominant; From the perspective of front placket shape, in the Song–Yuan Dynasty, Han–Mongol integrated dahu garments primarily adopted large plackets. During the Ming dynasty, the armour predominantly featured the pair plackets. The most distinctive feature of Qing-dynasty vests lies in the diversification of placket forms under Manchu–Han cultural integration. Judging from the overall shape of the collar-placket, the earliest collar-placket shapes of traditional vests were mostly cross-collar right placket, straight collar and pair plackets, round collar and slanted plackets, etc. By the Qing Dynasty, they primarily featured stand-up collars or round collars paired with various front placket shapes. This resulted in a uniquely distinctive Chinese-style vest shape that remains in use today and aligns with modern vest terminology. This shape also closely resembles the contemporary vest silhouette. During this evolutionary process, ancient vests underwent an important transformation from practical function to decorative expression.

A study of the collar-placket shape of the modern vest

"Shi Ming·Shi Yi Fu": "The collar is the neck, used to surround the neck. It is also called the 'overall collar,' as it forms the first part of the garment" [11]. "The collar is the most eye-catching part of clothing, surrounding the neck. It is an important factor in showing the overall shape of the garment" [12]. "Shi Ming·Shi Yi Fu": "Placket" means "closed off". "It is crossed in front, so as to prevent the wind and cold" [13]. The placket is the opening and closure of the garment [14]. It is designed to facilitate putting on and taking off the garment, and is an opening form. Its shape determines how the vest is worn. The front opening line is located at the front of the chest and abdomen, playing a crucial role in defining the overall style of the clothing [15].

Table 1

THE EVOLUTION OF VEST SHAPES IN THE PAST DYNASTIES

Name / Dynasty	The armour of the Qin Dynasty	Qin-Han Dynasty's Liangdang	The Northern and Southern Dynasties' Liangdang armour	Tang Dynasty's half-sleeve
Character outfit illustration				
Shape Illustration				
Name / Dynasty	The Song-Yuan Dynasty's dahu	Ming Dynasty's armour	The Ming Dynasty's bijia	The Qing Dynasty's vests
Character outfit illustration				
Shape illustration				

Through the analysis and organisation of 81 physical specimens and 76 image materials of modern vests from the Jiangnan University Folk Costume Museum and other institutions, modern vests exhibited diverse collar-placket shapes, comprising five shapes of stand-up collar and placket, eight predominant round collar placket shapes, and four unique collar-placket forms. From the regional distribution of modern vests, stand-up collar one-line plackets predominantly originated from Jiangnan; stand-up collar large plackets were common in Jiangnan and Shanxi; stand-up collar pair plackets were more prevalent in southern Fujian and northern Shanxi; round-collar plackets had widespread origins; while unique collar-placket forms were primarily from Shanxi and Shandong. Moreover, the collars and necklines of modern vests frequently employed decorative techniques such as edging. The wide variety of edging decorations and diverse craftsmanship contributed to a more structured silhouette.

Popular in the late Qing and early republican periods: the stand-up collar and placket shape

The origins of the stand-up collar can be traced back to the "vertical collar" of the mid-Ming Dynasty, which flourished during the late Qing Dynasty and early Republic of China, also known as the Chinese-style collar. The edges of the stand-up collar on modern vests typically feature trim, with a stiff lining sandwiched between the collar pieces to maintain a straight and upright appearance when worn. As shown in table 2, according to chronological development, five major combinations of vest collar–placket forms can be identified: first, the stand-up collar one-line placket from the early to mid-Qing dynasty, representing military practicality and aristocratic symbolism. The buttons are all fastened on the chest in a straight line, also known as the "multi-button vest". Initially, it was worn as ceremonial attire by royalty, princesses, and Manchu nobility, but later became popular among both men and women among the general populace. The second type is the stand-up collar pipa placket, which became common in the mid- to late Qing period as Manchu–Han integration extended traditional forms into civilian use. It is described in The Yangzhou Painting Boat Record: …Each wore a blue lotus cotton shirt with a reverse-curved collar structure. The lower right side of the collar was cut off to form a notch, which is known as a "pipa lapel" [16]. This was a type of slanting front placket with a missing panel, also known as a stand-up collar incomplete placket. Third, the stand-up collar large placket persisted from Han tradition into the Manchu-Han fusion era of the mid-to-late Qing. If the placket overlaps to the right, it is called a right front placket, and if it overlaps to the left, it is called a left front placket. In modern times, Han Chinese vests often feature a right front placket as a stylistic characteristic. Fourth, the stand-up collar pair placket emerged as unisex wear in the late Qing and early Republican era, constituting the largest proportion in terms of quantity. The garment panels align on both sides of the front placket when worn, with the left and right plackets parallel, suitable for layering beneath or over long robes, mandarin jackets, Cheongsams, or overcoats. The fifth type is the stand-up collar herringbone placket, characterised by decorative innovation from the late Qing to the Republican era. The herringbone placket has two structural forms: the first involves cutting the central sides of the front panel collar to create the opening, followed by stitching one placket edge; The other skips cutting, instead using lace or decoration to mimic a pair placket, giving the appearance of a double front. In both forms, the right side placket still serves the functional purpose of opening and closing [17]. The "herringbone placket" features a single button at the collar opening, with the lower sides of the collar slightly cut downward on both sides, causing the upper part of the placket to form a "human" shape, hence the name [18] was widely seen in modern women's vests and cheongsams.

Table 2

THE ANALYSIS RESULTS OF MODERN VEST STAND-UP COLLAR OPENING FORM

Type of collar-placket	Physical examples	Shape drawing	Number of items/ratio
Stand-up collar one-line placket			20 12.7%
Stand-up collar pipa placket			21 13.4%
Stand-up collar large placket			21 13.4%
Stand-up collar pair placket			28 17.8%
Stand-up collar herringbone placket			2 1.3%

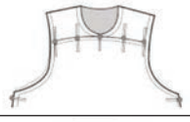
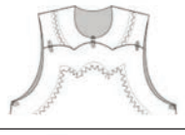
Continuation of tradition: round collar placket shape

The round collar, also referred to as the "panling", "tuanling", or "quling" in ancient texts, was prevalent during the Tang Dynasty and

inherited the tradition of collarless Hanfu. The round collar of the modern vest is usually reinforced with stiff interlining; most necklines are fitted with frog fastenings. In modern vests, the flat round collar is most common. When worn, it reveals the collars of the underlying aogua or cheongsam, creating a layered effect at the neckline. As shown in table 3, chronologically, eight major front-placket shapes can be identified. First, the round-collar large placket continues Han traditions in the early to mid-Qing period, as described in "Qing Bei Lei Chao · Clothing": "By custom the right hand is considered dominant, thus the right placket is called the large placket" [17]. In round-collar vests, the collar opening lies between the shoulder and neckline centre, with the placket arranged on the right side. Second, the round-collar pipa placket derived from Manchu riding and working garments in the mid to late Qing period, whose shape is quite similar to the large placket style. The placket surface resembles half a pipa (Chinese lute) cradled across the chest, hence the name "pipa placket". Third, the round-collar straight-line placket transitioned from military insignia to civilian wear in the late Qing and early Republican era. Due to the seven vertical buttons arranged horizontally along the front placket and three horizontal buttons arranged vertically along the side seams at the waist, totalling thirteen buttons, giving rise to the nickname "Thirteen Taibao"; fourth, a round-collar pair placket, which became the most prevalent during the late Qing and early Republican periods. The garment has two plackets opening symmetrically at the chest, making dressing and undressing convenient. Unrestricted by social rank, ethnicity, age or gender, it was widely worn by commoners and nobility alike among the Manchu, Mongol and Han peoples. Fifth, the decorative round-collar figure-eight placket of the mid-Republican era resembles the double-placket and straight-line placket shapes. The difference from the herringbone placket lies in the fact that the collar opening does not intersect with the double plackets at a single point, but instead the front placket is horizontally opened across the chest, resulting in an "eight-shaped" appearance; sixth, the round-collar wave-shaped placket combines decoration and functionality in the mid to late Republican period, with three frog buttons placed along a wavy line, one in the centre of the round collar, one on each side. The triple-fold curved line corresponds to three buttons, six fewer than the straight-line placket; Seventh, the round collar without placket of the late Republican period combines minimalism with functionality. Since there is no front placket, the collar curve is generally cut lower to facilitate putting on and taking off, and the front panel can display a complete auspicious pattern. This round collar without a placket is commonly seen in children's vests; the eighth, round-collar, shoulder-opening placket, blends functional and modernist exploration, also known as the shoulder-opening vest. It is primarily worn as innerwear for practical warmth. When worn in winter, they are lined with silk cotton. Due to its excellent warmth and universality across gender, age, and social class, it was widely popular in modern daily life.

Table 3

THE ANALYSIS RESULTS OF MODERN VEST ROUND COLLAR AND OPENING FORM

Type of collar-placket	Physical examples	Shape drawing	Number of items/ratio
Round-collar large placket			7 4.6%
Round-collar pipa placket			6 3.8%
Round-collar straight-line placket			6 3.8%
Round collar pair placket			32 20.4%
Round-collar figure-eight placket			1 0.6%
Round-collar wave-shaped placket			1 0.6%
Round collar without placket			1 0.6%
Round-collar shoulder-opening placket			2 1.3%

East-West coexistence: unique collar-placket form

With the influx of Western influences in modern times, the collar-placket shapes of women's vests became increasingly diverse, giving rise to forms that blended Chinese and Western elements. Westernised features appeared in collar-placket shapes, such as

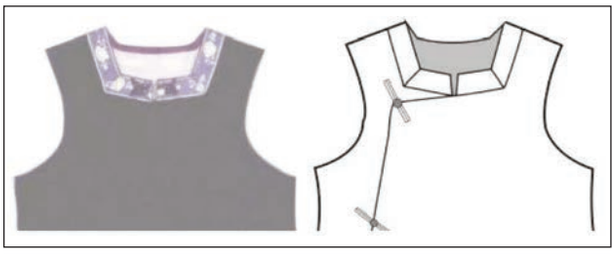


Fig. 2. Square-collar diagonal-placket vest collections and style



Fig. 3. Collections and style of boat-shaped collar and shoulder-opening placket vest

square collars, heart-shaped collars on shoulder-opening plackets, and oblique plackets. This reflected a coexistence of Eastern and Western elements, blending old and new. The square-collar diagonal-placket vest (figure 2) has square-shaped corners on both sides of the collar, with an opening at the centre front. It is a collarless form with a relatively deep and low neckline. Inside the square collar, one usually wears a standing-collar cheongsam or a cross-collar shirt. The boat-shaped collar emphasises the elegant combination of the neckline curve with the body's contours, giving the effect of lengthening the neck and refining the facial shape. The shoulder-opening placket extends from the edge of the boat-shaped neckline, following the collar and shoulder line, fastened at the shoulder with a horizontal button. This single-side opening at the shoulder seam allows for easy donning and removal (figure 3).

The heart-shaped collar slanted-placket vests adopt Western design principles with heart-shaped necklines. Figure 4 shows a black dark satin heart-shaped collar slanted-placket vest. The front placket features a slanted placket, while the neckline forms a heart shape. The lower hem with slits on both sides gradually tapers upward, giving the heart-shaped collar a delicate and refined appearance. Typically worn over a stand-collar cheongsam, it is suitable for young women. The through-head collar-placket originated from the typical attire of the Neolithic period, namely the pullover garment, representing the earliest form of collars. Mr Shen Congwen described the pullover garment in Research on Ancient Chinese Costume as: "an opening left at the upper centre for the head to pass through". This "central opening" served as the prototype for early collars, while the need to "allow the head to emerge" was the reason collars emerged. As shown in figure 5, it was a wrap-style vest, created by folding a rectangular piece of cloth and cutting an aperture to facilitate insertion of the head and neck. The garment panel is rectangular in cut, connected only at the right shoulder, with the left shoulder fastened by a button. These garments were generally small in size, primarily worn by infants and young children.

Modern vests digital fashion pairings and simulation effect evaluation

Though vests have existed since ancient times, they reached their peak popularity during the Qing Dynasty, worn by both men and women. Initially serving as an undergarment, their styles were relatively close-fitting. By the late Qing, styles became more varied, with refined edging and embellishments, and vests were often worn as outer garments. Entering the early Republican era, their shapes inherited Qing features, but decoration gradually Westernised, becoming shorter and more fitted, while still worn as outerwear. In the modern period, women's vest matching showcased far greater diversity. Presenting vest styling through digital virtualisation can more effectively showcase the varied expressions of women's attire matching across different social strata.

The evolution of modern vest wearing and matching

Early vests were decorated with black wide borders, limited to edging details like the collar and front placket, rarely employing embroidery or complex patterns. They were worn over long gowns or jackets, mostly shaped with stand collars and no sleeves. As society transformed, the occasions for wearing vests expanded further. Women often paired vests with inverted big-sleeve suits and long skirts, forming a typical new style of dress. At the same time, the integration of vests with Western-style garments began to emerge, with some women trying to combine vests



Fig. 4. Black dark satin heart-shaped collar slanted-placket vest collections and style



Fig. 5. Collections and style of the through-head collar-placket vest

with qipao or Western coats, reflecting a trend of Sino-Western aesthetic fusion.

Forms of vest matching with banner garments

In the early Qing dynasty, banner garments (qizhuang) were characterised by four-sided slits and narrow horse-hoof sleeves; at this time, vests served as functional outerwear. During the Qianlong reign, this prompted two major transformations in vest shape: firstly, the length extended to the knees, developing into the 'long vest'; secondly, it incorporated satin embroidery and multiple edging trims. In the late Qing period, under Manchu–Han cultural integration, fitted vests paired with banner garments exhibited diversified collar–placket shapes. As shown in type 6a, an old photograph of Su Guaerjia Youlan, the birth mother of Emperor Puyi, is a fitted banner dress with a stand-up collar, large placket, and floor-length hem. The low-standing collar and straight-fronted vest clearly retained Manchu sartorial traditions. Its silhouette was narrow and short, appearing more fitted compared to the wide robes and broad sleeves of Han attire. Manchu women cherished elaborate clothing styles, and vests were no exception. Their clothing matching emphasised a "multi-layered style", with vests worn over banner robes. The multi-layered contrasting trimmings occupied most of the vest's surface, embodying typical Qing craftsmanship and aesthetic features.

Forms of vest matching with gown and skirt

In the late Qing period, Han Chinese women continued the Ming-dynasty tradition of wearing an upper jacket and a lower skirt. Vests of this period retained the traditional loose-fitting style. The vest was worn over a wide women's gua, with a loose body and large cuffs, paired with a horse-face skirt. This ensemble exhibited a 'de-Manchuised' aesthetic, as illustrated in figure 6, a representation of women's vest collocation form in Qing figure paintings. The gua featured a wide cut and broad sleeves. When worn by women, the cuffs revealed the rolled sleeves of the undergarment. A capacious vest was layered atop; it could be matched with a horse-face skirt. After the Jiaqing and Daoguang reigns, the decorative edging on the collars and plackets of Han women's gua, as well as the edging on the collars and vests, tended to narrow. During this period, narrow decorative trims were in vogue. The overall outfit presented a relaxed and free-flowing silhouette. The fabric hung naturally, forming fluid and graceful folds that fully showcased the dignified and elegant static charm of Han Chinese attire.

The form of vest with cotton padded coat and pants

The combination of vests with Coat-and-Pants ensembles marked a transition from a three-layer to a two-layer clothing structure. The rise of pants was also linked to labour demands; before the Tongzhi era, working women predominantly wore coat-pants directly. By the Guangxu era, pants became widespread; By the Xuantong period, skirt wearers dwindled, with upper coats and pants becoming the dominant attire. Older women, maidservants, or northern women typically wore pants without skirts. A sleeveless vest was then layered over the long jacket, demonstrating the practical utility of pairing vests with cotton padded Coat and Pants. As shown in figure 6, in a late Qing photograph, a Han woman wears a brow-band on her head, a round-collar, large-placket cotton Coat with a wide cut, paired with trousers. The cotton Coat itself contains a cotton interlayer. Wearing the vest over the cotton Coat helped trap the static air within the cotton padding, thereby enhancing thermal insulation and cold resistance. The combination of the loose-fitting robe with its narrow sleeves and the tapered trousers reflected Han Chinese style while facilitating labour.

Vest pairings with inverted big sleeve suit

In the early 1920s, women in Shanghai were among the first to break away from traditional dress frameworks (figure 6). As autumn cooled, they frequently wore a vest extending below the calf over their robes and coats, replacing the function of a skirt. These vests typically featured a large placket, resembling a sleeveless cheongsam. As an outer garment substituting for skirts, it eliminated the need for additional skirts when worn over outer garments [19]. As shown in figure 6, the pairing of long vests with inverted-big-sleeve blouses in a 1920s calendar poster broke away from the traditional top-and-skirt feminine attire [20]. The pale orange plum blossom print on the long vest echoes the orange geometric print at the cuffs of the off-white inverted-sleeve blouse. The black lace trim on the stand-up collar large placket of the long vest harmonised with the black lace edging along the inverted-big-sleeve flared cuffs. The overall combination embodied an aesthetic of formal symmetry and resonance.

In fact, it was precisely this pairing of inverted-sleeve blouses and long vests that evolved into the later knee-length inverted-big-sleeve cheongsam style. The layering of long vest and inverted-big-sleeve blouse did not last long. Though warm in winter, it was stuffy in summer. Women cut away the blouse body, leaving only the sleeves attached to the vest shoulders, forming an integrated vest-cheongsam [21]. This design reduced layering while retaining the modesty of traditional robes and incorporating the convenience of Western-style dresses. It formed a unique "fusion of East and West" style. Another popular combination featured a short vest paired with an inverted-big-sleeve ensemble, creating the iconic look of the "New Woman". As seen on the cover of Liangyou Pictorial (figure 6). Over the straight-cut, rounded-hem jacket with inverted-big-sleeve, a fitted, stand-collared, large-placket vest was worn, exposing the flared sleeves. This demonstrates that women of the period were not confined to the simple pairing of tops with skirts, but instead flexibly layered vests of various styles.

Vest paired with Cheongsam

Following the widespread adoption of the Cheongsam, traditional constraints were entirely shed. As the cheongsam adopted a tightened waistline, a pairing



Fig. 6. Modern vest digital overall wear collocation display

of short vests with long cheongsams emerged [22]. Over time, their shape became increasingly Westernised, with colours and styles coordinated with the cheongsam [23]. As shown in figure 7 calendar poster, a black vest with dark floral patterns is paired with a blue cheongsam with black stripes, with sharp colour contrasts and clear layering. A white square-collared, large-placket vest worn with a standing-collar, large-placket cheongsam enhances the slenderness and grace of the woman's neck. A mid-sleeve, below-knee Chinese cheongsam combined with a fitted vest with a curved hem, paired with white leather high-heeled shoes, made the female figure appear more slender and carried a unique charm. The evolution of vest shape centred on the liberation of the female form, shifting from concealment to accentuating curves, mirroring society's redefinition of women's roles.

Evaluation of digital matching simulation effects of modern vests

Given the prominent role of modern women's vests in sartorial artistry, this paper employs CLO3D digital simulation technology to achieve an in-depth digital recreation of vest wearing forms. To ensure the credibility of simulated garments, the AHP fuzzy comprehensive evaluation method is utilised to validate the accuracy of simulation outcomes. The AHP method decomposes complex problems into multiple hierarchical levels, establishing the relative importance of factors through pairwise comparisons. This renders it suitable for evaluating multi-factor, multi-level digital vest matching. The fuzzy comprehensive evaluation



Fig. 7. The virtual display technology process of modern vest and cheongsam

method addresses ambiguity and uncertainty in the evaluation process, enabling a more accurate representation of the overall characteristics of digital vest matching. This approach aims to streamline the physical restoration process of modern vests and provide an intuitive representation of wearing effects. Simultaneously, the digital vest data facilitates storage, replication, and dissemination, enabling broader audiences to engage with traditional garments [24].

Three-dimensional simulation of modern vest digital matching

Through analysis and summary of vest styling in modern calendars and vintage photographs, six common vest styling forms are digitally presented. As illustrated in figure 7, using Republican-era calendar posters as reference: AI software first rendered patterns for a square-collar large-placket vest and a stand-collar large-placket cheongsam; ET software generated a pattern-drafting diagram; Photoshop rendered the subtle patterns and blue stripes. A virtual mannequin of 160 cm height was constructed based on modern female body measurements, with garment data meticulously reconstructed from historical artefacts and archival records. The garment pattern piece was then imported as a DXF file into a 2D view for fine-tuning, precisely positioned on the 3D mannequin, and virtually sewn according to garment construction. Further adjustments were made during virtual fitting to ensure high fidelity of pattern reproduction. Fabric properties were then analysed from extant artefacts to set restoration parameters, incorporating materials, colours, and patterns for enhanced realism. The final presentation showcased the virtual simulation pairing of waistcoat and cheongsam. The remaining six vest combinations underwent identical digital styling procedures for fashion presentation. This shows that through advanced 3D technology, traditional culture can be revitalised in the digital space, promoting the digital protection and display of cultural heritage [25].

Multi-level fuzzy comprehensive evaluation theory

To ensure the credibility of virtual simulation outcomes, four evaluation indicators are established: garment shape, detailed structure, fabric material, and garment craftsmanship [26]. In order to obtain a reasonable evaluation, the Analytic Hierarchy Process (AHP) is used to construct a judgment matrix and perform a consistency test to calculate the weights of the four indicators. The specific steps are as follows. Determination of the fuzzy evaluation matrix: Evaluate the indicators in u_i based on the n evaluation criteria in the evaluation set. Pairwise comparisons of elements in the matrix yield an n-order comparative judgment matrix $R_{i\times j}$ [27].

$$R_{i\times j} = \begin{pmatrix} r_{11} & r_{12} & r_{1\ldots} & r_{1j} \\ r_{21} & r_{22} & r_{2\ldots} & r_{2j} \\ r_{\ldots} & r_{\ldots} & r_{\ldots} & r_{\ldots} \\ r_{i1} & r_{i2} & r_{i\ldots} & r_{ij} \end{pmatrix} \quad (1)$$

Evaluation system of digital matching simulation effects of modern vest

The virtual reconstruction of modern vest ensembles employs a comprehensive approach, simulating key information such as overall structure, stylistic details, fabric characteristics, craftsmanship features, and wearing combinations based on physical artefacts, calendar cards, and historical photographs. To scientifically evaluate reconstruction outcomes, a three-tiered assessment framework, comprising target layer, criterion layer, and indicator layer, has been established, adhering to standard assessment paradigms. As shown in table 4, the target layer focuses on the digital matching and virtual reconstruction of modern vests. The criteria layer provides a comprehensive assessment framework across four dimensions: Garment shape u_1, Detailed structure u_2, Garment fabric u_3, and Garment craftsmanship u_4. The indicator layer refines the assessment content, including 14 indicators such as External silhouette u_{11}, Proportional allocation u_{12}, etc. To enhance the operational feasibility of the assessment system, concise 'evaluation criteria' have been added for each indicator at this level. For example, the evaluation criterion for external silhouette u_{11} is the degree of similarity between the overall ensemble silhouette of the reconstructed vest and that observed in the original reference materials, including the smoothness of the overall contour and proportional harmony.

Table 4

EVALUATION SYSTEM FOR DIGITAL-SIMULATED EFFECT OF MODERN VEST MATCHING

Target layer	Criterion layer	Indicator layer
Modern vest digital matching virtual restoration effect (U)	Garment shape u_1	External silhouette u_{11} Proportional allocation u_{12} Layered styling u_{13}
	Detailed structure u_2	Bodice structure u_{21} Sleeve structure u_{22} Collar structure u_{23} Hem structure u_{24} Front placket structure u_{25}
	Garment fabric u_3	Fabric colour u_{31} Fabric pattern u_{32} Fabric properties u_{33}
	Garment craftsmanship u_4	Patchwork technique u_{41} Fastening method u_{42} Embroidery/printing u_{43}

After constructing the evaluation system, it is necessary to determine the weight coefficients of each indicator. Different indicators exert varying influences on the assessment of modern waistcoat digital matching effects. This paper employs the Analytic Hierarchy Process (AHP) to calculate the weights of each indicator. Five experts specialising in modern costume evaluation were invited to apply a 1–9 point quantitative scoring system. Experts pairwise compared the importance of indicators across levels. Table 5 shows the linguistic scale of the 1–9 scoring standard.

Table 5

SCALE OF THE JUDGMENT MATRIX

Importance intensity	Definition	Content
1	Equal importance	Both indicators are equally important
3	Slightly important	The former is slightly more important than the latter
5	Clearly important	The former is clearly more important than the latter
7	Very important	The former is much more important than the latter
9	Extremely important	The former is much more important than the latter
2, 4, 6, 8	-	Between the adjacent indicators above
Reciprocal	-	If the importance ratio of indicator i to indicator j is a_{ij}, then the importance ratio of indicator j to indicator i is $a_{ij} = 1/a_{ij}$

Based on the scoring results from five experts, the judgment matrices G can be obtained: G_1 is the pairwise comparison judgment matrix for factors (u_1,u_2,u_3,u_4) under the objective layer; G_{21} is the pairwise comparison judgment matrix for the subordinate factors (u_{11},u_{12},u_{13}) of u_1; G_{22} is the pairwise comparison judgment matrix for the subordinate factors $(u_{21},u_{22},u_{23},u_{24},u_{25})$ of u_2, G_{23} is the pairwise comparison judgment matrix for the subordinate factors (u_{31},u_{32},u_{33}) of u_3, and G_{24} is the pairwise comparison judgment matrix for the subordinate factors (u_{41},u_{42},u_{43}) of u_4. For example, the matrix obtained from the scoring results of the first expert:

$$G_1 = \begin{pmatrix} 1 & 2 & 3 & 2 \\ \frac{1}{2} & 1 & 1 & 3 \\ \frac{1}{3} & 1 & 1 & 1 \\ \frac{1}{2} & \frac{1}{3} & 1 & 1 \end{pmatrix} \quad G_{21} = \begin{pmatrix} 1 & \frac{1}{3} & \frac{1}{2} \\ 3 & 1 & 2 \\ 2 & \frac{1}{2} & 1 \end{pmatrix}$$

$$G_{22} = \begin{pmatrix} 1 & 4 & 5 & 5 & 4 \\ \frac{1}{4} & 1 & \frac{1}{2} & 1 & \frac{1}{5} \\ \frac{1}{5} & 2 & 1 & 4 & \frac{1}{2} \\ \frac{1}{5} & 1 & \frac{1}{4} & 1 & \frac{1}{5} \\ \frac{1}{4} & 5 & 2 & 5 & 1 \end{pmatrix} \quad (2)$$

$$G_{23} = \begin{pmatrix} 1 & \frac{1}{3} & 2 \\ 3 & 1 & 3 \\ \frac{1}{2} & \frac{1}{3} & 1 \end{pmatrix} \quad G_{24} = \begin{pmatrix} 1 & 5 & \frac{1}{2} \\ \frac{1}{5} & 1 & \frac{1}{5} \\ \frac{1}{2} & 5 & 1 \end{pmatrix}$$

The eigenvector method is used to calculate weights. Taking matrix G_1 as an example, its largest eigenvalue is $\lambda_{max} = 4.1752$, yielding the corresponding weight vector $w = (0.4198, 0.2600, 0.1725, 0.1477)$.
Calculations proceed as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

where CI denotes the consistency index, and n represents the order of the matrix. The calculation yields $CI = 0.0584$. Given $RI = 0.90$, the consistency ratio is obtained as $CR = CI/RI = 0.0649 < 0.1$, thus passing the consistency test [28]. As a result, the weight coefficients of the first-level indicators were calculated as W = (0.4198, 0.2600, 0.1725, 0.1477). Using the same method, the weight coefficients for the second-level indicators are obtained. By synthesising the expert evaluation results, the weight coefficients for each indicator are derived, as shown in table 6.
From the table data, we obtain W = (0.3820, 0.1961, 0.2536, 0.1683), w1 = (0.3108, 0.3361, 0.3531), w2 = (0.4341, 0.0982, 0.1613, 0.0856, 0.2208), w3 = (0.2861, 0.5331, 0.1808), w4 = (0.3908, 0.1374, 0.4718). Therefore, the four evaluation indicators are ranked by importance as follows: Garment Shape > Garment Fabric > Detailed Structure > Garment Craftsmanship; Layered styling > Proportional allocation > External Silhouette; Bodice structure > Front Placket Structure > Collar Structure > Sleeve Structure > Hem Structure; Fabric Pattern > Fabric Colour > Fabric Performance; Embroidery & Printing > Patchwork Technique > Fastening Method.

Fuzzy comprehensive evaluation

After determining the weight coefficients for primary and secondary indicators using the Analytic Hierarchy Process (AHP), a questionnaire survey method was employed to evaluate each element within the secondary indicators. This ensured a high degree of objectivity in the digital matching simulation restoration of modern vests. The questionnaire employed a 1–5 evaluation scale, V = (V1, V2, V3, V4, V5) = (Excellent, Good, Average, Poor, Very Poor). The survey primarily targeted university students with knowledge of ancient attire and virtual clothing. A total of 243 questionnaires were distributed, with 233 valid responses collected, yielding a valid response rate of 95.9%. The compiled statistical results of the evaluations are presented in table 7.
Based on the statistical results, the single-factor fuzzy comprehensive evaluation matrix for secondary indicators is obtained:

$$R_1 = \begin{pmatrix} 0.39 & 0.46 & 0.12 & 0.01 & 0.02 \\ 0.36 & 0.55 & 0.07 & 0.02 & 0 \\ 0.41 & 0.53 & 0.05 & 0 & 0.01 \end{pmatrix}$$

$$R_2 = \begin{pmatrix} 0.38 & 0.44 & 0.11 & 0.04 & 0.03 \\ 0.35 & 0.56 & 0.07 & 0.02 & 0 \\ 0.43 & 0.47 & 0.08 & 0 & 0.02 \\ 0.41 & 0.50 & 0.06 & 0.03 & 0 \\ 0.33 & 0.54 & 0.12 & 0.01 & 0 \end{pmatrix}$$

$$R_3 = \begin{pmatrix} 0.36 & 0.57 & 0.04 & 0.01 & 0.02 \\ 0.33 & 0.53 & 0.10 & 0.03 & 0.01 \\ 0.43 & 0.47 & 0.08 & 0.02 & 0 \end{pmatrix} \quad (4)$$

$$R_4 = \begin{pmatrix} 0.42 & 0.51 & 0.05 & 0.02 & 0 \\ 0.40 & 0.43 & 0.13 & 0.01 & 0.03 \\ 0.39 & 0.44 & 0.14 & 0.03 & 0 \end{pmatrix}$$

Each row R_i represents the evaluation of the simulation effect of modern vest digital matching, examining the membership degrees of fuzzy subsets at different levels from various factors. According to multi-level fuzzy comprehensive evaluation theory, the matrices R_i were combined with the corresponding fuzzy weight vectors to yield the fuzzy evaluation results B [29].

Table 6

WEIGHT COEFFICIENTS OF EVALUATION INDICATORS FOR THE DIGITAL SIMULATION OF MODERN VEST MATCHING

Primary indicator	Weight	Second-level indicator	Weight	Comprehensive weight
Garment shape u_1	0.3820	External silhouette u_{11}	0.3108	0.1187
		Proportional allocation u_{12}	0.3361	0.1283
		Layered styling u_{13}	0.3531	0.1348
Detailed structure u_2	0.1961	Bodice structure u_{21}	0.4341	0.0851
		Sleeve structure u_{22}	0.0982	0.0192
		Collar structure u_{23}	0.1613	0.0316
		Hem structure u_{24}	0.0856	0.0167
		Front placket structure u_{25}	0.2208	0.0432
Garment fabric u_3	0.2536	Fabric colour u_{31}	0.2861	0.0725
		Fabric pattern u_{32}	0.5331	0.1351
		Fabric performance u_{33}	0.1808	0.0458
Garment craftsmanship u_4	0.1683	Patchwork u_{40}, Technique u_{41}	0.3908	0.0657
		Fastening method u_{42}	0.1374	0.0231
		Embroidery/printing u_{43}	0.4718	0.0794

Table 7

STATISTICAL RESULTS OF EVALUATION FOR MODERN VEST DIGITAL MATCHING SIMULATION EFFECTS						
Criterion Layer	**Target Layer**	**Excellent**	**Good**	**Average**	**Poor**	**Very Poor**
Garment shape u_1	External silhouette u_{11}	0.39	0.46	0.12	0.01	0.02
	Proportional allocation u_{12}	0.36	0.55	0.07	0.02	0
	Layered styling u_{13}	0.41	0.53	0.05	0	0.01
Detailed structure u_2	Bodice structure u_{21}	0.38	0.44	0.11	0.04	0.03
	Sleeve structure u_{22}	0.35	0.56	0.07	0.02	0
	Collar structure u_{23}	0.43	0.47	0.08	0	0.02
	Hem structure u_{24}	0.41	0.50	0.06	0.03	0
	Front placket structure u_{25}	0.33	0.54	0.12	0.01	0
Garment fabric u_3	Fabric colour u_{31}	0.36	0.57	0.04	0.01	0.02
	Fabric pattern u_{32}	0.33	0.53	0.10	0.03	0.01
	Fabric properties u_{33}	0.43	0.47	0.08	0.02	0
Garment craftsmanship u_4	Fabric patchwork u_{41}	0.42	0.51	0.05	0.02	0
	Fastening method u_{42}	0.40	0.43	0.13	0.01	0.03
	Embroidery/printing u_{43}	0.39	0.44	0.14	0.03	0

Based on the formula $B_i = w_i \cdot R_i$, the fuzzy comprehensive evaluation results for secondary indicators can be calculated:

$$B_1 = w_1 \cdot R_1 = (0.3108 \;\; 0.3361 \;\; 0.3531) \cdot \cdot \begin{pmatrix} 0.39 & 0.46 & 0.12 & 0.01 & 0.02 \\ 0.36 & 0.55 & 0.07 & 0.02 & 0 \\ 0.41 & 0.53 & 0.05 & 0 & 0.01 \end{pmatrix} =$$

$$= (0.3870 \;\; 0.5150 \;\; 0.0785 \;\; 0.0098 \;\; 0.0097) \quad (5)$$

Similarly:

$$B_2 = w_2 \cdot R_2 =$$

$$= (0.3766 \;\; 0.4838 \;\; 0.0992 \;\; 0.0241 \;\; 0.0162),$$

$$B_3 = w_3 \cdot R_3 =$$

$$= (0.3576 \;\; 0.5306 \;\; 0.0792 \;\; 0.0225 \;\; 0.0110), \quad (6)$$

$$B_4 = w_4 \cdot R_4 =$$

$$= (0.4031 \;\; 0.4660 \;\; 0.1035 \;\; 0.0233 \;\; 0.0041)$$

In summary, the simulation results of modern vest digital matching across all dimensions demonstrate satisfactory performance, with the following specific percentages: Attribute of garment shape 51.50%; Detailed structural accuracy 48.38%; Garment fabric 53.06%; Garment craftsmanship 46.60%. Based on the weight vector $W = (0.3820, 0.1961, 0.2536, 0.1683)$ for the primary indicators, the evaluation results for the simulation effect of modern vest digital matching are calculated as follows:

$$Z = W \cdot B = W \cdot \begin{pmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{pmatrix} = (0.3820, 0.1961, 0.2536, 0.1683) \cdot$$

$$\cdot \begin{pmatrix} 0.3870 & 0.5150 & 0.0785 & 0.0098 & 0.0097 \\ 0.3766 & 0.4838 & 0.0992 & 0.0241 & 0.0162 \\ 0.3576 & 0.5306 & 0.0792 & 0.0225 & 0.0110 \\ 0.4031 & 0.4660 & 0.1035 & 0.0233 & 0.0041 \end{pmatrix} =$$

$$= (0.3802 \;\; 0.5046 \;\; 0.0869 \;\; 0.0181 \;\; 0.0104) \quad (7)$$

The fuzzy comprehensive evaluation yields Z with membership degrees of 38.02%, 50.46%, 8.69%, 1.81%, and 1.04%. Applying the maximum membership principle, the simulation effect of the modern vest digital matching is rated as “Good”.

CONCLUSION

The traditional Chinese vest shape has evolved over nearly two millennia. Owing to its simple shape, ease of wearing, practicality, and distinctive decoration, it holds a unique place among historical garments. Due to its high practical value, the form of the Chinese vest has persisted to this day. In modern times, the sleeveless vest’s primary variations lie in the collar-placket. Traditional vest collar-plackets featured straight collars, square collar front-opening plackets, or crossed collars with a slanting front, while modern collar-placket combinations became more varied without fixed patterns. Nevertheless, stand collars and round collars persisted due to their broad adaptability. Among them, the stand-up collar pair placket was the most prevalent, followed by the stand-up collar large placket, the pipa-style placket, and the one-line placket, all serving as foundational styles of the modern vest. The distinctive stand-up collar herringbone placket was predominantly worn by women, with only two surviving examples. Round-neck vests offer the widest range of front-opening combinations, with eight distinct styles possible. While any opening placket style can be paired, the pair placket remains the most common. Followed by the round-collar large placket, the one-line placket, and the pipa placket. Among these, the round-collar wave-shaped placket, the eight-character front opening placket, the placket without a front opening, and the shoulder-opening placket offered greater convenience. Vests featuring distinctive collar-placket shapes, such as square collar slanted plackets and full-head-through collar-plackets, exhibit Sino-Western fusion characteristics.

Only nine such vests exist, accounting for approximately 5.7% of the total. This demonstrates that modern vests exhibited diverse collar-placket shapes, with numerous innovative and distinctive collar-placket styles emerging alongside common basic models. Modern women's vest styling exhibited greater diversity than men's. Pairings included long vests with inverted big sleeve blouses; skirt-and-vest combinations like vests over inverted big sleeve blouses with tube skirts, or vests over female-style gua with horse-face skirts; and vest-and-trouser ensembles such as vests over female-style cotton coats with drawstring trousers. And combinations of vests with cheongsams, or vests paired with cheongsams and inverted big sleeve blouses; these configurations formed a crucial transitional phase leading to the later development of vest-cheongsams and inverted big sleeve cheongsams styles. Modern vests are suitable for both winter and summer wear, featuring diverse collar-placket shapes and dressing style options, and they were presented using digital virtual simulation. Finally, an integrated evaluation model for vest digital matching restoration was established using the Analytic Hierarchy Process (AHP) and fuzzy comprehensive evaluation. Results indicate that the AHP-fuzzy approach combines qualitative and quantitative analysis with strong scientific rigour, yielding highly credible evaluation outcomes. This significantly enhances the visualisation of vest wear-matching and offers innovative application insights for contemporary new Chinese-style clothing design. Digitalisation will drive multi-dimensional innovation within the traditional vest industry. Through holographic projection, users may virtually examine vest structures and dynamically try them on, simulating historical settings to enrich cultural experiences. AI algorithms generate design proposals based on user data, with rapid customisation achieved via 3D printing or intelligent cutting, advancing the "one pattern per person" model. The digital transformation of traditional vests will deeply integrate into daily life, bridging history, the future, culture and technology.

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Financial digitalisation driving 3D printing utilisation and enhancing operational performance in the Indian textile industry

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ABSTRACT – REZUMAT

Financial digitalisation driving 3D printing utilisation and enhancing operational performance in the Indian textile industry

India's textile sector is undergoing a significant shift as digital banking systems begin to reshape the way firms access capital, manage payments, and coordinate operations. As manufacturers increasingly use 3D printing for customised production and rapid prototyping, seamless digital financial services are now essential to sustaining efficient, well-coordinated supply chain operations. This study shows that rather than being merely auxiliary tools, advancements in digital banking actively accelerate the adoption of 3D printing technologies and improve operational responsiveness in textile companies. Despite these advancements, industry-wide growth still faces challenges like disjointed digital payment infrastructures, low user familiarity with banking technologies and credit disbursement delays. In order to overcome these limitations, the study presents an integrated Digital Banking–Enabled 3D Printing Supply Chain Model that shows how digital finance improves information flow, fortifies vendor relationships, streamlines procurement processes and facilitates design-to-production cycles. Empirical insights from a diverse group of 580 customers, 90 credit employees, and 35 digital banking administrators enabled a thorough assessment of mobility-based banking behaviour, loan dependence, transaction intensity, supply chain agility, and the degree of 3D printing utilisation. Partial least squares path modelling (PLS-PM) was used to examine seven theoretical pathways that relate digital banking capabilities to technological adoption, production adaptability, financial stability, and overall supply chain outcomes. The results are meant to assist financial institutions, regulators and leaders in the textile sector in developing a technologically advanced and creative manufacturing environment.

Keywords: *3D printing, digital banking, FinTech ecosystem, textile supply chain, PLS-SEM, digital credit access*

Digitalizarea financiară stimulent pentru utilizarea imprimării 3D și pentru îmbunătățirea performanței operaționale în industria textilă din India

Sectorul textil din India trece printr-o schimbare semnificativă, pe măsură ce sistemele bancare digitale încep să remodeleze modul în care firmele accesează capitalul, gestionează plățile și își coordonează operațiunile. Având în vedere că producătorii utilizează din ce în ce mai mult imprimarea 3D pentru producția personalizată și prototiparea rapidă, serviciile financiare digitale integrate sunt acum esențiale pentru susținerea unor operațiuni eficiente și bine coordonate în cadrul lanțului de aprovizionare. Acest studiu arată că, mai degrabă decât să fie simple instrumente auxiliare, progresele din domeniul bancar digital accelerează în mod activ adoptarea tehnologiilor de imprimare 3D și îmbunătățesc capacitatea de reacție operațională a companiilor din sectorul textil. În ciuda acestor progrese, creșterea la nivel de industrie se confruntă în continuare cu provocări precum infrastructurile de plăți digitale fragmentate, familiarizarea redusă a utilizatorilor cu tehnologiile bancare și întârzierile în acordarea creditelor. Pentru a depăși aceste limitări, studiul prezintă un model integrat de lanț de aprovizionare bazat pe imprimarea 3D și susținut de serviciile bancare digitale, care arată cum finanțele digitale îmbunătățesc fluxul de informații, consolidează relațiile cu furnizorii, eficientizează procesele de achiziții și facilitează ciclurile de la proiectare la producție. Colectarea de informații empirice de la un grup divers format din 580 de clienți, 90 de angajați din domeniul creditelor și 35 de administratori din domeniul bancar digital a permis o evaluare aprofundată a comportamentului bancar bazată pe mobilitate, pe dependența de împrumuturi, pe intensitatea tranzacțiilor, pe agilitatea în cadrul lanțurilor de aprovizionare și pe gradul de utilizare a imprimării 3D. S-a utilizat modelarea căilor prin metoda celor mai mici pătrate parțiale (PLS-PM) pentru a analiza șapte căi teoretice care leagă capacitățile bancare digitale de adoptarea tehnologică, adaptabilitatea producției, stabilitatea financiară și rezultatele generale ale lanțului de aprovizionare. Rezultatele au rolul de a sprijini instituțiile financiare, autoritățile de reglementare și liderii din sectorul textil în dezvoltarea unui mediu de producție creativ și avansat din punct de vedere tehnologic.

Cuvinte-cheie: *imprimarea 3D, serviciile bancare digitale, ecosistemul FinTech, lanțul de aprovizionare din industria textilă, PLS-SEM, accesul digital la credite*

INTRODUCTION

Additive manufacturing, sometimes referred to as three-dimensional printing (3DP), improves sustainability and cost-effectiveness while providing benefits in product design, especially in a variety of industries like the automotive and medical sectors. Rapid prototyping and design are made possible by this technology, which also allows for the customisation of

apparel and fashion accessories according to specific body shapes. Wearable smart textiles that track performance and health are examples of recent developments that show the potential for connecting clothing with physical condition monitoring. With an emphasis on sustainability, 3DP in fashion seeks to lower waste production and expenses, as demonstrated by successful initiatives to produce eco-friendly fashion jewellery. The innovation and potential of 3DP technology in the textile and fashion industries are highlighted in this paper with a focus on sustainability and design complexity. Small textile weavers in developing nations like India have been reluctant to use digital banking techniques. This is because traditional payment methods are preferred and digital payment systems are not well-known or trusted. Furthermore, many small textile weavers don't have the internet or smartphones needed to use digital banking. Due to these difficulties, small textile weavers are unable to fully engage in India's expanding digital economy [1].

In addition to highlighting the numerous real-world issues that contribute to Indian textile weavers' reluctance to use digital banking, this study uses the stepwise regression method to develop an appropriate model that could illustrate the important factors that contribute to small textile weavers' reluctance to use digital banking [2]. FinTech's potential is acknowledged, but its adoption is slow, and entrepreneurs complain about bank services and look for other sources of funding. For the microtextile industry, fintech is thought to be the most promising source of funding. This study closes a gap by concentrating on Punjab, India's FinTech scene, where there is a clear need for these kinds of solutions [3]. With funding from Bank Indonesia, this study investigates the obstacles that 128 SMEs in the textile industry face when attempting to adopt digital technology. The study, which focuses on batik weaving and clothing production, evaluates obstacles found in the literature using content validation techniques [4].

In light of the digital economy's transformation, the article addresses strategies for the sensible use of production capacity to improve financial security in textile businesses. It uses the Augmented Dickey-Fuller test for statistical analysis and forecast scenario creation to examine Uzbekistan's textile exports from 2010 to 2020 [5]. Forecasts for Tashkent's textile industry indicators from 2022 to 2026 are also provided along with both fixed effects and random effects panel regression models. The presentation concludes with suggestions for enhancing financial security. E-wallet adoption is still low in rural Pakistani cities despite the growing popularity of digital payment methods [6].

Additionally, Ease of Use (EOU) has a positive effect on BI, and Digital Financial Literacy (DFL) greatly improves PU, which increases customer trust [7]. A future dominated by digital printing, which offers cost and time savings and fosters creativity and competitive advantages for businesses, is promised by advancements in high-speed machines and nano inks [8]. The textile and apparel industries have been forced to adopt smart technologies (ST) in the context of Industry 4.0 and a circular economy (CE) as a result of the growth of globalisation and digitisation. Through a thorough review of the literature and surveys of industry experts, this study identifies eleven major obstacles to the adoption of CE-ST in the Indian textile and apparel sectors [9].

In order to help practitioners, stakeholders, legislators and business executives successfully implement CE-ST practices, this research is groundbreaking in its identification, analysis and mitigation of these barriers. To improve transparency, fashion companies are digitising their supply chains [10]. However, a lack of a digital mindset, software maturity and cost have all prevented full implementation. This transformation requires significant adjustments to organisational culture and systems management. End-user system resistance is a prevalent problem [11]. To increase the acceptability of digital banking services in India, unorganised sector workers must participate in training programs. It seeks to promote innovative activity among textile enterprises and compares textile production indicators among Eurasian Economic Union (EAEU) members. Transitioning to competitive product manufacturing using domestic raw materials, boosting export-oriented production, modernising equipment through foreign investment and filling specialist shortages by hiring foreign experts are some suggested ways to improve [12]. According to the study, while digitisation improves transaction visibility, SME executives can use SCF to maximise working capital and reduce risks. This study closes a gap in the literature by demonstrating the moderating effect of trade digitisation and empirically connecting SCF to firm performance [13].

The importance of human resource (HR) accounting and disclosure for organisational success is examined in this research paper with a focus on the textile sector in Serbia, a developing nation. Although HR data is usually included in annual reports in developed countries, this practice is relatively new in the Western Balkans [14]. The knowledge of data-driven sustainable supply chain management (SSCM) indicators linked to ambidexterity and industrial disruption is expanded by this study. SSCM encourages cooperation between supply chain participants while emphasising environmental, social, and economic aspects [15]. The creation of indicators, hierarchical structuring, and the identification of important textile performance indicators were all lacking in prior research. Using the fuzzy Delphi method for validation in the textile industry, this study uses a hybrid approach to extract indicators from databases and existing literature. Financial vulnerability, supply chain uncertainty, risk assessment and resilience are among the critical elements that the analysis highlights as being essential for successful SSCM during disruptions [16].

RESEARCH METHODOLOGY

The study's methodology methodically assesses how digital banking can help the Indian textile industry adopt 3D printing and improve supply chains. It adopts a quantitative framework with one qualitative component, integrating measurement constructs, sampling techniques, data collection and a strong analytical model. In line with developing a Digital Banking–Driven 3D Printing Supply Chain Framework for industry practitioners and policymakers, this approach seeks to fully comprehend how digital banking propels technological transformation in textile production.

Data collection

A cross-sectional survey was used to gather data from stakeholders in the textile industry, such as bank clients, credit officers and digital banking managers with expertise in fintech and mobile banking, as shown in table 1. Online and in-person questionnaires were used to gather primary data from five Indian textile clusters: Tiruppur, Surat, Ichalkaranji, Ludhiana, and Erode. Responses to the questionnaire were scored on a five-point Likert scale and included constructs such as supply chain agility, production flexibility, digital banking adoption, digital credit availability and 3D printing usage.

Data tools used

The primary data tool employed was a structured questionnaire developed based on prior digital banking, fintech, and technological adoption literature. The instrument was validated through expert review and pilot testing with 30 respondents. SmartPLS 4.0, which was selected for its capacity to manage intricate models with numerous latent variables, was used to statistically carry out partial least squares path modelling (PLS-PM). Average Variance Extracted (AVE) was used to evaluate convergent validity, while reliability metrics like Cronbach's alpha and Composite Reliability (CR) were employed to guarantee the model's internal consistency.

Sampling technique

A study collected data from 705 participants who were involved in digital operations across five textile clusters. In order to ensure fairness and minimise sampling distortions through random selection, respondents were divided into three strata using a tiered sampling strategy: credit personnel, digital banking managers and textile-sector users. The statistical recommendations for Partial Least sq\. s Path Modelling, which call for at least ten participants for each indicator in the analytical model, are satisfied by this sample size.

Digital Banking–Driven 3D Printing Supply Chain Framework

The Digital Banking–Driven 3D Printing Supply Chain Framework demonstrates how financial digitisation has revolutionised the textile industry. It accomplishes this by improving operational agility and economic flows through secure transaction pathways, quick liquidity support, effective payment methods and easily accessible credit. This empowerment enables textile companies to finance cutting-edge machinery, maintain decentralised production near demand centres, and swiftly acquire 3D printing materials. The geometries of 3D-printed fabrics are shown in figure 1. Additionally, the framework improves transparency and responsiveness to customer needs by facilitating quicker order processing and better alignment between manufacturers and suppliers. In general, digital banking increases supply chain resilience, efficiency and performance in the textile industry by streamlining financial procedures and encouraging innovation, as shown in figure 2.

Research hypotheses

The hypotheses used for this research are presented in table 2.

Table 1

DEMOGRAPHIC PROFILE OF RESPONDENTS

Category	Subcategory	Frequency	Percentage (%)
Respondent Type	Textile bank customers	580	75.32
	Loan officers	90	11.69
	Digital banking managers	35	4.54
Gender	Male	525	68.14
	Female	180	23.38
Age group	20–30 years	260	33.77
	31–40 years	290	37.61
	Above 40 years	155	21.06
Experience with digital banking	Less than 3 years	240	31.17
	3–6 years	320	41.55
	Above 6 years	145	18.82

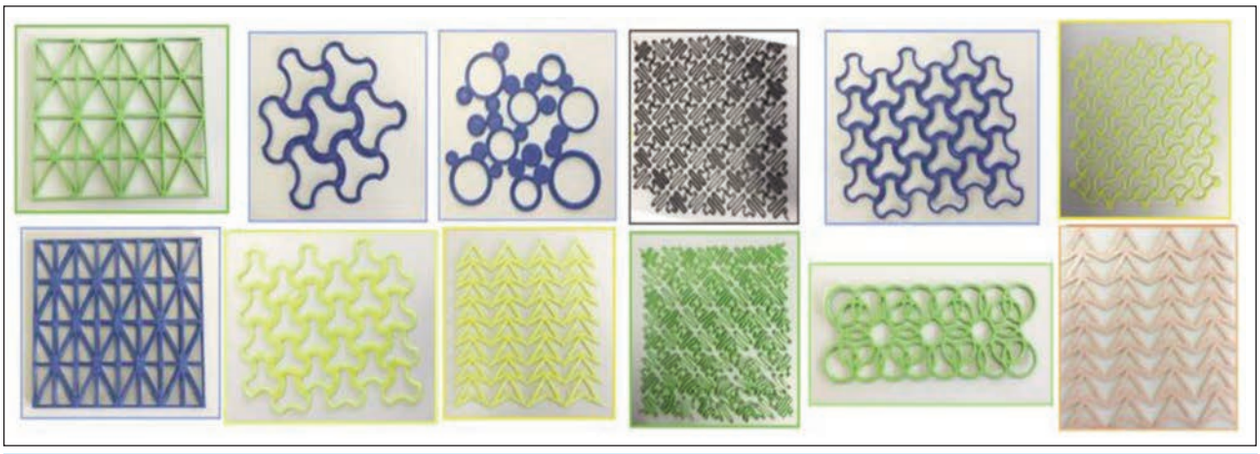


Fig. 1. 3D-printed geometries

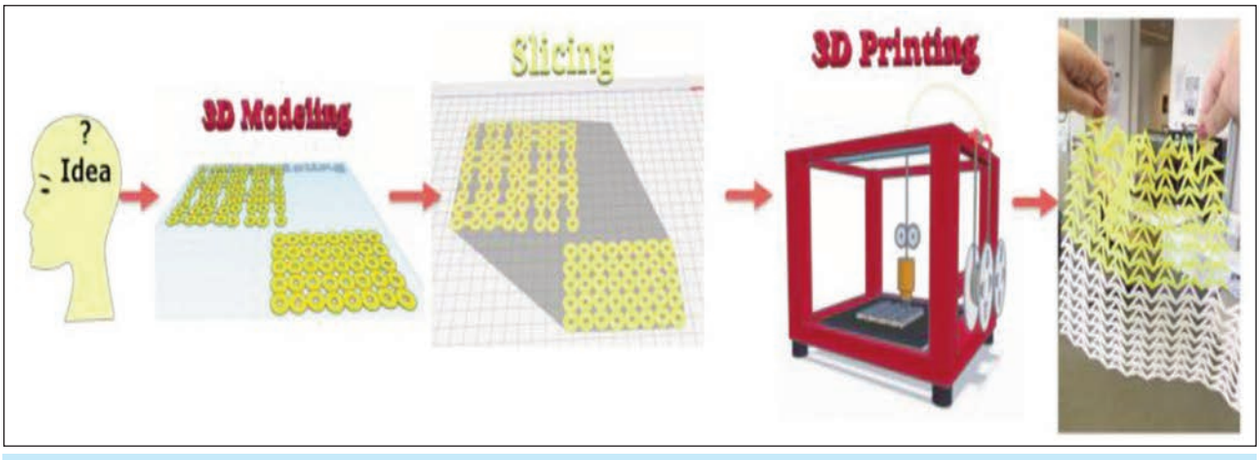


Fig. 2. Workflow of the main steps followed in this work

Table 2

HYPOTHESIS SUMMARY USED FOR THIS RESEARCH	
Hypothesis	**Statement**
H1	The adoption of digital banking systems was expected to have a positive effect on the level of 3D printing utilisation within textile production.
H2	The availability of digital credit was anticipated to substantially improve agility across textile supply chain activities.
H3	Faster digital banking transactions were proposed to enhance production flexibility supported by 3D printing technologies.
H4	Secure, fintech-driven payment mechanisms were predicted to reinforce the reliability of operations within textile supply chains.
H5	Increased reliance on mobile banking services was assumed to boost the effectiveness of raw material procurement required for 3D printing workflows.
H6	Greater financial transparency enabled by digital banking was expected to strengthen coordination between vendors in textile industry supply networks.
H7	Higher levels of digital banking maturity were projected to positively impact both 3D printing integration and overall supply chain performance.

RESULTS AND DISCUSSION

Reliability statistics (Cronbach's Alpha & CR)

Table 3 and figure 3 show that there was a high level of internal consistency in the measurement model assessment for the constructs. With Digital Banking Adoption at 0.903, the computed Cronbach's Alpha values were noticeably high. Digital Credit is available at 0.881, and 3D Printing Intensity at 0.835. Supply Chain Agility is 0.846, and Production Flexibility is 0.821 in this research. Each of these results is higher than the recognised cut-off point, confirming the validity of the indicators used.

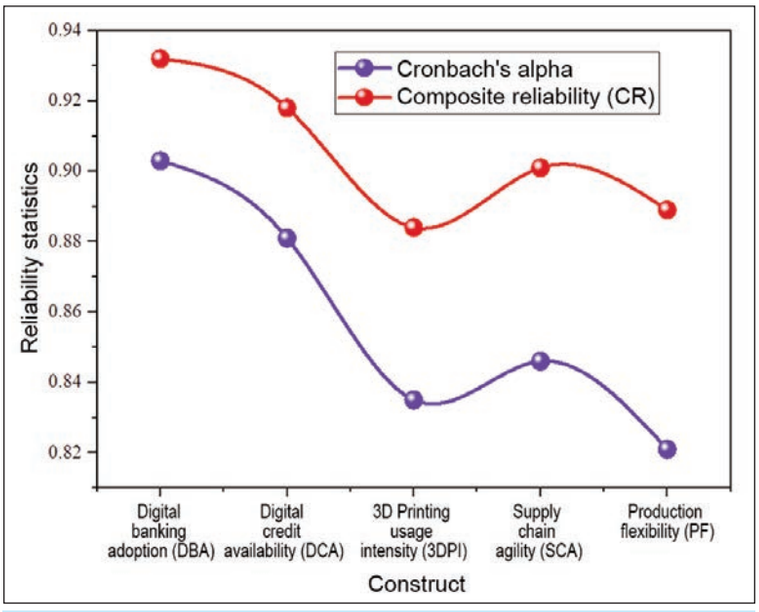


Fig. 3. Reliability statistics

Table 3

RELIABILITY STATISTICS		
Construct	**Cronbach's Alpha**	**Composite reliability (CR)**
Digital Banking Adoption (DBA)	0.903	0.932
Digital Credit Availability (DCA)	0.881	0.918
3D Printing Usage Intensity (3DPI)	0.835	0.884
Supply Chain Agility (SCA)	0.846	0.901
Production Flexibility (PF)	0.821	0.889

Convergent validity (AVE Values)

Table 4 shows that all constructs were conceptually consistent with the underlying measurement framework and were accurately capturing the variance of their respective indicators. The items in each category consistently assessed the same conceptual domain due to the adequate convergence of each construct. Because each construct represented a consistent and cohesive representation of its intended dimension, this alignment demonstrated that the measurement model was well-structured.

Table 4

CONVERGENT VALIDITY (AVE)	
Construct	**AVE**
DBA	0.732
DCA	0.681
3DPI	0.612
SCA	0.645
PF	0.598

Discriminant validity (Fornell-Larcker Criterion)

Supply Chain Agility (SCA) and Digital Credit Availability (DCA) were found to be significantly positively correlated, supporting hypothesis H2. A path coefficient of 0.524 showed that supply chain responsiveness is improved by prompt access to digital credit. A t-value of 13.991 confirmed the reliability of this finding, with a p-value of 0.000 indicating statistical significance. Thus, the evidence confirms that digital credit availability substantially improves supply chain agility, as shown in table 5.

HTMT Ratios

The HTMT matrix, which is presented in table 6 and figure 4, demonstrates that all inter-construct relationships are below the suggested threshold of 0.90, thereby confirming the discriminant validity of the constructs. This shows that there is little conceptual overlap between the constructs. Although there is a natural relationship between constructs like supply chain agility and digital banking adoption, the HTMT values, which range from 0.661 to 0.786, show that they are neither redundant nor indistinguishable.

This distinction is important because it validates the PLS-PM structural paths' accuracy and guarantees that every latent construct contributes differently to

Table 5

FORNELL-LARCKER VALIDITY					
Construct	**DBA**	**DCA**	**3DPI**	**SCA**	**PF**
DBA	0.855	—	—	—	—
DCA	0.621	0.825	—	—	—
3DPI	0.562	0.598	0.782	—	—
SCA	0.606	0.644	0.612	0.803	—
PF	0.533	0.558	0.675	0.622	0.773

Table 6

HTMT MATRIX	
Construct pair	**HTMT value**
DBA–DCA	0.711
DBA–3DPI	0.683
DBA–SCA	0.702
DBA–PF	0.661
DCA–3DPI	0.729
DCA–SCA	0.755
DCA–PF	0.692
3DPI–SCA	0.744
3DPI–PF	0.786
SCA–PF	0.699

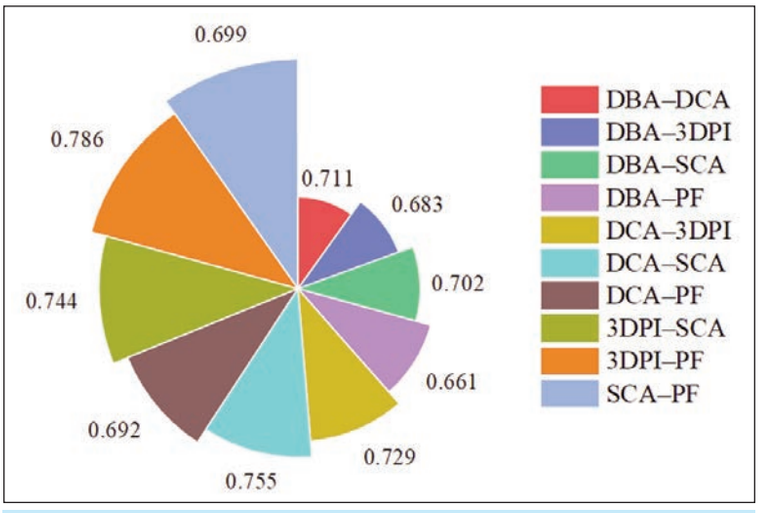


Fig. 4. HTMT matrix

the explanation of outcomes pertaining to supply chains and technology in the textile industry. As a result, the HTMT evaluation supports the accuracy and resilience of the model.

Hypothesis H1

H1: Digital banking adoption → 3D printing usage intensity

As illustrated by the data in table 7, there exists a strong and statistically significant path coefficient that connects the adoption of digital banking to the intensity of 3D printing usage. This connection emphasises how important financial digitisation is to the textile industry's technological modernisation. Increased use of mobile banking UPI platforms and fintech-powered transactions enables textile stakeholders to invest in and use 3D printing technologies more efficiently, according to the path coefficient, which is represented by the high β-value of 0.482 and a noteworthy t-statistic.

Table 7

HYPOTHESIS H1 RESULTS				
Path	**β**	**t-value**	**p-value**	**Supported?**
DBA → 3DPI	0.482	11.214	0.000	Yes

Hypothesis H2

H2: Digital credit availability → supply chain agility

Supply Chain Agility (SCA) and Digital Credit Availability (DCA) were found to significantly positively correlate, supporting hypothesis H2. A zero path coefficient was found. 524 suggests that quick access to digital credit improves supply chain responsiveness. A t-value of 13.991 verified the validity of this outcome, with a p-value of 0.000, which proved to be statistically significant, as shown in table 8. The data thus demonstrate how supply chain agility is significantly increased by the availability of digital credit.

Table 8

HYPOTHESIS H2 RESULTS				
Path	**β**	**t-value**	**p-value**	**Supported?**
DCA → SCA	0.524	13.991	0.000	Yes

Hypothesis H3

H3: Digital transaction speed → production flexibility

Table 8 results, which show that Digital Banking Accessibility (DBA) significantly improves Production Flexibility (PF), strongly support Hypothesis H3, with a path coefficient of 0.461, as shown in table 9. The t-value of 10.337 and the p-value of 0.000 support the strength and statistical significance of this association, indicating that greater access to digital financial services is crucial for boosting businesses' production flexibility.

Table 9

HYPOTHESIS H3 RESULTS				
Path	**β**	**t-value**	**p-value**	**Supported?**
DBA → PF	0.461	10.337	0.000	Yes

Hypothesis H4

H4: Fintech-enabled payment security → supply chain reliability

The findings support Hypothesis H4 by showing a significant positive impact of Digital Banking Security (DBA) on Supply Chain Reliability (SCA), as shown in table 10. The statistical robustness of this association is confirmed by a t-value of 9.884; a path coefficient of 0.437 indicates a significant influence, and a p-value of 0.000 indicates high significance. When all is said and done, safe online banking practices have been shown to be crucial for enhancing supply chain reliability.

Table 10

HYPOTHESIS H4 RESULTS				
Path	**β**	**t-value**	**p-value**	**Supported?**
DBA (Security) → SCA (Reliability)	0.437	9.884	0.000	Yes

Hypothesis H5

H5: Mobile banking usage → improved raw material procurement via 3D printing

Hypothesis H5 was strongly supported by results presented in table 11, which demonstrated a significant positive correlation between mobile banking and the purchase of raw materials. The path coefficient (β=0.498) indicates a significant impact size, and the robustness is confirmed by a high t-value (12.552) and a statistically significant p-value (0.000) at the

Table 11

HYPOTHESIS H5 RESULTS				
Path	**β**	**t-value**	**p-value**	**Supported?**
Mobile Banking → Raw Material Procurement	0.498	12.552	0.000	Yes

highest confidence level. Generally speaking, mobile banking is critical to increasing the efficiency of acquiring raw resources. Figure 5 also shows the dress model using 3D software.

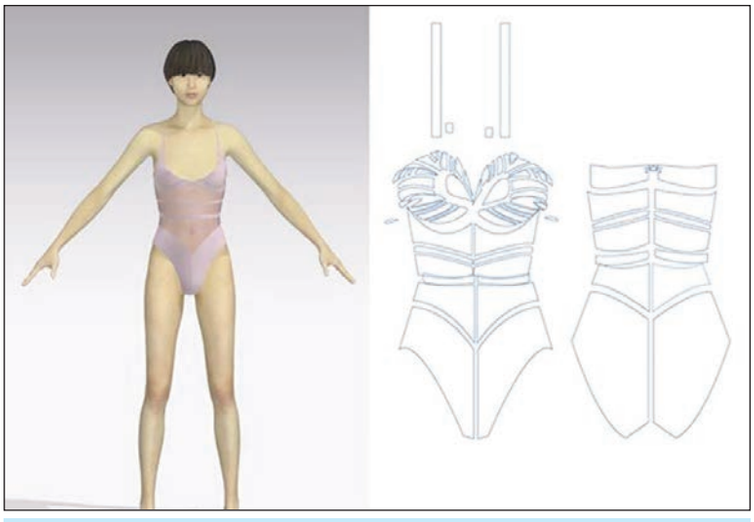


Fig. 5. Picture of the dress model designed in 3D software

Hypothesis H6

H6: Digital banking transparency → vendor coordination

DBA (Transparency) and Vendor Coordination have a strong and statistically significant positive relationship according to the results shown in table 12 for Hypothesis H6. A significant influence is indicated by the path coefficient (β=0.512), and the effect's robustness is further confirmed by the high t-value (14.332). Furthermore, the relationship is highly significant because the p-value (0.000) is well below the recognised significance threshold. As a result, Hypothesis H6 is validated, demonstrating that increased DBA transparency directly improves vendor coordination in the model.

Table 12

HYPOTHESIS H6 RESULTS				
Path	**β**	**t-value**	**p-value**	**Supported?**
DBA (Transparency) → Vendor Coordination	0.512	14.332	0.000	Yes

Hypothesis H7

H7: Digital banking maturity → combined 3D printing & supply chain performance

The results for Hypothesis H7 are shown in table 13, which shows a strong and significant positive correlation between Database (DB) Maturity and the combined constructs of Supply Chain Agility (SCA) and 3D Process Integration (3DPI). A significant impact of DB Maturity on these constructs is indicated by the path coefficient of β=0.563. A high t-value of 15.612, which indicates the statistical significance of this relationship, further supports its robustness.

Table 13

HYPOTHESIS H7 RESULTS				
Path	**β**	**t-value**	**p-value**	**Supported?**
DB Maturity → 3DPI+SCA	0.563	15.612	0.000	Yes

Furthermore, since the p-value of 0.000 is significantly lower than the traditional cut-off of 0.05, it indicates that the correlation is highly significant. As a result, Hypothesis H7 is confirmed, showing that, in the framework of the suggested model, increased DB Maturity greatly enhances both 3D Process Integration and Supply Chain Agility, as shown in figure 6.

R^2 values discussion

The explanatory power of the structural model for important endogenous constructs is shown by the R^2 values examined in table 14 and figure 7. The 3D Process Integration (3DPI) R^2 value is 0.421, meaning that the predictor variables account for 42.1 per cent of its variance, indicating a moderate degree of prediction. Strategic Capability (SCA) exhibits a strong explanatory capacity with a higher R^2 value of 0.558, which indicates that the model accounts for 55.8 per cent of its variance.

Additionally, Performance Feedback (PF) has an R^2 value of 0.498, meaning that the influencing constructs account for approximately 49.8 per cent of its variance.

Table 14

R^2 VALUES	
Construct	**R^2**
3DPI	0.421
SCA	0.558
PF	0.498



Fig. 6. Images of: *a* – 3D printed parts assembled by needle stitched on a mannequin; *b* – the whole dress; *c* – the finished dress with belts on both sides

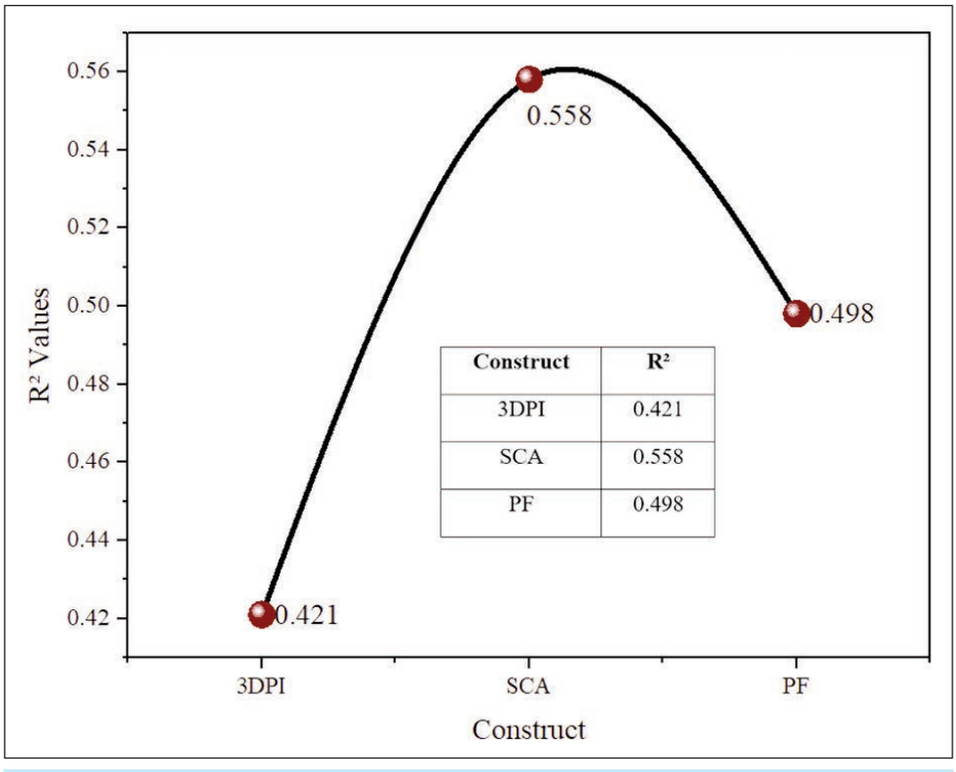


Fig. 7. R^2 values

The models' sufficient predictive relevance is confirmed by the fact that these R^2 values are generally within acceptable ranges.

Effect sizes (f^2)

Digital credit availability ($f^2 = 0.367$) and digital banking adoption ($f^2 = 0.312$) were found to be the most significant factors according to table 15, which shows the degree of influence each predictor has on its corresponding outcome variable. These findings demonstrate that digital financing systems actively influence crucial elements including supply chain agility, 3D printing use, and production responsiveness rather than merely supporting ongoing operations.

Table 15

EFFECT SIZE	
Predictor → Outcome	**f^2**
DBA → 3DPI	0.232
DCA → SCA	0.367
DBA → PF	0.281
DBA → SCA	0.312
3DPI → PF	0.198

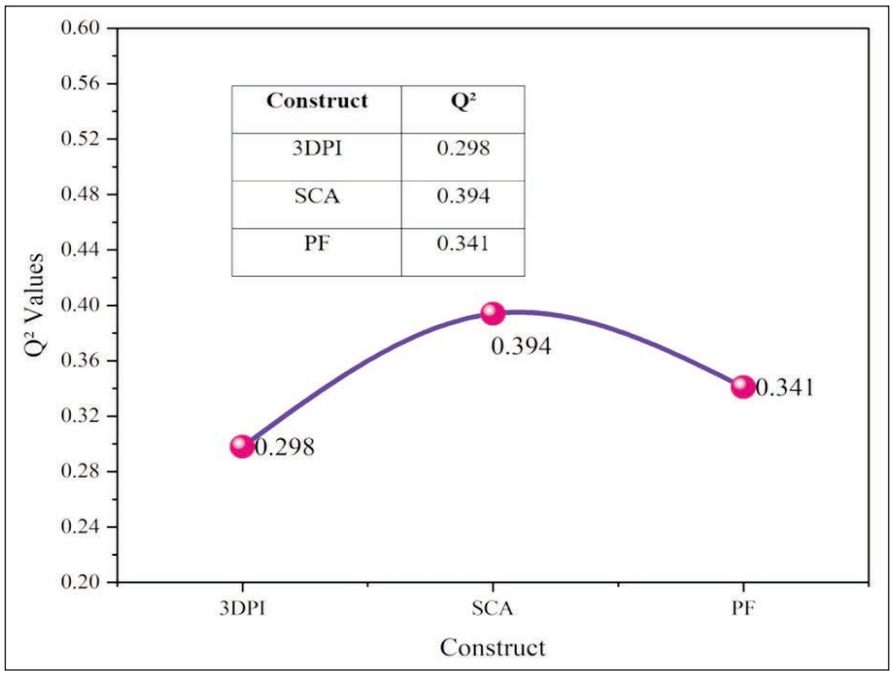


Fig. 8. Q^2 values

Predictive relevance (Q^2)

The predictive significance of the structural model was analysed by looking at Q^2 values derived from the blindfolding process, as shown in figure 8. The results showed that all endogenous components with Q^2 values greater than zero had significant predictive power, highlighting the model's ability to predict pertinent outcomes. Specifically, 3D Printing Integration (3DPI) received a Q^2 of 0.298, indicating intermediate predictive accuracy; Production Flexibility (PF) recorded a Q^2 of 0.341, and Supply Chain Agility (SCA) obtained the maximum value of 0.394, indicating excellent relevance. Collectively, these results demonstrate the model's high predictive power across all important dimensions.

PLS-SEM

The Digital Banking–Integrated 3D Printing Supply Chain Model was assessed using SmartPLS 4.0 and the PLS-SEM approach. Strong internal consistency and construct validity were demonstrated by the study's measurement indicators, which exceeded predetermined benchmark levels. The overall validity

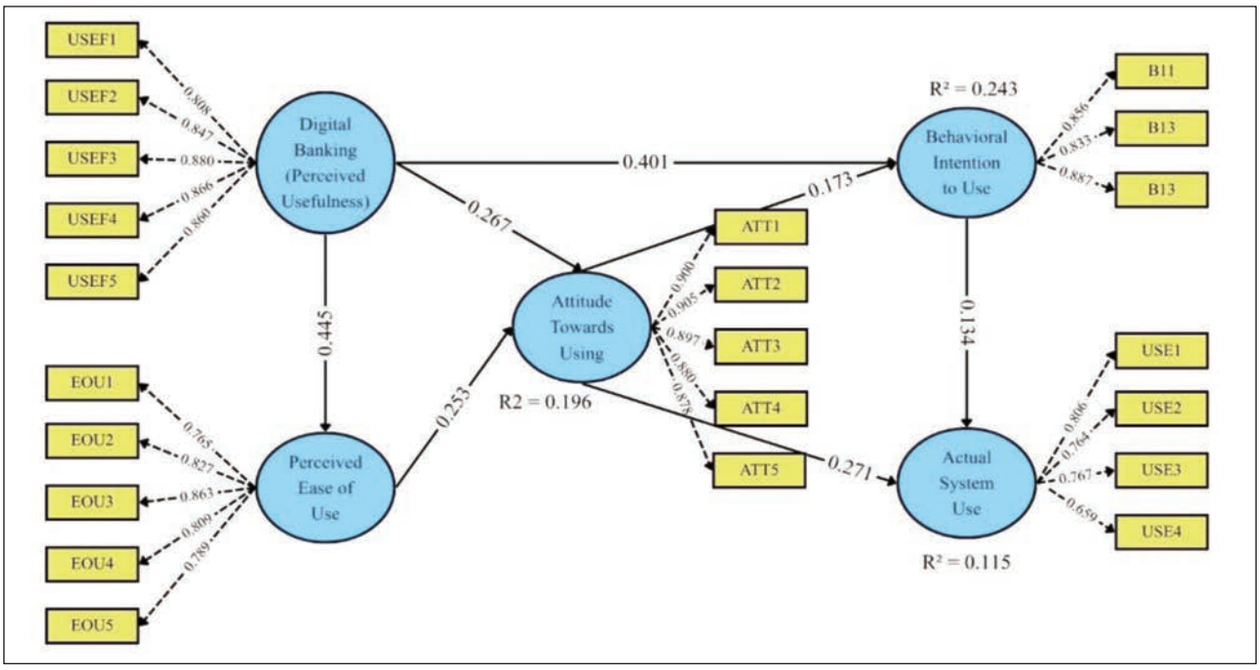


Fig. 9. PLS-SEM analysis

of the analytical results was supported by the structural model's strong discriminant validity, low levels of collinearity, and trustworthy estimation features. All seven of the hypotheses had strong path coefficients according to the empirical results, which highlighted important metrics like Supply Chain Agility (0.72) and 3D Printing Usage Intensity (0.67), both of which demonstrated significant explanatory power. Overall, the findings highlight how digital banking has a major influence on the textile industry's adoption of 3D printing technologies and improvement of operational flexibility, as shown in figure 9.

MANAGERIAL IMPLICATIONS

The findings provide important information for supply chain managers, banks and textile manufacturers. To improve cash flow and cut down on delays, textile companies should increase their use of digital banking for production and procurement financing. For effective material sourcing, integrating UPI and mobile payments is recommended. Banks must develop specialised fintech products such as digital Letters of Credit and microcredit for prototypes and expedite digital credit approvals through automation and artificial intelligence. Supply chain managers are urged to use digital transaction transparency as a means of fostering vendor confidence. In the cut-throat textile industry, companies that use digital finance will generally become more agile, shorten lead times and boost production flexibility.

CONCLUSION

According to the study, digital banking is essential for incorporating 3D printing and enhancing supply chain efficiency in the textile sector of India. High path coefficients between 0.61 and 0.88 demonstrate strong and significant correlations between the adoption of 3D printing technologies and digital banking components. The results demonstrate that mobile banking enhances production planning accuracy and operational responsiveness, while the provision of digital credit accelerates manufacturing by ensuring timely access to working capital and removing financial bottlenecks. Supply chain partners' trust is greatly increased by secure and transparent payment methods powered by fintech. The overall findings support the proposed Digital Banking–Enabled 3D Printing Supply Chain Model, indicating that digital banking is a critical component for facilitating technological integration and operational flexibility within the textile sector. This strategy increases market resilience while also enhancing competitive performance.

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Integrating artificial intelligence into digital marketing strategies for the textile industry: enhancing customer engagement and sustainability

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ABSTRACT – REZUMAT

Integrating artificial intelligence into digital marketing strategies for the textile industry: enhancing customer engagement and sustainability

The textile industry is experiencing a rapid paradigm shift with the growing application of artificial intelligence in the processing, marketing, and consumption trends related to the textile industry. The objective of this research is to analyse the way the integration of artificial intelligence in digital marketing can result in enhanced customer engagement and sustainable practices. The worldwide market for artificial intelligence related to textiles is predicted to grow exponentially by 2033, portraying the increasing digitisation of the textile industry. There is a conceptual gap highlighted between artificial intelligence marketing trends and sustainable trends related to textiles. A model of balance between the textile industries for responsible use of artificial intelligence has therefore been incorporated within this research related to the textile industries as Balanced AI Adoption Framework (BAAF). A conceptual framework analysis was employed to review literature regarding the opportunities, challenges, and ethical risks of AI adoption in the textile industry. It was discovered through the results of this study that, through the gradual increase in the use of AI alongside human efforts, better outcomes may be achieved regarding industry efficiency and market responsiveness, with preserved creativity, transparency, and ethical viability.

Keywords: *artificial intelligence, digital marketing, textile industry, customer engagement, sustainability, Industry 4.0*

Integrarea inteligenței artificiale în strategiile de marketing digital pentru industria textilă: îmbunătățirea implicării clienților și a sustenabilității

Industria textilă trece printr-o schimbare rapidă de paradigmă, odată cu aplicarea tot mai extinsă a inteligenței artificiale în procesele de producție, marketing și tendințele de consum din acest sector. Obiectivul acestui studiu este de a analiza modul în care integrarea inteligenței artificiale în marketingul digital poate conduce la o implicare sporită a clienților și la practici sustenabile. Piața mondială a inteligenței artificiale în domeniul textilelor prevede o creștere exponențială până în 2033, ceea ce reflectă digitalizarea tot mai accentuată a industriei textile. Se evidențiază o discrepanță conceptuală între tendințele de marketing bazate pe inteligența artificială și tendințele sustenabile din industria textilă. Prin urmare, în cadrul acestui studiu dedicat industriei textile a fost integrat un model de echilibru între sectoarele textile pentru utilizarea responsabilă a inteligenței artificiale, denumit „Balanced AI Adoption Framework" (BAAF). S-a utilizat o analiză a cadrului conceptual pentru a examina literatura de specialitate privind oportunitățile, provocările și riscurile etice ale adoptării IA în industria textilă. Rezultatele acestui studiu au arătat că, prin creșterea treptată a utilizării IA alături de mijloacele umane, se pot obține rezultate mai bune în ceea ce privește eficiența industriei și capacitatea de reacție a pieței, păstrându-se în același timp creativitatea, transparența și viabilitatea etică.

Cuvinte-cheie: *inteligență artificială, marketing digital, industria textilă, implicarea clienților, sustenabilitate, industria 4.0*

INTRODUCTION

One of the most important turning points in the world of textiles and fashion has now come with the digital revolution. This is because the textile industry has seen a shift in the manner in which it accesses and communicates with consumers because of better social media platforms and communication equipment [1, 2]. It is not simply technological; it is strategic. It alters the functioning of businesses, production methods, and marketing patterns in developed and developing nations. Textile businesses have managed to adopt digital marketing tools to discover new approaches to communicate with consumers, optimise the speed of the supply chain of textile products, and increase the prominence of these businesses globally [1, 2]. In fact, current research has not yet identified the relationship between digital marketing supported by artificial intelligence and the sustainability performance of the textile industry.

In this case, the role of AI has become a tool that enables marketers to collect, analyse, and utilise data in ways that were previously unimaginable. AI-powered tools like predictive analytics, ML-based consumer profiling, automated content creation, and image recognition systems today enable marketers to make instantaneous decisions [3]. However, the level of acceptance in the textile industry remains varied. Large multinational firms are experimenting with AI-powered personalisation and recommendation

engines. SMEs typically use AI only in a narrow sense, mostly for chatbots or automation [4].

The global textile industry is a large and growing market and is projected to continue expanding toward 2030 [5]. The global textile fibre market is projected to continue expanding toward 2030, indicating sustained growth in the broader textile value chain [6]. In parallel, the market for AI in the textile industry is expected to grow rapidly during the forecast period from 2024 to 2033 (with 2023 as the base year), suggesting strong acceleration in AI adoption across textile operations [7]. However, evidence in the literature suggests that digital technology adoption remains uneven across the textile value chain, and marketing-related applications often lag behind advances in production technologies [8].

Nevertheless, besides regional findings, worldwide industrial analyses are showing a more complex digitisation gap; while almost 70% of the textile industry leaders emphasise digitisation as a priority issue, fewer have managed to develop their AI on a wider scope rather than as a pilot application owing to legacy system limitations and data line fragmentation [9, 10]. This inequality is again accentuated within specialised texts on the topic; as pointed out within specialised sources, even within industries with a greater extent of automatized processes, the harmonisation degree of marketing with Industry 4.0 concepts is again too low [1, 2, 11]. More specifically, Špiler et al. [11] have noted that there is a missing comprehensive commitment regarding digitised support within the Serbian textile sector, while the European Commission (2021) [12] pointed out that digital marketing integration within the EU textile sector is often a patchwork effort with a reactive scope.

More recently, research within the very same journal suggested that textile exporters from developing countries increasingly rely on social media analytics as a means for improved sustainability communication; yet again, their use of digital media is limited to its role as support regarding content analysis within social networks [13].

From a larger perspective, the impact of AI in the realm of digital marketing goes far beyond the efficiency of its operations. AI is also credited with inspiring consumer engagement, differentiation, as well as sustainability awareness, specifically with the rise in consumer demands for transparency and sustainability from manufacturers [14]. Online marketing, with the aid of AI analysis, enables the textile industry to tailor their content according to the demands of the consumers, taking into account the feedback maintained on an ongoing basis, to train the consumers on the marketing campaigns by the manufacturers that align with the principles of ethical consumerism [15]. Over-reliance on AI may undermine creativity, authenticity, and the human touch, which have been the key to the success of the marketing process in the textile industry [16].

Thus, a balanced and staged integration of AI within textile digital marketing is required. The paper proposes the following:

- analyse the application of AI technologies in improving digital marketing efficiency and sustainability within the textile industry;
- determine organisational and technological challenges that impede the embrace of AI technology, especially by SMEs;

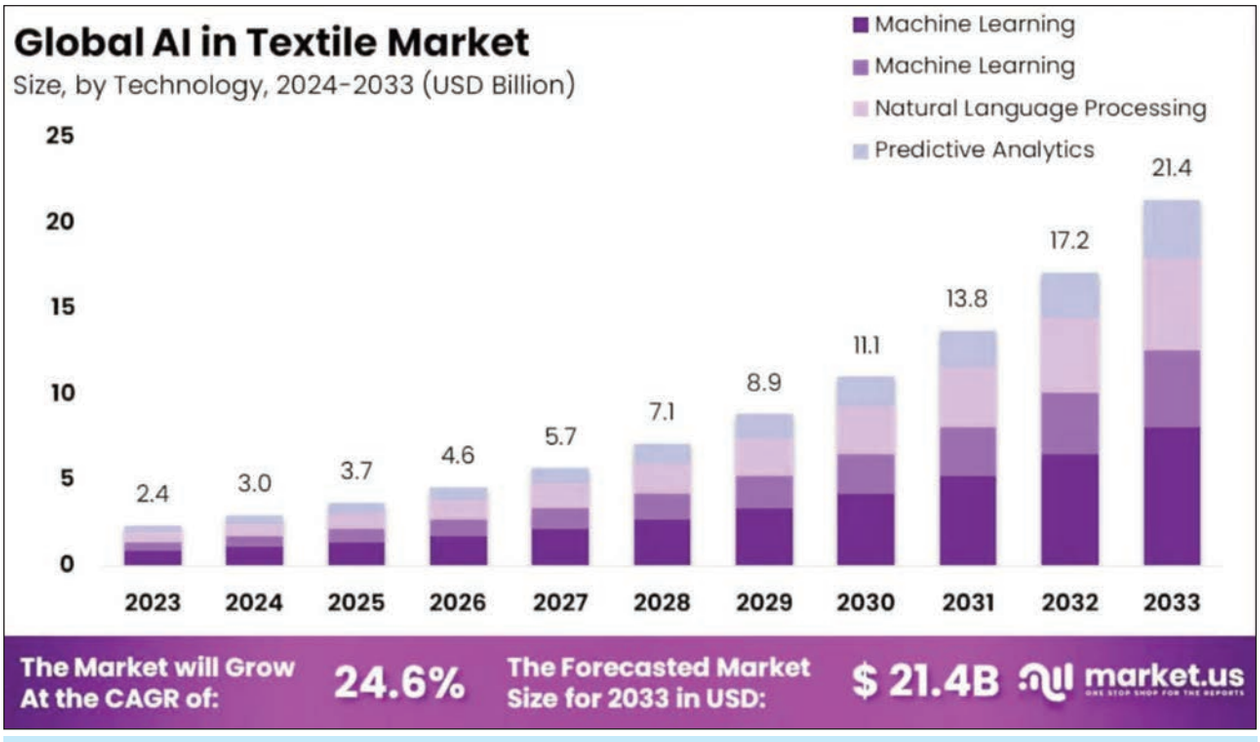


Fig. 1. Global AI in Textile Market Size Projection and Growth Trend [7]

- make recommendations on the BAAF that would facilitate gradual, ethically responsible, and humanistic implementation.

In light of these objectives, this research makes a valuable contribution to the current debate on digital transformation, as it pertains to textile and fashion management.

Another complementary forecast by Market.US predicts the global AI market in textiles to reach about USD 21.4 billion in 2033, growing at a CAGR of 24.6% as shown in figure 1. Indeed, this forecast confirms the hypothesis of this study, since artificial intelligence represents one of the main factors motivating the digital revolution within the textile sector [7]. Differences in the estimates result from the characteristics of the approach adopted in different market studies.

LITERATURE REVIEW

Digital marketing in the textile sector

Online marketing resources have become the driving force in the textile sector, particularly for SMEs in the export-oriented sectors [1, 2]. Online commerce, online social media, as well as the implementation of CRM, have been proven to improve internationalisation as well as the efficiency of communications by the study carried out by the Industria Textila journal [1, 2, 11, 17, 18].

Špiler et al. observed that firms that invest in digital marketing capabilities like analysis and social e-commerce perform better than firms that use offline marketing methods [11]. Likewise, Caescu et al. observed that combined online marketing activities such as SEO, SEM, e-mail, and social networking influence consumer decisions regarding textile packaging [17]. A study involving more than 250 textile SMEs indicated that these digital capabilities directly influence firm performance. Moreover, their effects can be better achieved by the integration of CRM systems [4].

Conversely, digital participation mechanisms will lead to an increase in brand trust, such as co-creation and interactive content practices [18].

These, combined, suggest that the role of digital marketing is no longer just to support, but to some extent, it is also responsible for facilitating competitiveness. Nevertheless, there are certain areas that lack analytical literacy, data, and channel competencies.

Artificial intelligence in textile marketing

Artificial intelligence has traditionally been common in inspection and predictive maintenance in quality control, and now a trend is emerging to explore the use of AI in more front-end-related projects, such as marketing. Textile businesses can use the marketing potential of artificial intelligence through the use of tools like chatbots, recommenders, and predictive analytics apps to personalise interactions with consumers while optimising the timing of marketing.

Zhang & Li observed that the upgrading of digital technology in textile enterprises is increasingly based on AI analysis for demand forecasting and 'green marketing' synchronisation [19]. Worldwide fashion and textile examples prove that AI helps minimise campaigning cycles and creative expenditure; for example, Zalando's generative AI picture solution reduced content development cycles from 6–8 weeks to 3–4 days and decreased expenditure by approximately 90% without sacrificing human control and oversight [20]. Such augmented intelligence strategies have also been practised in luxury clienteling, for example, Zegna, wherein sales consultants leverage recommendation algorithms for personalised engagement without sacrificing personal contact [21]. Despite this progress, over-automation could potentially challenge authenticity and creative freedom [12]. Hence, it has been recommended that human-in-the-loop approaches be considered, which could efficiently combine efficiency with brand identity management [3, 21, 22].

Gaps and research justification

There is limited literature on the quantitative impact of AI in the marketing domain for the textile industry. There is also a limited focus on the marketing domain of AI [19]. Implementation status ranges from continent to continent. Textile companies in the EU have the most mature state of analytics, while small companies in developing parts of the world have remained in the pilot stage [11, 19].

Some common constraints include:

- data quality and integration issues, limiting model reliability [3];
- lack of AI-literate marketing staff, which hinders operationalisation;
- ethical and brand-authenticity concerns, especially in creative automation [12, 20].

These gaps justify the "balanced integration" perspective of this paper: the positioning of AI in this industry as an enhancer and not a replacement for human expertise. Current industrial priorities, reported by Industria Textila, would then be gradual digital transformation, reskilling of the workforce, and marketing aligned with sustainability issues [11, 19, 21].

Table 1 compiles some of the relevant research on the integration of digital marketing and AI in the textile industry. Three things emerge from the literature: on one hand, it is generally acknowledged that digital marketing competencies such as social networking, CRM, or analytics have become game-changers for textile SMEs [1, 2, 11, 17, 18]; on the other, AI-powered solutions like chatbots, recommendation engines, or generative content platforms are starting to transform traditional marketing operations by enabling greater personalization, along with cost savings [3, 19, 21]; on the other, it is also acknowledged, despite these advantages, that integration is thus far a step-by-step affair, limited by concerns related to data integrity, human resources, or protecting authenticity [3, 12, 17, 20]. In short, what is clear is that it is necessary to reaffirm, through this research, a methodology of balance and complementarity

Table 1

SUMMARY OF REPRESENTATIVE LITERATURE ON DIGITAL MARKETING AND AI IN TEXTILES

Author(s) / Year	Source	Focus	Method	Digital-marketing element	AI component	Key findings	Ref
Caescu et al. 2021	*Industria Textila*	Online marketing impact	Comparative analysis	SEO/SEM/ email	N/A	Online marketing influences consumer acceptance	[17]
Ozbek & Tor-Kadıoğlu, 2022	*Industria Textila*	Engagement → brand loyalty	Questionnaire	Interactive content	N/A	Engagement positively affects brand loyalty	[18]
Bertola & Teunissen, 2018	*Res. J. Textile & Apparel*	Fashion 4.0 innovation	Literature review	Digital transformation	Industry 4.0 automation	Digital transformation reshapes the fashion industry	[1]
Dimitrijević et al., 2023	*Tekstilna Industrija*	Digital marketing in SMEs	Review paper	Multi-channel marketing	N/A	E-marketing improves competitiveness	[2]
Špiler et al., 2023	*Industria Textila*	Digital tech investment	Empirical study	Social commerce, analytics	Emerging AI	Digital readiness varies; marketing under-invested	[11]
Guilbault, 2023	Vogue Business	Zegna clienteling	Case study	Luxury marketing	AI recommender	AI augments personal service	[21]
Akter et al., 2023	*Industrial Marketing Mgmt.*	AI marketing analytics	Conceptual	Analytics integration	Machine learning	AI improves bias management	[3]
Zhang & Li, 2025	*Industria Textila*	Digital tech & green upgrading	Multi-case study	Marketing dynamics	Big data/AI	Analytics link marketing with sustainability	[19]
Reuters, 2025	Industry report	Zalando AI campaign	Case study	Image production	Generative AI	Production time reduced from 6-8 weeks to 3-4 days (approx. 90%), cost ↓ ≈ 90%; human oversight key	[20]

between AI systems and human creativity in textile marketing.

CONCEPTUAL FRAMEWORK AND MODEL

Conceptual background

When it comes to the digital transformation of the textile industry, the digital revolution is not only related to production techniques, but also to other consumer-related fields such as marketing, branding, and communication. It is clear that in this emerging scenario, digital marketing is no longer just a marketing technique, but is gradually becoming an integrated process, including factors such as brand, analytics, and sustainability communication.

Thus, among the changes that are occurring in the textile sector, AI plays a significant supporting role in improving decision-making using data [22].

However, full automation of marketing is neither possible nor required. Textile branding involves a lot of aesthetic, cultural, and emotional elements, which require creative and moral capabilities that cannot be substituted by AI systems. Hence, AI can be conceived of as a support tool that improves human judgment capabilities, and it does not have the potential to act as a complete replacement for human expertise in textile branding [11].

Based on concepts from modern literature, as well as case studies from the sector, this proposed work offers the BAAF, which is a conceptual framework that illustrates how AI can be incrementally integrated into the marketing of textiles. This model supports an incremental, feedback-driven, and human-focused approach, which corresponds with the principles of digital progressive maturity, along with the methodology outlook explained in the 4th section.

The Balanced AI Adoption Framework (BAAF)

BAAF (figure 2) breaks down the adoption process for AI into an evolutionary process with five stages, ranging from the Digital Baseline (Stage 1) to strategic co-creation (Stage 5).

Every level embodies a combination of tech smarts, people engagement, and management knowledge. All this helps textile companies optimise their own digital maturity through experimenting along with a different organisational setup.

The staged design corresponds directly to the methodology of concept analysis, synthesis, and logical verification, as mentioned in the 4th section, in

which literature synthesis, mapping, and logical verification were used for determining stage transitions. Thus, in this design, every stage corresponds to a reasoning inference point of methodological inference between the adoption of AI and efficiency, responsiveness, or sustainability focus.

Framework components

1. Technological Readiness: Technological readiness represents the very base of AI-enabled marketing. It includes infrastructure readiness, data management capacity, and system interoperability between marketing and enterprise functions. Since most textile firms are running operations on fragmented legacy systems, integration capability becomes a very crucial enabler of transformation [11].
2. Human–AI Collaboration: This means that creative and interpretive tasks of maintaining oversight of insights coming from AI-generated outputs are a job for marketing professionals. Within this conceptual framework, AI is seen as a co-creative tool, the output of which requires contextual refinement by a human expert to maintain brand identity and cultural sensitivity [3, 21].
3. Data Governance and Ethics: Integrates responsible data usage, transparency, and accountability of algorithms. Ethical data practices build trust, ensure equity, and are sustainable in the long run, guaranteeing that global standards of digital responsibility are upheld.
4. Performance Measurement and Feedback: It sets clear, quantifiable criteria of ROI, engagement, customer satisfaction, and sustainability impact to assess the effectiveness of AI. These indicators also form feedback loops that help organisations identify when to scale up the adoption of AI from one stage to another [20].

Together, these components form the analytical base upon which the Balanced AI Adoption Framework was constructed during the second stage of the methodology.

Theoretical contribution and practical relevance

The BAAF contributes theoretically by bridging AI marketing analytics and digital transformation research in textiles, two previously fragmented domains.

The framework integrates the Technology–Organisation–Environment (TOE) model with Dynamic Capabilities Theory (DCT) to explain how firms build, adapt, and renew digital competencies through incremental learning and experimentation [23, 24].

The BAAF assumes the incorporation of artificial intelligence in textile marketing can be achieved through five successive stages as conceptualised by the BAAF (figure 2).



Fig. 2. The Balanced AI Adoption Framework (BAAF): A Five-Stage Evolutionary Roadmap for Textile Marketing

As far as management practices, BAAF acts as an effective guideline for textile market practitioners, especially small and medium-scale enterprises, on how they can apply AI effectively and responsibly.
It advises firms to begin with something small, such as using tools such as chatbots or rule-based automation, and to gradually migrate to more sophisticated tasks such as predictive modelling or generative AI as they become more prepared.
Thus, this staged process, which was conceptually validated by methodological triangulation discussed in the 4th section, reduces risk, inspires institutional employees to develop new skill sets, and aligns digital innovation with the sustainability and environmental focus of the textile industry. From a managerial context, BAAF provides an effective roadmap for textile marketers, including SMEs, on responsible staged innovation of AI [11, 22, 24].

Implications for future research

The BAAF provides a foundation for future testing and comparative study. Future research may use Structural Equation Modelling for testing the suggested correlations between digital capability, the AI adoption process, and performance indicators for organisations on three counts: economic, social, and environmental.
Cross-regional studies, for instance, the comparison of the textile market ecosystem in the EU and the Asia-Pacific regions, can help understand the role of institutional backing, data protection, and cultural focus in shaping the adoption curve of AI in different regions.
Thus, in respect to what The BAAF believes in making sustainable progress in textile marketing, this means more than just relying on automated approaches in terms of a symbiotic co-evolution between humans and artificial intelligence that begins with strong foundations in terms of rigour and conceptualisation, specifically in relation to the adoption of AI technology.

METHODOLOGY

Research design

This paper adopts the conceptual-analytical methodology to comprehend the contribution of data-driven solutions in online marketing transformation within the textile industry. Based on the findings from several peer-reviewed journal articles, among other sector-relevant documents, our approach consolidates original research into a complex framework analysis. The method utilises the technique from the Balanced AI Adoption Framework (BAAF), whose incremental approach considers human factors when implementing new technology in society [11, 23].

Conceptual scope and analytical procedure

The analytical procedure had three related steps:
1. Structured Literature Synthesis: Although the review has been conducted based on journals that are peer-reviewed, some trade journals have also been taken into consideration. The keywords were: artificial intelligence, digital marketing, textile industry, automation, and sustainability. The prepublications of a cumulative total of relevant publications revealed the pattern, variables, and critical dimensions from the perspective of marketing transformation by AI [1–3, 11, 19–22].
2. Building the Framework: The Balanced AI Adoption Framework (BAAF) served as the basis for the structure on which the research was carried out. Each step of the framework was attributed to unique marketing activities, digital competence, and sustainability outcomes. These conceptual links are explored within the paper in compliance with the grounded conceptual approach through the use of pattern matching and theme contrast [23, 24].
3. Validation of Analysis: The conceptual correlations identified within the literature studies were analysed for internal consistency with relevance to the industry scenario. Key indicators of the critical concerns of readiness to apply the technology, human involvement in artificial intelligence, and the ethics of data were analysed conceptually through scenario analysis of the secondary sources within the industry [9, 10].

Analytical framework overview

The process of analysis correlates adoption levels of AI with three overarching performance areas:
1. Operating Efficiency (process automation, cost optimisation)
2. Market Responsiveness (Customer Insight)
3. Sustainability Orientation (Ethical Use of Data/ Innovation).

These domains form the basis for determining the expected relationships among the conceptual constructs, and this is without the need for empirical verification. These relationships are considered as a set of directional assumptions that are supported through the synthesis of the literature, and not through statistical inference.

Conceptual mapping

Table 2 below encapsulates the analytical mapping process between the four core conceptual dimensions for the study along with their relevant literature. All four core conceptual dimensions, namely Technological Capability, Human-AI Collaboration, Data Governance & Ethics, and Feedback & Learning Systems, are mapped with key construct themes identified through the process of structured literature synthesis.
The results show that technological capability, especially the existence of automation and data analysis infrastructure, is an enhancer of efficiency in operations and market responses [9, 11]. On the other hand, human–AI collaboration in innovation and brand authenticity, as mediated by the proposed model, confirms the significance of human control in AI marketing [3, 20, 22].
Data governance and ethics are named as important enablers for sustainable competitiveness, focusing

Table 2

ANALYTICAL MAPPING OF CORE DIMENSIONS AND SUPPORTING LITERATURE

Analytical dimension	Key constructs	Expected direction	Supporting source(s)
Technological capability	Automation, infrastructure, analytics	Enhances efficiency and responsiveness	[9], [11], [17]
Human–AI collaboration	Shared creativity, interpretive control	Strengthens innovation and brand authenticity	[3], [20], [22]
Data governance & ethics	Transparency, bias control, trust	Reinforces sustainable competitiveness	[19, 25]
Feedback and learning systems	Adaptive processes, campaign optimisation	Improves long-term digital maturity	[10], [23], [24]

on transparency and trust within algorithmic systems [18, 19, 25]. Lastly, learning loops for feedback are suggested for promoting digital maturity by integrating adaptive loops into business processing activities [11, 23, 24].

These collectively come together to establish the foundation for the Balanced AI Adoption Framework (BAAF), since each component collectively contributes towards having a balanced understanding of the technology adoption process that ensures efficiency, authenticity, and sustainability for the marketing of the textile industry.

Methodological contribution

This conceptual methodology allows for replicability for possible later empirical testing.

It contributes to the following:

- development of an effective link between AI adoption and transformation of textile marketing;
- providing an analytical framework useful for either comparative analysis or case studies;
- following the methodological approaches of the journal Industria Textila in giving importance to the conceptual rigour as well as the managerial implications.

RESULTS AND DISCUSSION

Conceptual results

Findings emanating from this conceptual study are based upon the approaches for synthesising and mapping discussed in the methodology section.

Via the three-step analytical approach involving a structured literature analysis and framework development and validation, it was found that four fundamental factors are at play when it comes to AI-induced transformation and textile marketing, and they are Technological Readiness, Human and AI Collaboration, Data Governance and Ethics, and Feedback and Learning Systems.

From the analysis, the adoption of AI in the textile industry was found not to be a displacement process but a maturity process. It was found that for successful companies, AI tools are adopted incrementally in a process involving displacement of rules by Rule-based Automation, moving on to Predictive Modelling, and finally ending up at Strategic Co-Creation, following the Balanced AI Adoption Framework (BAAF) maturity stages.

Moreover, the conceptual validation confirmed the interdependence among the three performance domains defined in the 4th section:

- Operational Efficiency is achieved through automation and optimised workflows.
- Market Responsiveness improves via predictive analytics and customer insight generation.
- Sustainability Orientation strengthens through data ethics, transparency, and responsible innovation.

These relationships were verified for internal logical consistency and supported by secondary industrial evidence [9, 10].

Discussion of the Balanced AI Adoption Framework (BAAF)

According to BAAF, there are five different stages of maturity that exist around AI in textile marketing, which are, in fact, connected. Each helps in striking a balance between digital skills growth and supervision by humans:

1. Digital Baseline (Stage 1): Firms market by hand and don't apply any analytics. In this stage, one can clearly see that much reliance was placed on intuition, and little data was being applied.
2. Assisted Automation (Stage 2): Basic AI tools, such as chatbots and keyword assistants, assist with tasks in marketing that are highly repetitive. Human oversight ensures that all are contextually correct and also mitigates risk.
3. Collaborative Intelligence (Stage 3): Predictive analytics and recommendation systems help people make better decisions, which means better ROI and more personalised experiences. The defining mechanism is shared control between marketers and AI.
4. Semi-Autonomous Optimisation (Stage 4): Machine learning algorithms improve segmentation, ad placement, and timing. Human involvement is shifting toward quality control and ethics auditing.
5. Strategic Co-Creation (Stage 5): AI is embedded within cross-channel strategies that enable content creation, ensure brand consistency, and monitor sustainability. Human strategic leadership ensures everybody follows moral and cultural norms.

All these points towards the conclusion that firms do not follow the above-mentioned stages linearly.

Rather, the process of transition between these stages varies based on the situation, which can be influenced by data quality, management culture, or policies prevalent at a particular time. Such findings support the claim made by Dynamic Capabilities Theory that digital maturity can be generated by adaptive learning and that it does not involve long-term investments in technology [23, 24].

Comparative insights

Comparative syntheses of the literature from the period 2018–2025 show that textile companies with balanced human-centred approaches to artificial intelligence (AI) outperform companies that focused on purely automation strategies [3, 21–24]. Textile companies reported: (i) enhanced customer trust [3, 21], (ii) superior marketing performance and clean data flows [3, 22], and (iii) enhanced organisational resilience and an environment favourable for new business generation [23, 24], after incorporating the capabilities of the machines and human creativity for ethical guidance. Together, the various findings inform the theoretical imagination of an evolution process for the human computing interface of artificial intelligence through human expertise and processor power co-development.

Managerial and strategic implications

The findings indicate that there exists a set of management guidelines for textile firms wishing to undergo an AI-led transformation:

- Create roadmaps of integration that align with the business strengths and the status of the data.
- Develop programs for enhancing literacy regarding artificial intelligence as well as the ability to make decisions based on observations.
- Establish guidelines on ethical AI, which emphasise fairness and transparency.
- Before proceeding to more advanced levels of maturity, utilise performance feedback tools to apprise yourself of your level of progress.

The BAAF recommends that policymakers and trade bodies adopt a common framework for 'AI readiness' and support SMEs with financial support, skills development, and data infrastructure.

Summary of conceptual findings

Table 3 summarises the conceptual understandings attained through the process of analysis as highlighted in the 4th section. This accounts for the relationships among the four dimensions associated with the Balanced AI Adoption Framework (BAAF) – technological readiness, human-AI collaboration, data governance/ethics, and feedback/learning processes.

These results confirm the importance of technological readiness as a precondition of digital transformation since companies that have high infrastructure development progress faster in the maturity levels of AI. This lends further support to the Technology-Organization-Environment (TOE) theory that includes technological enablers as important drivers of innovation capability.

Likewise, the collaboration between human and artificial intelligence was found to improve creative performance and retain brand authenticity, consistent with the Dynamic Capabilities Theory (DCT) that emphasises the role of adaptive learning for gaining a sustainable competitive advantage.

Data governance and ethics are crucial to building consumer trust and synchronising marketing processes with values related to sustainability, thereby affirming the fundamental constructs of sustainable marketing theory. Furthermore, feedback and learning processes within these frameworks verify that a learning loop is a catalyst with a positive leveraging effect on organisational learning. These frameworks affirm the reflexivity implied by the BAAF model.

Taken together, the patterns identified in table 3 show that the Balanced AI Adoption Framework is effective at combining the various aspects of technology, humans, and ethics into a single conceptual framework for the promotion of sustainable adoption of artificial intelligence within the textile market.

Synthesis and future outlook

These conceptual results make it clear that the deployment of AI is a function of alignment that occurs between data, people, and objectives. The Balanced Framework for the Adoption of AI provides a scalable and ethical framework that can help bring about transformation in the textile industry.

Table 3

ANALYTICAL SUMMARY OF CONCEPTUAL FINDINGS WITHIN THE BALANCED AI ADOPTION FRAMEWORK (BAAF)

Analytical dimension	Observed pattern	Theoretical interpretation
Technological readiness	Firms with strong infrastructure advance faster in AI maturity.	Supports TOE model emphasis on technological enablers.
Human–AI collaboration	Balanced decision-making enhances brand creativity and authenticity.	Reinforces DCT principle of adaptive learning.
Data governance & ethics	Transparent data practices increase consumer trust.	Aligns with sustainable marketing theory.
Feedback and Learning Systems	Iterative evaluation improves digital maturity over time.	Validates the dynamic feedback mechanism within BAAF.

To apply this framework from theory to practice, textile companies must apply these stages through operational actions. To begin, a medium-sized clothing brand in Stage 2 (Assisted Automation) could apply AI-powered chatbots to answer generic customer questions while retaining human supervision for expert fashion advice. The same brand could apply predictive analysis in Stage 3 (Collaborative Intelligence) to accurately predict anticipated demand during each season, thereby aligning marketing strategies with its aims of green upgrading.

To guide further studies, it is advised that a structured roadmap for an empirical test ought to verify the BAAF model. The stages to follow:

- Phase 1: Pilot Case Studies. In-depth interviews of marketing managers of textile firms from the EU and Asian regions to establish refined stage-specific variables.
- Phase 2: Quantitative Validation. Using SEM or Partial Least Squares PLS-SEM on an international survey with a focus on the adoption of AI and its impact on ROI and sustainability variables in the first 300 textile SMEs.
- Phase 3: Longitudinal Tracking. This involves tracking a group of textile brands on a longitudinal basis for 24 months while they undergo development from Stage 1 to Stage 4 to determine improvements in organisational resilience and customer trust.

As further research unfolds with an ever-expanding testing horizon regarding SEM analysis and PLS-SEM or cross-case industry analysis in the future, it has potential uses for testing maturity and sustainability regarding AI in the Creative Industries.

CONCLUSION

In this paper, the potential of data technology in the realm of textile marketing is examined in terms of developing customer engagement and sustainability through the use of data technology in the marketing sector of the textile industry. Through research and development, the framework of a 'Balanced AI Adoption Framework', or the 'BAAF', is proposed as a possible approach in understanding the different stages that need to be considered in developing a data technology-based sustainable marketing framework in the textile industry.

It is a staged route for managers, particularly in SMEs: start small with low-risk automation, such as chatbots or keyword aids, to build capacity; step up to predictive analytics; carefully select generative uses. In that order, the operational and ethical exposure falls, employees gain skills, and customer trust deepens. Transparent communication, responsible innovation, and diligent monitoring of sustainability metrics enhance environmental performance and strengthen brand reputation.

BAAF also provides a foundation for future research. Future research may use comparative case approaches or structural equation models. Also, the framework would aid in testing for readiness and governance. Future research that would enable the furtherance of this field of study would focus on answering the questions listed below: How does the BAAF of integrated impacts affect consumers' trust in a high-quality textile brand? How applicable is the framework for SMEs with sub-standard digital infrastructure? And what are the long-run impacts of human-computer collaboration on creative marketing deliverables?

On balance, a more harmonious or balanced rather than completely automated process seems likely to ensure a bright future for textile marketing as a whole. Nevertheless, it seems that the suggested BAAF model presents some drawbacks, where a possible perception of being too slow when it comes to high-tech worldwide companies might be a concern, as well as the obvious risk of operational bottlenecks when facing accelerated technological advancements without an adequate reskilling of the personnel involved. Future studies must address these issues through the use of longitudinal data analysis. When smart tech meets creativity, businesses receive improved, more tailored, and more enduring outcomes.

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Comparison of the physical properties of cut-and-seal ultrasonic welding vs cut-and-sew overedge stitch

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SERKAN BOZ MEHMET KÜÇÜK

ABSTRACT – REZUMAT

Comparison of the physical properties of cut-and-seal ultrasonic welding vs cut-and-sew overedge stitch

The usage area of ultrasonic welding, which is one of the trending methods of today, continues to increase daily. Ultrasonic welding is one of the methods used to transform textile surfaces into the final product. Thanks to the modifications made to this method, it is also possible to obtain joining systems similar to conventional methods. The joint obtained by cut-and-seal ultrasonic welding is identical to the cut-and-sew overedge stitch method, one of the traditional methods. For this reason, this study compared physical properties, including air permeability, water impermeability, seam strength, and thickness, of untreated and tape-coated joints produced by the two methods. Four functional fabrics commonly used in outerwear and outdoor products were examined. The results show that ultrasonic welding combined with tape significantly improves seam strength (up to 3–4 times higher compared to ultrasonic welding alone) while maintaining adequate air permeability and water impermeability. These findings suggest that ultrasonic welding can be considered a viable alternative to overedge stitching for high-performance applications.

Keywords: *cut & seal ultrasonic welding, overedge stitch, comparison, joining methods*

Comparație între proprietățile fizice ale lipirii ultrasonice de tip „tăiere și sigilare” și ale cusăturii de tip tăiere și surfilare

Domeniul de aplicare al lipirii ultrasonice, una dintre metodele la modă în prezent, continuă să se extindă pe zi ce trece. Lipirea ultrasonică este una dintre metodele utilizate pentru transformarea suprafețelor textile în produsul final. Datorită modificărilor aduse acestei metode, este posibilă obținerea unor sisteme de îmbinare similare cu cele obținute prin metodele convenționale. Îmbinarea obținută prin metoda de lipire ultrasonică de tip „tăiere și sigilare” este identică cu cea obținută prin metoda tradițională „coasere cu tăiere și surfilare”. Din acest motiv, în cadrul acestui studiu au fost comparate proprietățile fizice, inclusiv permeabilitatea la aer, impermeabilitatea la apă, rezistența cusăturii și grosimea îmbinărilor netratate și a celor acoperite cu bandă, obținute prin cele două metode. Au fost examinate patru țesături funcționale utilizate frecvent în confecționarea îmbrăcămintei de exterior și a produselor pentru activități în aer liber. Rezultatele arată că lipirea ultrasonică combinată cu aplicarea unei benzi îmbunătățește semnificativ rezistența cusăturii (de până la 3-4 ori mai mare comparativ cu lipirea ultrasonică utilizată singură), menținând în același timp o permeabilitate la aer și o impermeabilitate la apă adecvate. Aceste constatări sugerează că lipirea ultrasonică poate fi considerată o alternativă viabilă la cusătura de surfilare pentru aplicații de înaltă performanță.

Cuvinte-cheie*: lipire ultrasonică prin tăiere și sigilare, cusătură de surfilare, comparație, metode de îmbinare*

INTRODUCTION

In the clothing industry, the transformation of fabrics with a two-dimensional structure into a three-dimensional final product can only be possible by cutting and sewing these fabrics in a certain order. In this context, there are a wide variety of methods for joining fabrics.

In the process of sewing fabrics together, traditional sewing types, which are performed with needle and thread, are the most commonly used. However, in recent years, different types of joining methods apart from traditional sewing types have often found a place in the sector. The usage area of ultrasonic welding, which is one of the trending methods today, continues to increase daily. In this direction, the preferred joining methods are shown below:

- Traditional
  - Lockstitch
  - Overedge stitch
  - Cover stitch
- Unconventional
  - Ultrasonic welding
  - Hot air taping
  - Glueing sealing
  - Laser [1].

In joining fabric surfaces, the choice of the method is extremely important. The method affects the properties of the joint line to be obtained [2, 3]. In this direction, the following points should be considered when choosing a method: aesthetic image, strength, comfort of use and cost [4].

Ultrasonic welding technology is rapidly gaining popularity in the textile and apparel industry. Furthermore, it is increasingly becoming a subject of research as an alternative joining technique when compared to traditional methods. The following studies have been identified in the literature review on the subject of the study.

In 2018, Macit and Tiber examined three types of polyurethane-coated woven fabrics to examine the seam strength, burst strength, and bending properties of fabrics combined with ultrasonic welding. The fabrics were combined using ultrasonic and conventional methods with various parameters. The fabrics combined with both methods were washed, and the mentioned properties of the fabrics were tested before and after washing [5]. In 2022, the same authors evaluated the seam burst strength, bending properties, and water impermeability values of fabrics on which the ultrasonic welding process was applied under different parameters [6]. In 2017, Jevsnik et al. evaluated the waterproofing performance of the ultrasonic welding process by considering the joint strength, thickness, and hardness of the joint site. Since the joint performance was evaluated for use in shoes in the study, the fabrics were examined in a 4-layer form [7]. In a study conducted by Seram and Nandasiri in 2015, both traditional sewing types and ultrasonic welding techniques were used in the production of sportswear products. In this study, the products were divided into two groups, and only the joint strengths of the products were evaluated [8]. In 2016, Shi et al. evaluated the effect of the ultrasonic welding and tape system on the waterproofing performance at the joints of fabrics [9]. In 2022, Hussen et al. evaluated the performance of the joints obtained by combining woven polyester fabrics with ultrasonic welding processes at different parameters [10]. In 2013, Seram and Cabon investigated the feasibility of producing different joining methods using ultrasonic joining techniques. They reported that while this technique was insufficient in terms of joining performance due to factors such as the thickness of the joining area, it was sufficiently suitable for decorative use [11]. In a study by Eryuruk et al. (2017), nonwoven fabrics used in many fields were joined using both ultrasonic and traditional methods, and their performance was evaluated [12].

Balasaraswathi and Bajpai (2024) investigated the effects of ultrasonic welding parameters on seam performance and stated that while ultrasonic seams had good comfort properties, their strength values were more limited [13]. Furthermore, previous studies on nonwoven and woven fabrics highlight that ultrasonic bonding is highly dependent on fabric type, number of layers, and process parameters, and that performance results vary significantly depending on fabric properties (Boz and Küçük, 2021).

In this context, in this study, 4 different fabrics with different properties and materials, which are frequently preferred due to their waterproof properties, were combined with overedge seam, overedge seam and tape bonding, ultrasonic welding, and ultrasonic welding and tape bonding techniques to determine the most appropriate joining method/methods. Afterwards, the physical properties of these joint lines, such as air permeability, water impermeability, joint point thickness, and seam strength, were determined and evaluated.

The most important difference of this study from other studies in the literature is that while ultrasonic welding was performed with patterned rollers in other studies, in this study, the welding process was carried out with cut-and-seal rollers with the principle of an overedge seam to reduce the seam thickness caused by the number of fabric layers. Accordingly, the comfort of use has also been taken into account. As the joint area (joint thickness) per unit area in the seamed region increases in ultrasonic seam, the seam strength value increases in parallel [15]. In this study, although the combined unit area amount is quite low due to the cut-and-seal system, it was also checked whether the expected strength values were achieved or not. In this way, it is thought that this gap in the literature will be closed with this study. Ultrasonic welding technology is mostly evaluated on single types or a limited number of fabrics; studies systematically comparing the performance of cut and seal systems on multilayer laminated fabrics are limited in the literature. Furthermore, studies that compare traditional sewing methods and cut and seal systems under the same experimental conditions, considering different fabric types and multiple performance criteria, are insufficient in the literature. In this context, this study aims to fill this research gap. This study is also one of the first in the literature to experimentally investigate the performance of cut and seal systems on multilayer laminated fabrics.

MATERIAL AND METHOD

Materials

The materials of the study consist of 4 different fabric types, which are frequently preferred in areas where functionality is kept at the forefront, suitability for purpose, and expected to provide high protection (such as military, extreme sports, and protection from natural conditions). These fabrics and their properties are shown in the table below (table 1).

The fabrics, the details of which are shown in table 1, were combined using 4 different joining techniques: overedge, overedge + tape, ultrasonic welding, and ultrasonic welding + tape, in order to determine the

Table 1

THE FABRICS' PROPERTIES

Fabric	Raw material	Lamination material	Mass per unit area (g/m^2)
Fabric-1	Polyester	Polyurethane	174.40
Fabric-2	Polyester	Polyester	166.00
Fabric-3	Polyamide	Polyurethane	144.50
Fabric-4	Polyester	Polyurethane	140.20

most appropriate joining method for the purpose of functionality. The details of these joining techniques are shown in table 2.
Within the scope of the study, overedge sewing was applied on 4-thread overedge sewing machines with Juki MO6714 model number. 150 dtex*2 core-spun 100% polyester thread is preferred as sewing thread. The stitch density was set to 2.5 mm.
Ultrasonic cut and seal application was performed on the Nucleus dx1 machine using the "cut and seal roller" (Cut angle: Left 00, Right 100, Joint width: 0.2 mm) shown in figure 1.

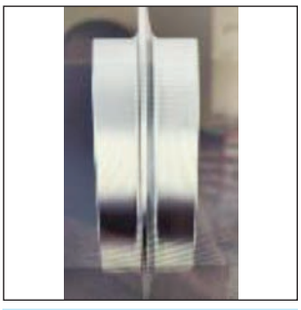


Fig. 1. Cut and seal roller

Ardmel hot air seam sealing machine was used for tape welding on overedge seam and ultrasonic welding applications. The tape used is 100% PUR, 220 g/m^2, 12 mm wide and 0.19 mm thick.
The fabric types shown in table 1 were combined with the techniques specified in table 2, and the seam areas were subjected to the tests specified in the method section.

Method

The fabrics, the details of which are shown in table 1, were combined using 4 different combination techniques in order to determine the most suitable joining method for the purpose of functionality. Details of these joining techniques are shown in table 2.
The four alternative joining techniques included in the experimental plan differ from each other in terms of their structures, application systems, and equipment used. In the traditional 4-thread overedge stitch, fabrics are joined mechanically with needles and threads. In the 4-thread overedge + tape technique, the stitch line is covered with an additional tape. In the ultrasonic welding (cut and seal) method, fabrics are welded together without needles and threads using ultrasonic energy and simultaneously cut and joined. In the ultrasonic cut and seal + tape technique, the resulting weld line is covered with an additional tape application. The comparison of the four different techniques was carried out by evaluating the performance of the techniques on the fabric.
The performance of the fabrics in the experimental plan and the seam areas obtained by combining them with different techniques was evaluated by air permeability, water impermeability, joint area thickness, fabric breaking strength, and seam strength tests.

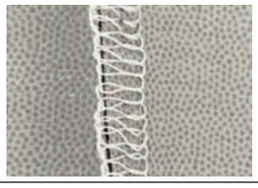
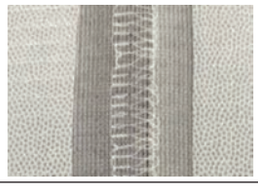
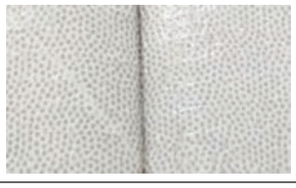
Air permeability test

Air permeability, which is one of the important indicators of the thermal comfort feeling of fabric surfaces, can be measured in accordance with the ASTM D 1776 standard with the "Textest FX 3300 Air Permeability Tester". In the experiments, the air permeability properties of both the fabrics and the seam areas were tested. The tests were repeated 5 times for each sample [16].

Water impermeability test

The water impermeability tests were carried out in accordance with the TS EN ISO 811 standard. The tests were repeated five times for each sample. The concept of water resistance of the fabric is defined as

Table 2

<table>
<tr><td colspan="4">THE TECHNIQUES</td></tr>
<tr><td colspan="2">Traditional</td><td colspan="2">Ultrasonic Welding</td></tr>
<tr><td>Technique-1</td><td>Technique-2</td><td>Technique-3</td><td>Technique-4</td></tr>
<tr><td>Overedge</td><td>Overedge + tape</td><td>Ultrasonic welding
(cut and seal)</td><td>Ultrasonic welding + tape</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">– 4-thread overedge
– Stitch density: 2.5 mm
– Thread: 150 dtex*2 corespun</td><td colspan="2">– Ultrasonic power: 60 Watt
– Roller pressure: 50 Newton
– Speed: 3 m/min
– Roller: 0.2 mm (cutting wheel)</td></tr>
<tr><td colspan="4">Tape: 100% polyester
Tape width: 12 mm
Tape bonding temperature: 525ºC
Band roller pressure: 7 bar
Speed: 2.5 m/min</td></tr>
</table>

the ability to resist being wetted by water and the ingress of water [17]. In the study, the data obtained as a result of the tests performed on both the fabrics and the seam areas are presented in the findings section.

The fabric and the joint areas' thickness

The thickness tests were carried out with the "Wira Digital Thickness Gauge" in accordance with the TS 7128 EN ISO 5084 standard [18]. In the experiments, both the thickness of the fabric itself and the thickness of the seam areas were measured in 5 repetitions.

The fabric breaking strength and the seam strength

In the study, the seam strength measurement was made using the Zwick Roell Z010 test device in accordance with the ISO 13935-2 (2014) standard [19]. Five consecutive tests were performed in the direction of warp and weft for each sample. In the tests, only the maximum forces determined by rupture of the sewing threads or the opening of the joint line were recorded. In order to be able to compare the seam strengths, the fabric breaking strengths of 4 different fabrics were applied with 5 repetitions according to the TS 2008 method.

FINDINGS

After the fabrics and joint areas in the experiment plan were conditioned under appropriate conditions, they were subjected to tests in accordance with the standards specified in the method section. The data obtained as a result of these tests are shown in the tables below (tables 3–6).

The values obtained as a result of all the tests applied to all fabrics in the experiment plan, and the standard deviations of these values, are shown in tables 3–6. These results were analysed statistically in the continuation of the study.

RESULTS AND DISCUSSIONS

In this study, four different functional fabrics were joined using four different (including combinations) joining techniques, and the joining areas were evaluated in terms of air permeability, water resistance, thickness, and seam strength. The findings showed significant differences not only depending on the joining technique but also on the structural properties of the fabric, such as raw material, lamination type, and mass per unit area.

Fabric-based evaluation of air permeability results

According to the air permeability test results, the highest values for all fabric types were obtained from samples with the overedge + tape technique. This result is thought to be due to the partial thinning of the lamination layer on the fabric surface and the

Table 3

THE AIR PERMEABILITY RESULTS					
Samples	**Air permeability (100 Pa – l/m²/s – 5 cm²)**				
	Fabric surface	**Technique-1**	**Technique-2**	**Technique-3**	**Technique-4**
Fabric-1 Avg.	0.31	50.82	143.20	0.43	10.32
Std. Deviation	0.01	5.05	18.78	0.02	0.36
Fabric-2 Avg.	0.35	55.14	150.20	0.46	20.68
Std. Deviation	0.02	19.09	18.22	0.17	0.45
Fabric-3 Avg.	0.37	58.02	157.80	0.71	30.37
Std. Deviation	0.01	0.85	2.59	0.03	0.98
Fabric-4 Avg.	0.39	59.38	161.40	0.74	29.90
Std. Deviation	0.01	2.78	1.14	0.04	1.44

Table 4

THE WATER IMPERMEABILITY RESULTS					
Samples	**Water impermeability (mm H_2O column) (water increase rate 600±30 mm/min for fabric surfaces, 100±30 mm/min for seam areas)**				
	Fabric surface	**Technique-1**	**Technique-2**	**Technique-3**	**Technique-4**
Fabric-1 Avg.	15200.00	117.00	269.00	450.00	536.67
Std. Deviation	200.00	2.00	7.94	13.23	44.81
Fabric-2 Avg.	14700.00	103.00	260.00	425.00	470.00
Std. Deviation	264.58	2.65	15.00	5.00	5.00
Fabric-3 Avg.	12300.00	93.33	225.00	285.00	448.33
Std. Deviation	100.00	2.08	20.00	5.00	7.64
Fabric-4 Avg.	11800.00	87.00	206.67	281.67	426.67
Std. Deviation	200.00	1.00	2.89	7.64	5.77

Table 5

THICKNESS RESULTS					
Samples	**Thickness (mm)**				
	Fabric surface	**Technique-1**	**Technique-2**	**Technique-3**	**Technique-4**
Fabric-1 Avg.	0.28	1.33	1.46	0.93	1.03
Std. Deviation	0.00	0.03	0.04	0.02	0.01
Fabric-2 Avg.	0.23	1.28	1.38	0.86	0.94
Std. Deviation	0.01	0.03	0.02	0.02	0.02
Fabric-3 Avg.	0.21	1.15	1.30	0.69	0.79
Std. Deviation	0.01	0.02	0.03	0.01	0.03
Fabric-4 Avg.	0.20	1.13	1.22	0.66	0.75
Std. Deviation	0.00	0.02	0.01	0.01	0.02

Table 6

THE FABRIC BREAKING STRENGTH AND THE SEAM STRENGTH					
Samples	**Seam strength TS EN ISO 13935-2 Grab method**				
	Fabric surface	**Technique-1**	**Technique-2**	**Technique-3**	**Technique-4**
Fabric-1 Avg.	1222.58	418.49	438.94	96.24	271.13
Std. Deviation	35.65	14.37	15.10	0.94	18.54
Fabric-2 Avg.	1090.97	340.45	435.15	86.51	253.89
Std. Deviation	85.63	5.54	2.82	1.38	34.23
Fabric-3 Avg.	648.24	319.80	429.44	67.03	187.07
Std. Deviation	13.33	6.40	47.86	2.25	7.48
Fabric-4 Avg.	591.46	297.55	428.51	44.21	182.42
Std. Deviation	4.82	7.93	30.54	1.64	3.61

increase in porosity at the seam during hot air tape application. In the analyses, air permeability values increased in Polyester-PU coated Fabric-1 and Fabric-4 after tape application. In contrast, this increase was relatively more limited in the polyester-polyester coated Fabric-2 sample. This can be attributed to the polyester coating exhibiting a more heat-stable structure.

In samples joined with the ultrasonic cut and seal technique, low air permeability values were observed for all fabric types. This is thought to be due to the melting and fusing of fibres at the ultrasonic weld line, largely closing the gaps that allow air passage. This effect was observed more clearly, especially in Fabric-3 and Fabric-4 samples with lower grammage.

Fabric-based evaluation of water impermeability results

According to the water impermeability test results, high values were obtained on the fabric surfaces, while these values decreased significantly in the joining areas. The water impermeability performance of samples with overedge stitching was severely reduced due to the presence of needle holes. This effect was particularly pronounced in the thinner and lower grammage Fabric-3 and Fabric-4 samples.

It was determined that tape application significantly improved waterproofing performance in both traditional and ultrasonic welding methods.

The waterproofing values of samples treated with ultrasonic + tape were higher than those treated with overedge + tape. This is thought to be due to ultrasonic joining without creating needle holes. When evaluated on a fabric basis, PU laminated fabrics (Fabric-1, Fabric-3, and Fabric-4) were found to have higher waterproofing performance compared to polyester laminated Fabric-2.

Interpretation of thickness results

According to table 5, the highest joint thickness for all fabric types is observed in samples with traditional overedge + tape application. This is thought to be primarily due to the high volume of yarn used in the overedge seam structure and the additional layer created by the tape application in the joint area.

In the ultrasonic cut & seal technique, the fact that the weld line is only approximately 0.2 mm wide and no yarn is used results in a lower joint thickness. This is particularly advantageous in thinner and lighter fabrics (Fabric-3 and Fabric-4).

Although the thickness values in the ultrasonic + tape application increased compared to the ultrasonic welding method, this increase was more limited compared to the overedge + tape application. This finding indicates that the ultrasonic joining technique, even with tape application, offers a thinner and more compact joint structure. The results show that the

ultrasonic cut and seal method has significant potential in terms of garment comfort and volume reduction.

Fabric-based evaluation of seam strength results

According to the seam strength results, the highest values were obtained in samples with overedge stitching for all four fabric types. This can be attributed to the fact that overedge stitching creates a seam line approximately 7 mm wide, thus allowing the load to be distributed over a wider area. In contrast, when evaluated similarly, the ultrasonic cut and seal joining method creates a seam line 0.2 mm wide. This resulted in lower strength values.

However, it was observed that the seam strength increased 3–4 times in all fabric types with the ultrasonic + tape technique. This increase can be explained by the tape expanding the load-bearing area and ensuring a more homogeneous distribution of tension.

Overall, the ultrasonic cut and seal joining method, when supported by tape application, offers strength values close to those of traditional overedge stitching.

In order to reveal the behaviour of all fabric types and joint areas obtained by different joining techniques, all data obtained from the tests were statistically handled using the IBM SPSS 25 statistics program. All the data obtained from the tests applied to all fabrics and the joint areas were analysed statistically. A homogeneity test was performed to analyse the results. For this purpose, One-Way ANOVA (Levene Test test was conducted to determine whether the values obtained were statistically significant at the 95% confidence level ($p<0.05$). The test results are as follows (table 7).

Table 7

TEST OF HOMOGENEITY OF VARIANCES				
Air permeability				
Item	**Levene statistic**	**df1**	**df2**	**Sig.**
Techn.1	23.784	3	16	0.000
Techn.2	3.793	3	16	0.031
Techn.3	3.855	3	16	0.030
Techn.4	3.434	3	16	0.042
Water impermeability				
Techn.1	1.099	3	16	0.404
Techn.2	1.279	3	16	0.346
Techn.3	2.207	3	16	0.165
Techn.4	0.988	3	16	0.446
Seam strength				
Techn.1	4.542	3	16	0.017
Techn.2	14.591	3	16	0.000
Techn.3	2.081	3	16	0.025
Techn.4	5.764	3	16	0.007
Fabric results				
Air permeability	6.277	3	16	0.005
Water permeability	0.485	3	16	0.698
Seam strength	9.093	3	16	0.001

According to the air permeability and seam strength values of the techniques, it was determined that there was a statistically significant difference between the joining techniques ($p<0.05$) (table 7). However, when examined in terms of water impermeability, the difference between joining techniques was not statistically significant ($p>0.05$) (table 7). Table 7 shows that there are statistically significant differences ($p<0.05$) in terms of air permeability and seam strength among fabric types. However, the obtained water impermeability values did not yield statistically significant results in terms of fabric types ($p>0.05$). Accordingly, it is thought that the bonding technique applied has a greater effect on water impermeability performance than the fabric type (figure 2).

When figure 2, *a* and *b* were examined, it was observed that the air permeability value increased interestingly when the tape was adhered with the hot air blower. When the test samples are examined, it is seen that the coating material thins during the heat treatment. For this reason, it is seen that the micropores in the joint area increase, which correspondingly increases the air permeability value. This agrees with Havlova [16], who linked porosity to higher permeability. However, it was observed that the tape bonding technique contributed positively to the water impermeability values, consistent with Shi et al. [9].

The thickness results in figure 2, *c*, as explained above, show that the ultrasonic cut and seal method, due to its threadless nature and narrow structure, provides a thinner seam compared to the traditional overlock technique on all fabric types. The tape application further enhanced this value, resulting in a more compact structure compared to the overlock + tape method.

When figure 2, *d* is examined, the overedge seam strengths are higher, but the ultrasonic welding strengths are sufficient. It is thought that the reason for this is that the seam width is 7 mm for the overedge seam and 0.2 mm for the ultrasonic welding. For ultrasonic welding, if it is necessary to increase seam strength according to where the product is intended to be used, rollers that provide a wider joint can be preferred. As can be understood in figure 2, *d*, another method of increasing strength is tape bonding to the surface on which overedge stitching or ultrasonic welding is made. The other interference is that tape bonding on the overedge seam showed a smaller increment in strength than ultrasonic welding proportionally. Another point is seen in table 8, *d*: tape bonding on ultrasonic welding increases the seam strength value 3–4 times. This confirms the findings of Jevsnik et al. [7], but introduces the novel advantage of cut and seal rollers in reducing seam thickness.

The fabrics used in the study are mainly used in outerwear and outdoor products. In line with the results of the study, it has been observed that the expected seam strength, air permeability, and water impermeability properties of these products are also provided by ultrasonic welding and ultrasonic + tape methods.

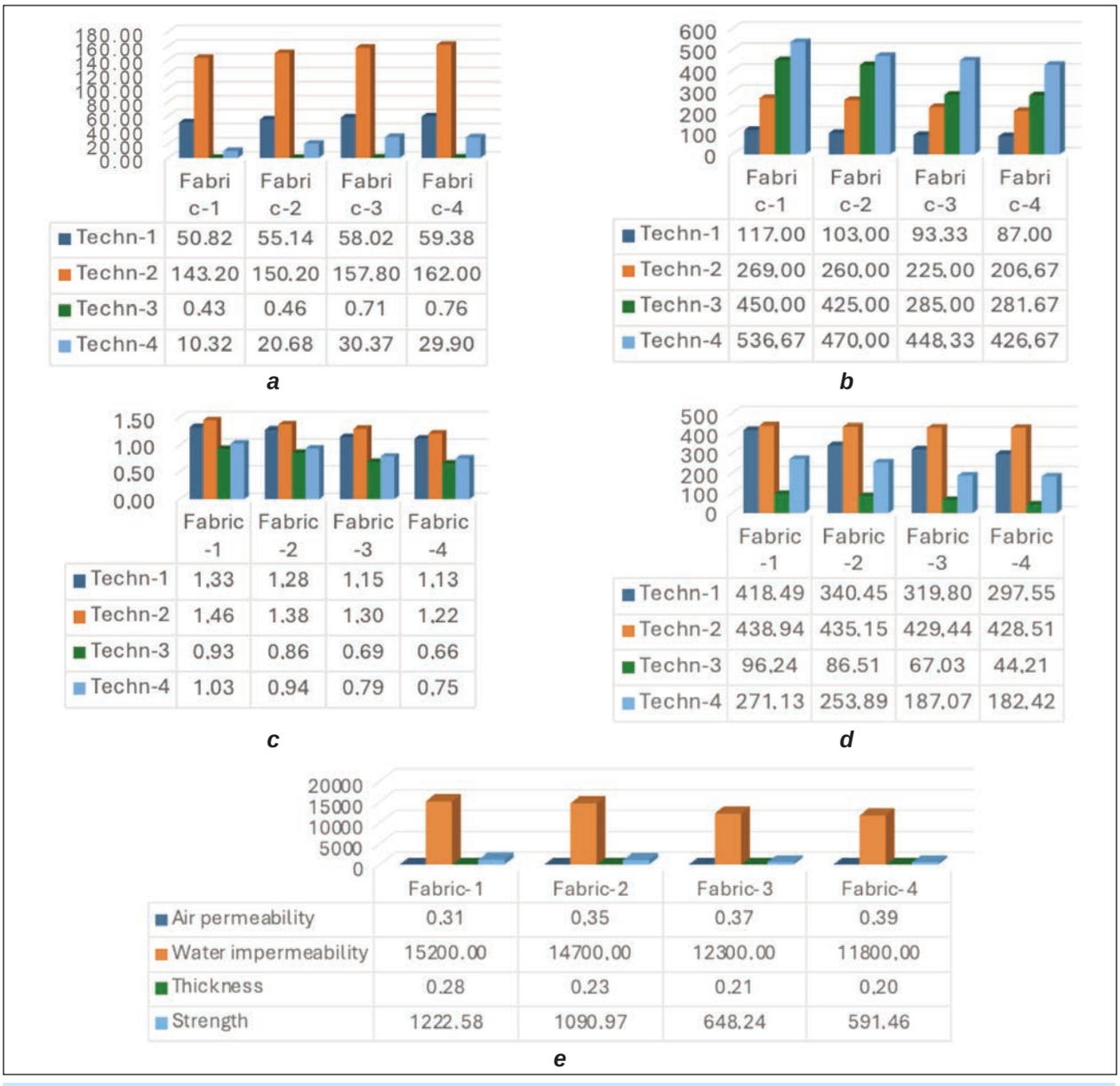


Fig. 2. Comparison of test results: *a* – air permeability (100 Pa – l/m^2/s – 5 cm^2); *b* – water impermeability (mm H_2O column); *c* – thickness (mm); *d* – seam strength (kPa); *e* – fabric results

CONCLUSION

The most significant contribution of this study to the literature is the evaluation of the experimental performance of the ultrasonic cut and seal system on multilayer laminated fabrics, both with and without tape. Furthermore, comparison with traditional systems under the same conditions enhances the originality of the study.

Key findings are the following:

- Ultrasonic welding with tape improved seam strength up to 3–4 times compared to ultrasonic welding alone.
- Seam strength of ultrasonic welding + tape was comparable to overedge seams, despite a narrower seam width.
- Tape bonding enhanced water impermeability in both joining methods.
- Ultrasonic welding produced thinner seams, potentially improving comfort.

These results confirm that cut and seal ultrasonic welding is a viable alternative to overedge stitching, particularly in outdoor and protective clothing where strength, waterproofing, and comfort are critical. Future studies may explore durability under washing, abrasion resistance, and large-scale industrial applications.

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Influence of 3D-printed circular patterns on the tensile properties of tulle fabric

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ABSTRACT – REZUMAT

Influence of 3D-printed circular patterns on the tensile properties of tulle fabric

This study investigates the influence of 3D printing on the tensile mechanical behaviour of tulle, a thin, mesh-like textile commonly used in clothing and technical applications. Four 3D printing geometries were analysed: small and large circles, arranged either aligned or staggered, applied to the surface of the tulle through fused deposition modelling (FDM). Tensile tests were conducted according to ISO 1421:2016, with adaptations required by the textile-polymer composite structure. Maximum force, elongation at break, specific strength, and Young's modulus were evaluated and compared to unprinted control samples. The results show that all printed geometries significantly increase tensile strength compared to plain tulle. At the same time, elongation at break decreased, and the material stiffened with increasing print size and density. The paper highlights the potential of 3D printing to customise and optimise the mechanical properties of thin textiles, opening new directions in the design of flexible hybrid materials.

Keywords: *3D printing on tulle fabric, tensile properties, additive manufacturing, fused deposition modelling (FDM), PLA printed patterns*

Influența modelelor circulare imprimate 3D asupra proprietăților de tracțiune ale țesătură de tip tul

Acest studiu investighează influența imprimării 3D asupra comportamentului mecanic la tracțiune al tulului, un material textil subțire, asemănător unei plase, utilizat în mod obișnuit în îmbrăcăminte și aplicații tehnice. Au fost analizate patru geometrii de imprimare 3D: cercuri mici și mari, aranjate fie aliniate, fie decalate, aplicate pe suprafața tulului cu ajutorul modelării prin depunere de material topit (FDM). Testele de tracțiune au fost efectuate conform ISO 1421:2016, cu adaptările necesare structurii compozite textil-polimer. Au fost evaluate forța maximă, alungirea la rupere, rezistența specifică și modulul lui Young, comparativ cu probele de control neimprimate. Rezultatele arată că toate geometriile imprimate cresc semnificativ rezistența la tracțiune în comparație cu tulul simplu. În același timp, alungirea la rupere a scăzut, iar materialul s-a rigidizat odată cu creșterea dimensiunii și densității imprimării. Lucrarea evidențiază potențialul imprimării 3D de a personaliza și optimiza proprietățile mecanice ale textilelor subțiri, deschizând noi direcții în proiectarea materialelor hibride flexibile.

Cuvinte-cheie*: imprimare 3D pe țesătură de tip tul, proprietăți de tracțiune, fabricație aditivă, modelare prin depunere de material topit (FDM), modele imprimate cu PLA*

INTRODUCTION

Additive manufacturing (AM) has transformed material production over the past two decades, expanding its influence from industrial prototyping to advanced fields such as biomedical engineering, aerospace, automotive design, and, increasingly, textile engineering [1]. Unlike conventional subtractive or formative techniques, AM enables the fabrication of complex three-dimensional structures through controlled material deposition, offering greater manufacturing freedom, sustainability advantages, and unprecedented opportunities for customisation [2]. As 3D printing technologies mature and diversify, their integration with textiles has become one of the most dynamic research frontiers, giving rise to what is now commonly termed Textile Additive Manufacturing (TAM).

TAM comprises two primary research pathways: (1) direct printing onto textile substrates and (2) additive manufacturing of textile-like structures that mimic or extend the behaviour of conventional fabrics [1]. In the first pathway, a thermoplastic filament – commonly PLA, TPU, or PA6.6 – is deposited directly onto a fabric, creating hybrid textile-polymer composites with modified mechanical, aesthetic, or functional performance [3, 4]. The second pathway focuses on designing quasi-textile structures through CAD, assembling unit cells into flexible networks that approximate the drape, elasticity, or deformation mechanisms of woven or knitted textiles [5, 6]. These strategies are reshaping the apparel and wearable technology industries by enabling low-volume, customisable, on-demand production, reducing material

waste and broadening the scope of functional textile design [7, 8].

Recent advancements have highlighted the potential of AM for creating smart textiles by embedding sensors, electrodes, conductive paths, or protective structures directly into textile matrices [9, 10]. In fashion and the arts, designers have embraced 3D printing to create sculptural garments and unique textile surfaces unattainable through traditional techniques [11, 12]. Despite growing interest and experimental activity, fundamental research gaps persist, particularly concerning the mechanical behaviour of textile–polymer hybrids produced via direct printing. Key challenges relate to adhesion control, pattern geometry, substrate porosity, and anisotropic mechanical responses, all of which must be rigorously understood before TAM can mature into a reliable manufacturing paradigm.

The adhesion between the printed polymer and textile substrate is one of the most critical determinants of the mechanical integrity and performance of hybrid materials [3, 4]. Adhesion arises through a combination of mechanical interlocking, thermal bonding, diffusion, and pressure-induced consolidation [13]. The degree of interpenetration of molten filament into the textile pores is influenced by extrusion temperature, print speed, layer height, nozzle-to-fabric Z-distance, and substrate morphology [14, 15]. For example, higher temperatures and lower Z-distances facilitate deeper penetration of molten polymer, improving bond strength but potentially risking fabric deformation or damage [4]. Conversely, insufficient melting or excessive nozzle elevation leads to weak adhesion, delamination, and early mechanical failure.

Fabric pretreatments, such as washing or chemical surface modification, can enhance adhesion by removing surface contaminants or increasing surface energy [4]. Studies comparing cotton, polyester, viscose, and mesh fabrics have shown that adhesion is highly substrate-dependent, with porous structures allowing better mechanical anchoring of polymer filaments [3, 16]. Moreover, the challenge intensifies for ultralight materials such as tulle, whose delicate open mesh structure is highly susceptible to thermal and mechanical disturbances during 3D printing.

Beyond adhesion, geometric parameters of the printed pattern play an essential role in determining the global mechanical performance of textile–polymer composites. Studies have demonstrated that tensile behaviour is strongly influenced by pattern size, orientation, topology, and spatial density [8, 16]. Printed features act as localised stiffening elements, altering load-transfer mechanisms within the fabric and redistributing stresses across the composite structure. For instance, Fajardo et al. (2023) highlighted that linked-unit 3D-printed fabrics exhibit significantly different tensile strengths depending on the type of structural connection, with specific designs acting to delay crack propagation or enhance elongation [5].

Similarly, auxetic structures, which exhibit negative Poisson's ratios, have been shown to provide enhanced energy absorption and resilience, with their behaviour being highly sensitive to unit-cell geometry [6, 17]. These findings underscore the critical interaction between pattern geometry and mechanical performance, reinforcing the need for systematic investigations into how specific geometric features – such as circles, hexagons, grids, or chiral cells interact with textile substrates under tensile loading.

Despite extensive research on textile printing, most studies focus on relatively stable, medium-weight fabrics [4, 8]. In contrast, tulle presents distinct challenges due to its extremely low mass per unit area, high porosity and open-mesh geometry, sensitivity to thermal fluctuations, and pronounced anisotropy that depends on mesh orientation.

In addition to the studies already discussed, earlier foundational work in additive manufacturing, such as Crump's (1989) patent on Fused Deposition Modelling, provides the technological basis for contemporary textile integration [18]. More recent analyses have highlighted the influence of calibration procedures and printing environments on interlayer adhesion and melt flow behaviour. Ghafar et al. (2024) and Gkertzos et al. (2024) demonstrate that ambient temperature, enclosure conditions, and extrusion stability significantly alter polymer viscosity and bonding strength, factors especially relevant when printing on delicate substrates such as tulle [19, 20]. Kozior et al. (2020) further conceptualise adhesion at textile–polymer interfaces by integrating wetting, diffusion, and pressure, offering a theoretical framework that supports the findings of Gorlachova and Mahltig (2021) and extends their applicability to ultralight fabrics [4, 13]. From a textile science perspective, Parajuli et al. (2021) emphasise the historical and structural distinctions among regenerated, synthetic, and natural fibres, underscoring why open mesh fabrics like tulle behave mechanically differently from denser textiles traditionally used in 3D printing experiments [21]. Complementary industrial developments, including Stratasys Ltd.'s (2023) release of textile-oriented AM platforms, indicate a growing movement toward commercial adoption, which further necessitates systematic mechanical investigations such as the present study [22]. Work by Thumsorn et al. (2023) on heat-distribution effects in filament deposition, together with Ren et al.'s (2020) insights into energy absorption in cellular printed geometries, also supports the notion that pattern geometry, even when reduced to simple circular nodes, can drastically modify deformation pathways [23, 24]. Finally, recent research on surface texturing of polymers and on metamaterial printing across different fabric types provides additional evidence that small-scale geometric modifications and substrate interactions can have disproportionate effects on tensile and flexural properties, reinforcing the need to study how circular pattern size and arrangement influence the performance of highly porous textiles like tulle [25–28].

These factors make tulle highly responsive to pattern-induced structural reinforcement, but also highly

vulnerable to pattern-induced stress concentrations. The porous mesh may allow substantial mechanical interlocking, but pattern rigidity can lead to premature rupture of the textile ligaments. The literature contains almost no systematic studies examining how 3D-printed patterns – especially circular patterns of varying size and spacing – affect the tensile behaviour of tulle. This represents a crucial knowledge gap, given the widespread use of tulle in fashion, costume design, scenography, and emerging fields requiring ultralight functional textiles.

Circular geometries are especially relevant because they distribute stresses uniformly, avoid sharp edges that typically concentrate stresses, lend themselves to parameterisation (diameter, spacing, arrangement), are aesthetically compatible with fashion and textile applications, and can act as isotropic reinforcement nodes in an anisotropic mesh fabric.

Patterns with varied circular sizes and arrangements provide a structured framework for investigating how discrete reinforcement zones modify the tensile properties of open-structured textiles. Such studies can lead to design guidelines applicable to both artistic and functional contexts, enabling the creation of robust, lightweight textile–polymer composites.

Mechanically, the printed circles can be conceptualised as localised rigid inclusions embedded within a compliant matrix (the tulle fabric). Under tensile loading, stress redistributes around these inclusions, with the degree of stress concentration being influenced by:

- circle diameter (larger elements stiffen greater surface area);
- spacing (tighter spacing increases composite stiffness);
- arrangement (grid, staggered, radial, alternating patterns);
- adhesion effectiveness (stronger bonding increases load transfer into polymer nodes);
- substrate anisotropy (tulle's warp/weft relation determines load paths).

Prior work on 3D-printed fabrics indicates that printed elements can either strengthen the substrate or induce premature failure depending on their rigidity relative to the textile [5, 16]. For tulle specifically, the interaction between polymer inclusions and mesh apertures likely plays a decisive role, suggesting a mixed-mode failure involving both textile rupture and interfacial detachment.

Given the scarcity of data on ultralight substrates in TAM research, the present study seeks to address a fundamental gap: How do circular 3D-printed patterns of different sizes and spatial arrangements influence the tensile properties of tulle fabric?

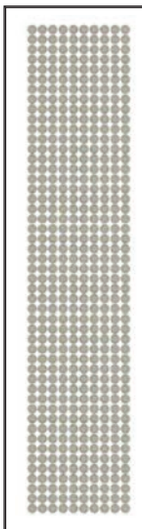
This work contributes to the field by providing the first systematic mechanical evaluation of 3D-printed circular patterns on tulle, comparing how diameter and arrangement affect strength/ stiffness/ elongation, examining interactions between polymer reinforcement nodes and delicate mesh structures, and generating design principles for future applications in lightweight hybrid textiles.

These insights have implications for industries seeking to integrate AM into fashion, performance costumes, millinery, wearable art, protective composites, and emerging metamaterial textiles.

MATERIALS AND METHODS

The primary material used in this research was tulle, a 100% polyester textile chosen for its fine mesh structure and lightweight properties. The tulle has a nominal thickness of approximately 0.23 mm and was supplied in the form of a swatch from which the test specimens were cut. Each tensile test specimen was a strip of tulle 50 mm wide and 250 mm long, of which 200 mm were effectively tested, with the remaining 50 mm clamped (in accordance with standard dimensions for tensile testing of textile strips). Various polymer models were 3D printed onto these tulle specimens using a 3D printer with Fused Deposition Modelling (FDM) additive manufacturing. The printing material was a polylactic acid (PLA) filament, chosen for its ease of printing, good adhesion to textile materials, and its sustainability as a biodegradable material. Before printing, each tulle sample was secured on the printer bed to keep it taut and stationary throughout the printing process.

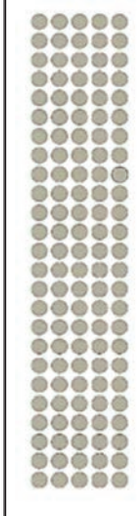
Four different geometrical patterns were designed using Autodesk Fusion software. The file was saved in *.stl format and later processed in Bambu Studio, where the printing operation was optimised by fitting 4 samples simultaneously. The print height was also adjusted to 6 layers (1 mm thickness). The printing parameters were modified, and the necessary pause was added between layers 1 and 2, at which point the textile substrate is added. The final step in obtaining the test samples involved slicing the files and printing the tulle specimens using the Bambu Lab P1P printer with PLA Basic filament from Bambu Lab, along with a control sample with no printing. The 3D printer was equipped with a 0.4 mm nozzle. A layer height of 0.16 mm was used for all printed structures, while the initial layer height was increased to 0.2 mm to enhance adhesion between the polymer and the textile substrate. The extrusion width was set to 0.42 mm to ensure dimensional accuracy and uniform deposition of the circular patterns. Printing speeds were adapted to ensure stable deposition on the flexible textile substrate. The initial layer speed was reduced to 50 mm/s to improve adhesion, while higher speeds were used for internal structures and infill (up to 200 mm/s) to optimise printing time. Acceleration parameters were set to 4000 mm/s² for standard printing and up to 10000 mm/s² for travel movements, ensuring efficient operation without inducing excessive mechanical stress on the textile. No support structures were required due to the planar geometry of the printed elements. A textured PEI build plate was used to ensure sufficient adhesion during printing without additional adhesives. The printing process was conducted in a layer-by-layer sequence, allowing partial penetration of the molten polymer into the tulle mesh, resulting in mechanical



SAC: **S**mall **A**ligned **C**ircles (50 x 10 pieces): A regular grid of small circular patches printed on the tulle. Each circle had a diameter of 4 mm, and circles were aligned in rows and columns (forming a straight lattice pattern along the warp and weft directions of the fabric). Adjacent circles in the grid were spaced with a centre-to-centre distance slightly larger than the diameter, such that the circles did not touch but were evenly distributed.

SSC: **S**mall **S**taggered **C**ircles (50 x 10 pieces): The same small circle diameter was used, but the pattern was arranged in an intercalated (staggered) manner. Rows of circles were offset such that each circle in a given row was positioned in the gap between circles in the adjacent rows (analogous to a hexagonal or triangular lattice arrangement). This staggered configuration spreads the circles more uniformly and avoids continuous straight columns of polymer.





LAC: **L**arge **A**ligned **C**ircles (25 x 5 pieces): A grid of larger circular patches (diameter 8 mm) printed in aligned rows/columns on the tulle. The spacing between these larger circles was set such that there were distinct gaps of bare fabric between patches, with circles aligned vertically and horizontally.

LSC: **L**arge **S**taggered **C**ircles (25 x 5 pieces): The same large circle size arranged in a staggered pattern (each row offset relative to the next), similar to the small staggered pattern but with larger features.



Fig. 1. The 3D-printed pattern geometries

interlocking at the interface. This mechanism has been identified as a key factor in improving adhesion between polymeric materials and textile substrates. The selected parameters were optimised to ensure a balance between adequate adhesion and the preservation of the textile structure. Lower initial layer speeds and increased first-layer thickness contributed to improved bonding, while controlled extrusion and acceleration parameters minimised deformation of the lightweight tulle fabric.

All patterns consisted of circular disk-shaped polymer patches, differing in size and arrangement, as presented in figure 1.

Each pattern was printed in 6 layers of filament approximately 1.1 mm thick, ensuring that the polymer just fused to the surface of the tulle without completely penetrating or excessively bulking the fabric. All printing was done with identical machine settings (nozzle diameter, layer height, print speed, and extrusion temperature) to maintain consistency; only the pattern geometry differed between samples. For each of the five sample types (one control and four patterned variants), multiple specimens (8 replicates per variant) were produced to ensure reproducibility of results (figure 2).

Because the experiment involves a textile and 3D-printed assembly, it can be treated analogously to a coating or applied layer. This makes it more justifiable than testing it as a purely textile sample (for which the original ISO 13934-1:2013 standard was designed), as the standard explicitly states that it is not usually applicable to coated fabrics [29].

For the present study, ISO 1421:2016 was considered one of the most relevant standards: 'Rubber- or plastics-coated fabrics – Determination of tensile strength and elongation at break' [30]. This standard covers fabrics coated with plastics or rubber and is therefore more closely aligned with the present research scenario of 'fabric + 3D printed layer'.

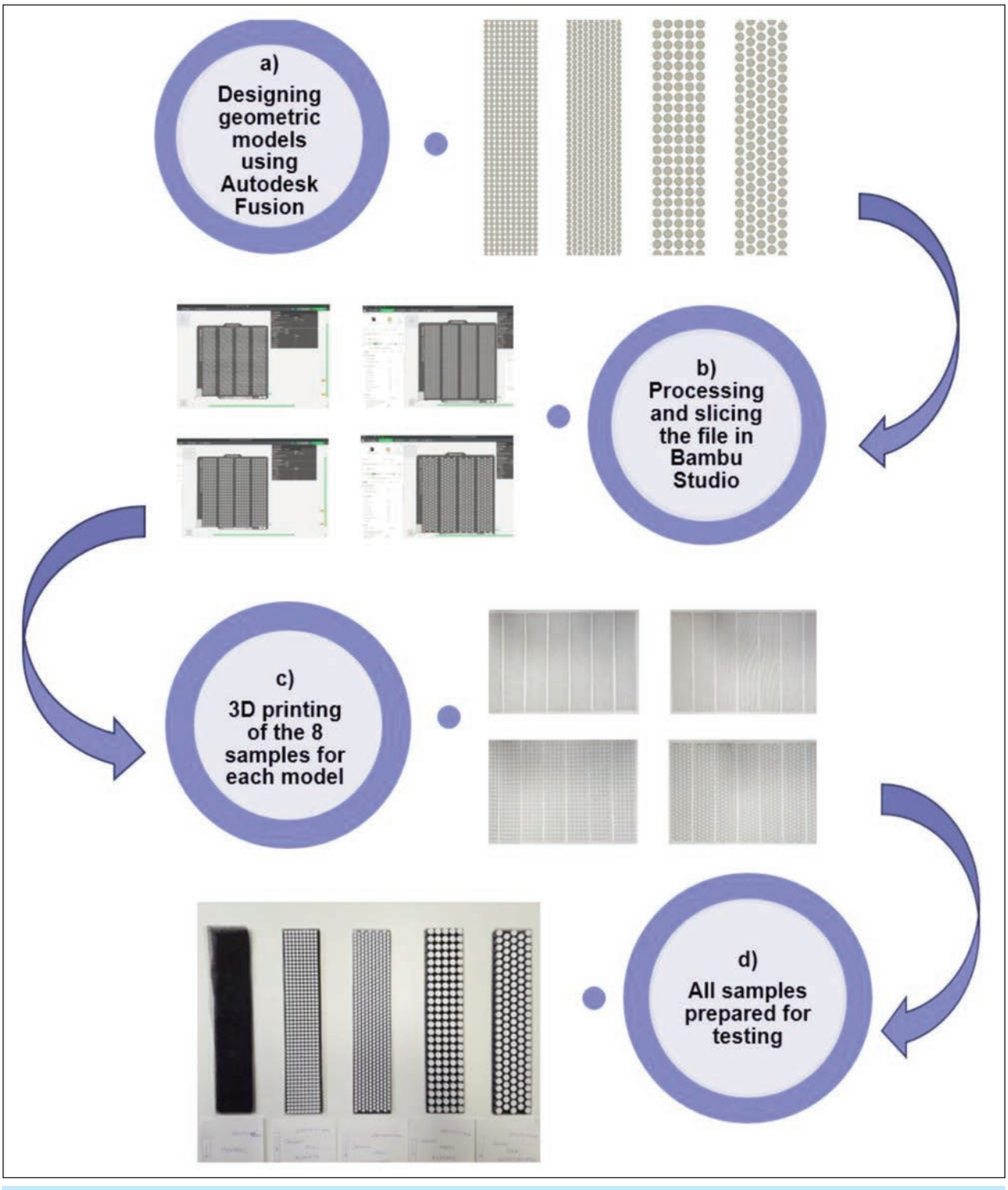


Fig. 2. The stages of making test samples

As such, ISO 1421:2016 was adopted as the methodological basis, with some adaptations, since the most important requirement for conducting a comparative test between unprinted tulle specimens and 3D printed tulle specimens, beyond complying with standard procedures, is to ensure that all samples are tested under identical conditions, including:

- specimen geometry (same width and same gauge length);
- testing machine and settings (same tensile speed, same type and size of grips);
- environmental conditions (same temperature and humidity);
- parameter definitions (% elongation, breaking strength in N/mm, maximum force in N, Young's modulus in N/mm²).

To ensure comparability, the "strip" method from ISO 1421 was used, applying the following test parameters:

- specimen width: 50 mm;
- specimen length: 200 mm;
- test speed: 100 mm/min.



Fig. 3. Testing the samples at STM 466

After printing, all samples were conditioned under standard laboratory atmosphere (approximately 20 ± 2°C and 65% ± 5 relative humidity) and stored in zipper bags with desiccant for at least 24 hours before testing, to minimise any influence of temperature or moisture on the behaviour of the fabric or polymer. Uniaxial tensile tests were performed using a universal testing machine ("Tensile Testing Centre STM 466"). Each specimen was clamped with an initial gauge length (distance between grips) of 200 mm. Tensile load was applied at a constant crosshead speed of 100 mm/min until the specimen failed. During each test, force–extension data were continuously recorded. The main mechanical parameters were derived from the force–extension curves: maximum force at break (peak load, which for a given sample width corresponds to tensile strength), elongation at break (extension at the breaking point, expressed as a percentage of the initial gauge length), and initial elastic stiffness (quantified by Young's modulus or initial slope, calculated within the linear elastic region of the curve).

The testing procedure was identical for all sample types. For printed specimens, care was taken to ensure that the orientation of the printed pattern relative to the loading direction was consistent: aligned patterns had rows of circles oriented either parallel or perpendicular to the loading direction (warp/weft alignment). In contrast, for staggered patterns, the grid's general axis of symmetry was aligned with the loading direction. After testing, the fracture surfaces of selected specimens were visually examined to qualitatively assess failure modes (e.g., yarn breakage in the tulle, print detachment, or a combination of both).

All measured data were collected and averaged for each sample group, and results were compared to evaluate the effect of pattern geometry on tensile performance (figure 3).

RESULTS AND DISCUSSION

The data reveal distinct mechanical behaviour of the tulle fabric depending on the geometry of the 3D-printed pattern applied to its surface and the testing direction (warp direction – column-wise vs. weft direction – row-wise).

The unprinted specimens (Control) exhibited the highest values for Young's modulus and elongation, indicating a homogeneous, elastic, and strong textile network. Overall, 3D printing reduced stiffness and elasticity, though in some cases it increased maximum force and breaking strength. The warp direction (columns) consistently demonstrated greater stiffness and strength than the weft direction (rows), regardless of the printed pattern geometry (tables 1 and 2).

Elongation at break (%)

The control sample, unprinted tulle, exhibited very high elasticity in the row (weft) direction, with an average elongation of 85.11%, which is typical for a thin textile material with a wide-mesh structure.

After 3D printing, the elongation was significantly reduced:

- 0 – Control sample: 85.11%
- SAC (small aligned circles): 33.86%
- SSC (small staggered circles): 37.93%
- LAC (large aligned circles): 28.79%
- LSC (large staggered circles): 29.04%

In the column (warp) direction, where extensibility is naturally lower, the values were even more reduced:

- 0 – Control sample: 26.76%
- SAC: 20.66%
- SSC: 18.22%
- LAC: 14.67%
- LSC: 14.61%.

It can be observed that 3D printing limits the deformability of the textile fibres, with the large circle patterns (LAC, LSC) being the most rigid and thus the least extensible in both directions (figure 4).

Table 1

THE AVERAGE VALUES MEASURED FOR THE COLUMN TESTING DIRECTION AND FOR DIFFERENT SAMPLES								
Control sample, 0 – unprinted tulle (column direction)								
0	Elongation (%)	Area (mm^2)	Breaking strength (N/mm)	Maximum force (N)	Sample length (mm)	Sample width (mm)	Thickness (mm)	Young's modulus (N/mm^2)
Mean	26.761	11.500	5.345	267.229	200.000	50.000	0.230	1412.654
Std Dev	2.210	0.000	0.708	35.421	0.000	0.000	0.000	47.318
Max	30.610	11.500	6.552	327.600	200.000	50.000	0.230	1469.699
Min	23.410	11.500	4.530	226.500	200.000	50.000	0.230	1347.766
3D-printed tulle sample with small aligned circles, SAC (column direction)								
SAC	Elongation (%)	Area (mm^2)	Breaking strength (N/mm)	Maximum force (N)	Sample length (mm)	Sample width (mm)	Thickness (mm)	Young's modulus (N/mm^2)
Mean	20.656	11.500	6.566	328.300	200.000	50.000	1.100	285.031
Std Dev	0.663	0.000	0.212	10.612	0.000	0.000	0.000	12.498
Max	21.163	11.500	6.780	339.000	200.000	50.000	1.100	305.956
Min	19.425	11.500	6.254	312.700	200.000	50.000	1.100	273.203
3D-printed tulle sample with small staggered circles, SSC (column direction)								
SSC	Elongation (%)	Area (mm^2)	Breaking strength (N/mm)	Maximum force (N)	Sample length (mm)	Sample width (mm)	Thickness (mm)	Young's modulus (N/mm^2)
Mean	18.221	11.500	6.281	314.300	200.000	50.000	1.100	309.298
Std Dev	1.649	0.000	0.629	31.748	0.000	0.000	0.000	12.831
Max	20.838	11.500	7.126	358.200	200.000	50.000	1.100	321.423
Min	15.500	11.500	5.204	260.500	200.000	50.000	1.100	283.221
3D-printed tulle sample with large aligned circles, LAC (column direction)								
LAC	Elongation (%)	Area (mm^2)	Breaking strength (N/mm)	Maximum force (N)	Sample length (mm)	Sample width (mm)	Thickness (mm)	Young's modulus (N/mm^2)
Mean	14.672	11,500	6.205	312.143	200.000	50.000	1.100	418.911
Std Dev	0.935	0.000	0.349	19.718	0.000	0.000	0.000	32.669
Max	15.713	11.500	6.718	336.700	200.000	50.000	1.100	469.050
Min	12.925	11.500	5.698	284.900	200.000	50.000	1.100	385.790
3D-printed tulle sample with large staggered circles, LSC (column direction)								
LSC	Elongation (%)	Area (mm^2)	Breaking strength (N/mm)	Maximum force (N)	Sample length (mm)	Sample width (mm)	Thickness (mm)	Young's modulus (N/mm^2)
Mean	14.611	11.500	6.162	310.763	200.000	50.000	1.100	410.402
Std Dev	1.228	0.000	0.449	20.651	0.000	0.000	0.000	7.052
Max	16.800	11.500	6.954	347.700	200.000	50.000	1.100	418.591
Min	13.475	11.500	5.776	297.000	200.000	50.000	1.100	394.968

Table 2

THE AVERAGE VALUES MEASURED FOR THE ROW TESTING DIRECTION AND FOR DIFFERENT SAMPLES								
Control sample, 0 – unprinted tulle (row direction)								
0	Elongation (%)	Area (mm^2)	Breaking strength (N/mm)	Maximum force (N)	Sample length (mm)	Sample width (mm)	Thickness (mm)	Young's modulus (N/mm^2)
Mean	85.1105	11.500	1.279	101.588	200.000	50.000	0.230	128.337
Std Dev	8.567	0.000	0.835	12.935	0.000	0.000	0.000	5.806
Max	94.620	11.500	2.400	123.200	200.000	50.000	0.230	140.230
Min	69.400	11.500	0.314	79.300	200.000	50.000	0.230	121.023

THE AVERAGE VALUES MEASURED FOR THE ROW TESTING DIRECTION AND FOR DIFFERENT SAMPLES								
3D-printed tulle sample with small aligned circles, SAC (row direction)								
SAC	Elongation (%)	Area (mm^2)	Breaking strength (N/mm)	Maximum force (N)	Sample length (mm)	Sample width (mm)	Thickness (mm)	Young's modulus (N/mm^2)
Mean	33.859	11.500	1.439	105.483	200.000	50.000	1.100	73.378
Std Dev	4.143	0.000	0.885	1.973	0.000	0.000	0.000	2.481
Max	39.888	11.500	2.032	108.300	200.000	50.000	1.100	75.711
Min	28.638	11.500	0.212	102.400	200.000	50.000	1.100	69.674
3D-printed tulle sample with small staggered circles, SSC (row direction)								
SSC	Elongation (%)	Area (mm^2)	Breaking strength (N/mm)	Maximum force (N)	Sample length (mm)	Sample width (mm)	Thickness (mm)	Young's modulus (N/mm^2)
Mean	37.930	11.500	1.717	104.313	200.000	50.000	1.100	70.656
Std Dev	3.025	0.000	0.391	1.835	0.000	0.000	0.000	3.286
Max	42.263	11.500	1.986	106.700	200.000	50.000	1.100	75.057
Min	32.988	11.500	0.918	102.000	200.000	50.000	1.100	65.957
3D-printed tulle sample with large aligned circles, LAC (row direction)								
LAC	Elongation (%)	Area (mm^2)	Breaking strength (N/mm)	Maximum force (N)	Sample length (mm)	Sample width (mm)	Thickness (mm)	Young's modulus (N/mm^2)
Mean	28.791	11.500	0.938	98.575	200.000	50.000	1.100	89.780
Std Dev	4.560	0.000	0.808	2.366	0.000	0.000	0.000	6.450
Max	34.888	11.500	1.962	101.600	200.000	50.000	1.100	97.693
Min	23.488	11.500	0.172	94.200	200.000	50.000	1.100	83.431
3D-printed tulle sample with large staggered circles, LSC (row direction)								
LSC	Elongation (%)	Area (mm^2)	Breaking strength (N/mm)	Maximum force (N)	Sample length (mm)	Sample width (mm)	Thickness (mm)	Young's modulus (N/mm^2)
Mean	29.038	11.500	0.538	91.238	200.000	50.000	1.100	98.373
Std Dev	2.970	0.000	0.479	2.730	0.000	0.000	0.000	2.202
Max	34.525	11.500	1.554	96.100	200.000	50.000	1.100	100.728
Min	24.750	11.500	0.156	88.300	200.000	50.000	1.100	95.118

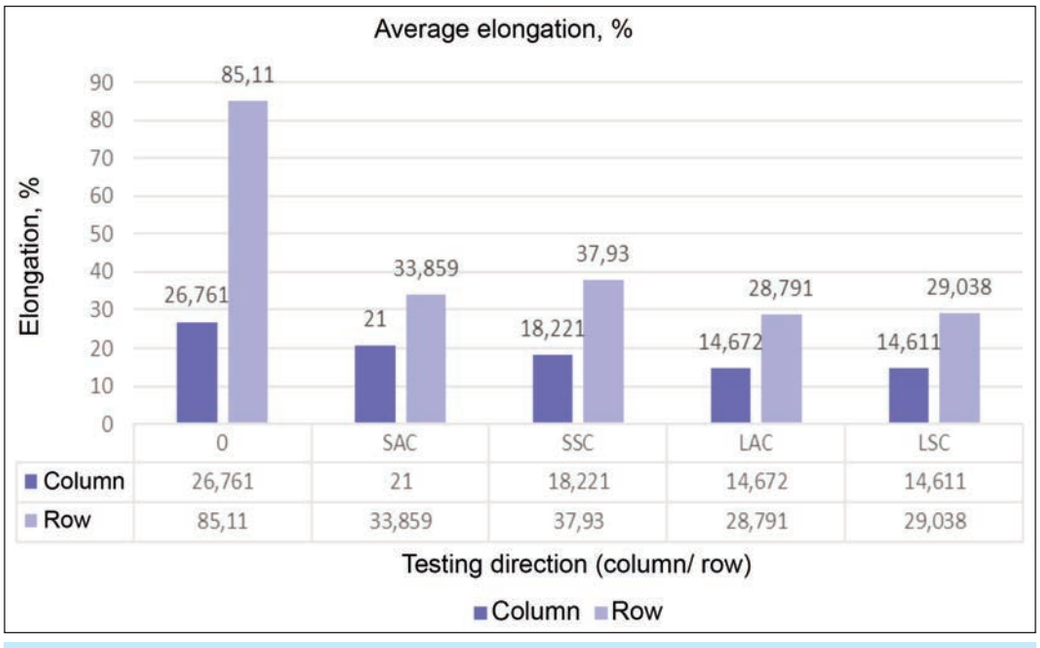


Fig. 4. Average elongation (%) depending on the testing direction

Breaking strength (N/mm)

An interesting observation is that the breaking strength increased in the column (warp) direction for all the printed samples:

- 0 – Control sample: 5.345 N/mm
- SAC (small aligned circles): 6.566 N/mm
- SSC (small staggered circles): 6.281 N/mm
- LAC (large aligned circles): 6.205 N/mm
- LSC (large staggered circles): 6.162 N/mm.

This suggests that the printed material absorbs part of the mechanical load, delaying complete rupture.

In the row (weft) direction, the values are significantly lower, but a strengthening effect is observed for:

- SSC: 1.717 N/mm (compared to 1.279 N/mm in the control)
- SAC: 1.439 N/mm.

The large circle patterns (LAC, LSC) performed poorly in this direction, likely due to stress concentration at the edges of the printed zones. Overall, 3D printing brings structural benefits in the warp direction, but it may cause local weakening in the transverse direction depending on the printed geometry (figure 5).

Maximum force (N)

The maximum force follows a similar trend to the breaking strength, but it reflects the overall load-bearing capacity rather than just the point of break.

In the column (warp) direction, all printed models outperformed the control sample:

- 0 – Control sample: 267.229 N
- SAC (small aligned circles): 328.300 N (highest value)
- SSC (small staggered circles): 314.300 N
- LAC (large aligned circles): 312.143 N
- LSC (large staggered circles): 310.763 N.

In the row (weft) direction, although the values are lower overall, all printed models recorded comparable or higher forces than the control:

- 0 – Control sample: 101.588 N
- SAC: 105.483 N
- SSC: 104.313 N.

The printed layer acts as a reinforcement within the mechanical structure of the sample. Even with reduced elongation, the total force sustained by the material increases significantly, especially in the warp direction (figure 6).

Young's modulus (N/mm²)

In the column (warp) direction, the control sample (unprinted tulle) exhibited a high average Young's modulus of 1412.65 N/mm², indicating a rigid and low-extensibility structure. In contrast, all four printed models showed a substantial decrease:

- SAC (small aligned circles): 285.03 N/mm²
- SSC (small staggered circles): 309.30 N/mm²
- LAC (large aligned circles): 418.91 N/mm²
- LSC (large staggered circles): 410.40 N/mm².

The significant drop in stiffness suggests that the addition of the printed material alters the stress distribution within the tulle's mesh structure.

In the row (weft) direction, where tulle is naturally more flexible, the Young's modulus was lower even in the control sample (128.34 N/mm²). The printed patterns resulted in a slight increase in stiffness, particularly for:

- LSC: 98.37 N/mm²
- LAC: 89.78 N/mm².

The denser coverage and geometry of the printed material (in the LSC and LAC models) provide additional resistance in the weft direction. However, it does not reach the inherent stiffness levels observed in the warp direction (figure 7).

Qualitative analysis of the failure

Following the tensile tests, it was observed that most specimens ruptured near the edge of the grip jaws, at

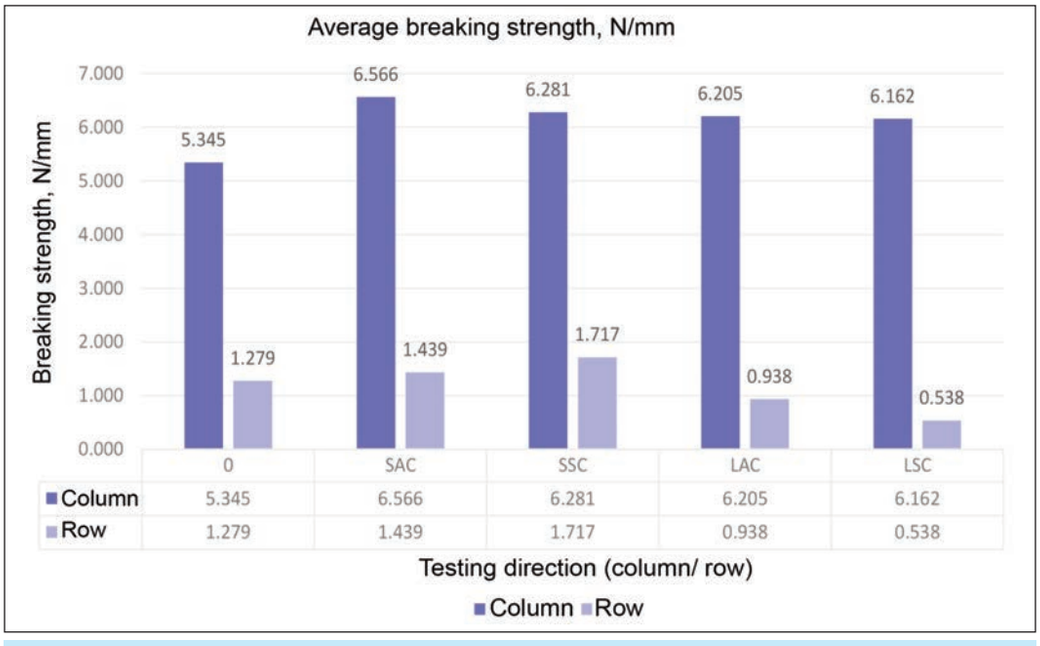


Fig. 5. Average breaking strength (N/mm) depending on the testing direction

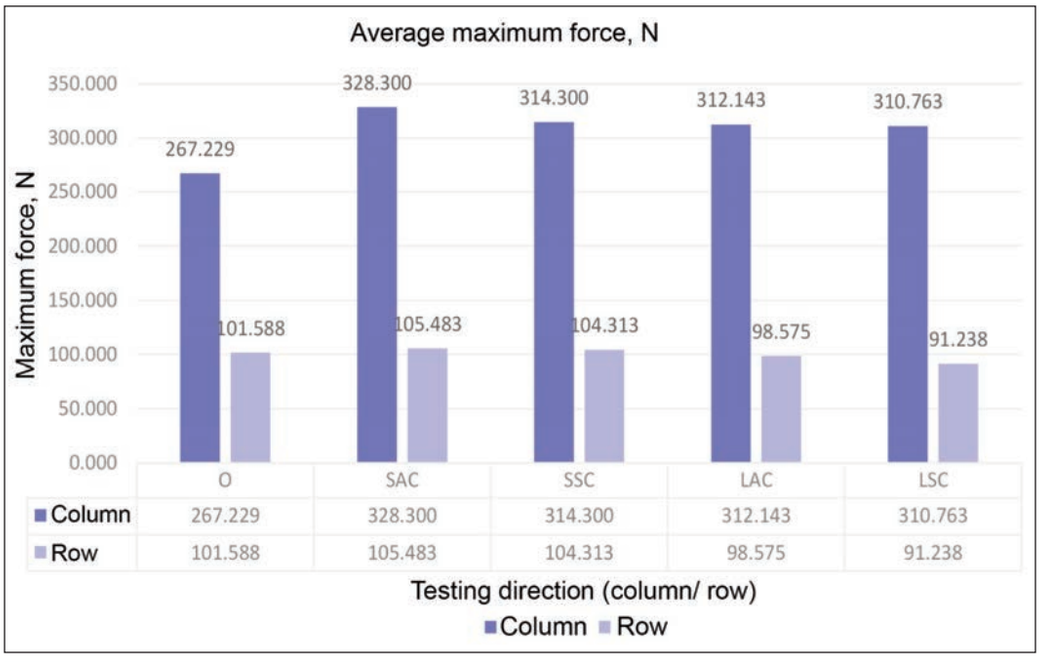


Fig. 6. Average Maximum force (N) depending on the testing direction

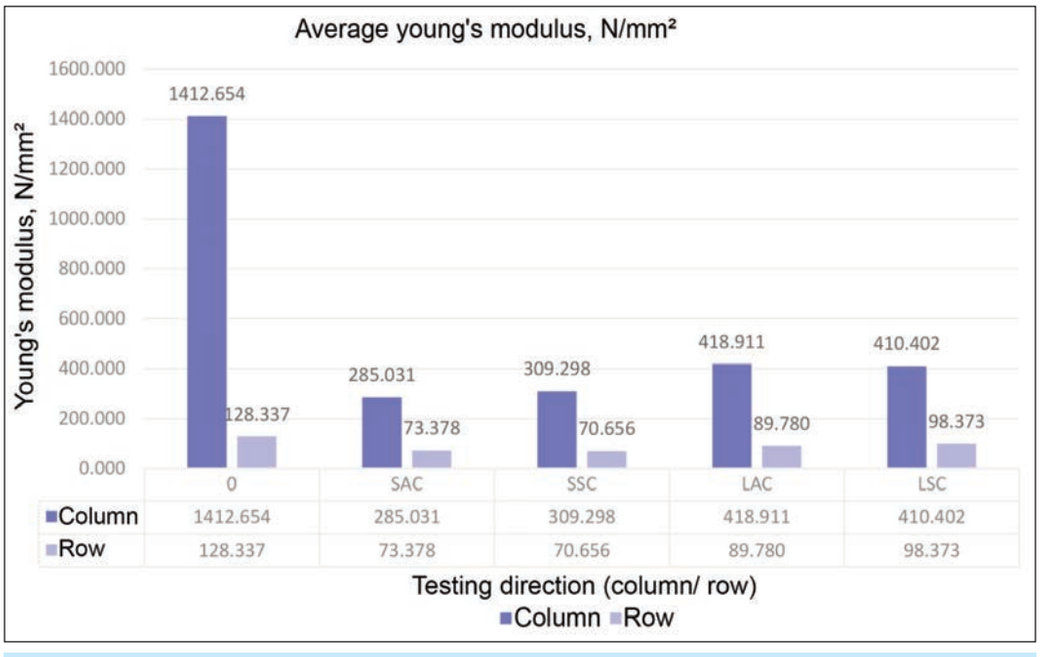


Fig. 7. Average Young's modulus (N/mm^2) depending on the testing direction

the boundary between the clamped and free portions of the sample. According to ISO 1421, the rupture should occur in the central region between the clamps, so that the stress distribution accurately reflects the material's mechanical behaviour.

However, considering the specific nature of the tested material, tulle, a lightweight, perforated, and flexible textile, the rupture at the jaw boundary can be explained by:

- stress concentration within the mesh openings in contact with the grip surface;
- local deformation of the material due to mechanical clamping pressure;
- the atypical behaviour of net-like materials, which do not allow for uniform stress distribution.

To limit this effect, appropriate gripping accessories were used, and the tests were conducted with careful specimen alignment. Since all samples were subjected to the same testing protocol and exhibited consistent rupture behaviour, the results were considered valid and relevant for comparing the printed and unprinted tulle variants.

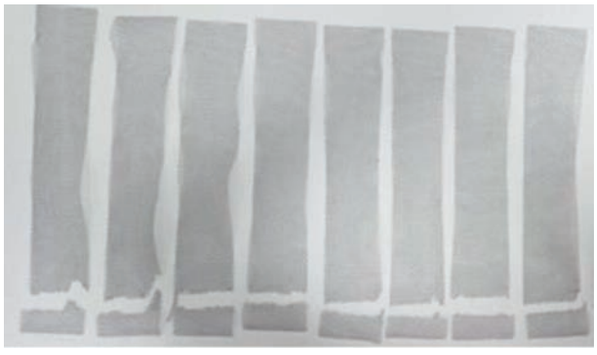
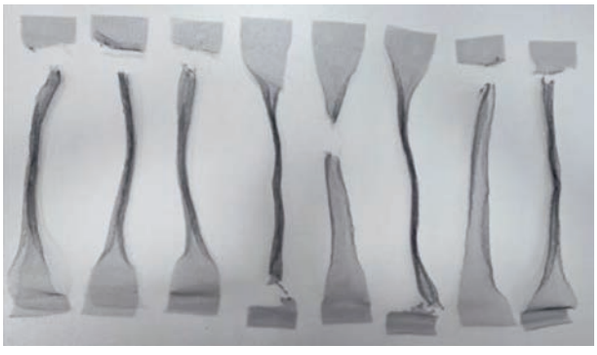
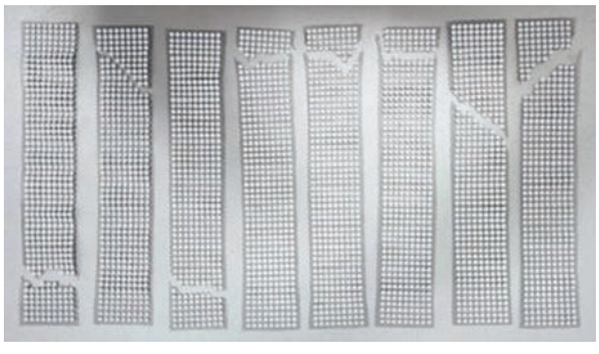
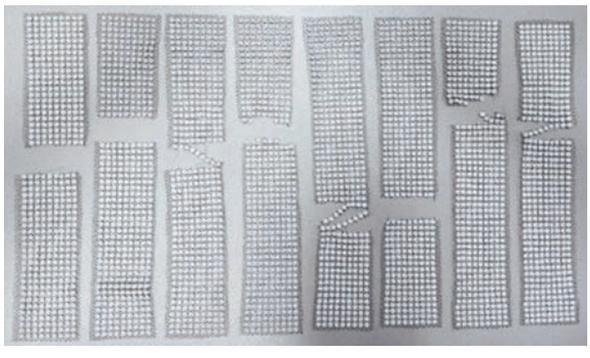
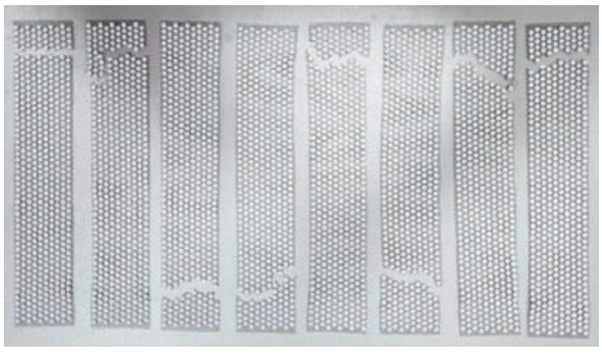
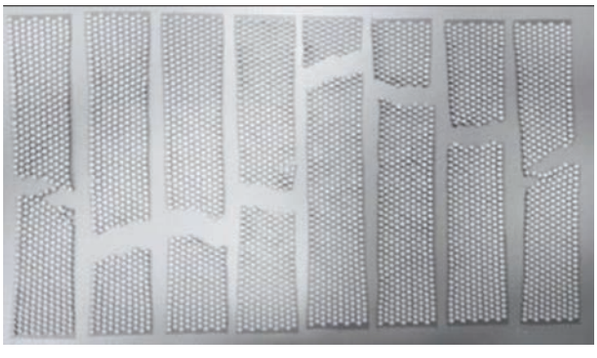
Table 3 presents the qualitative visual appearance of the samples after uniaxial tensile testing and an analysis of post-tested samples by direction, organised as follows:

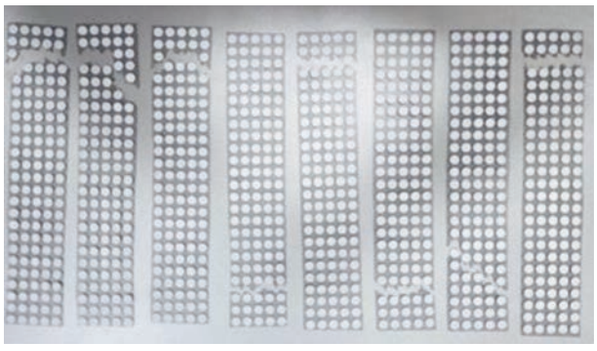
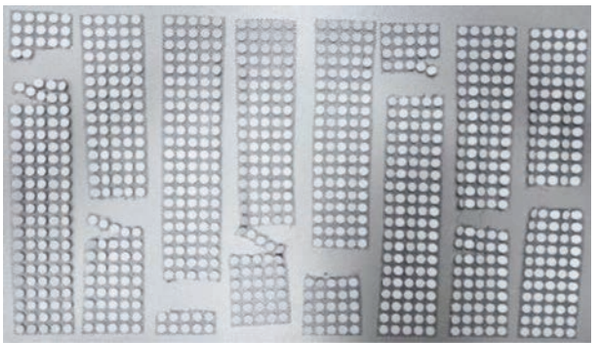
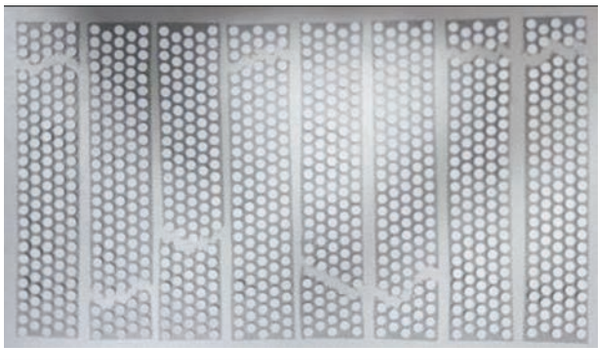
- Left column: samples tested in the column/warp direction;
- Right column: samples tested in the row/weft direction.

Each row corresponds to a different sample type (from unprinted tulle to various 3D-printed geometries). Distinct fracture patterns are evident, influenced by the load orientation and print configuration.

Table 3

QUALITATIVE ANALYSIS OF THE FAILURE MODE OF THE SAMPLES

Column (left)	**Row (right)**
	
0 – Control samples (unprinted tulle)	
Column direction: Clean, abrupt tears occur just outside the jaw grips, highlighting stress concentration at the clamp exit. The homogeneous textile mesh allows a uniform strain response.	**Row direction (right)**: Significant necking and elongation are visible before rupture, typical of the more elastic weft orientation. The mesh stretches significantly, often leading to irregular edge curling.
	
SAC – Small Aligned Circles	
Column direction: Fracture paths follow vertical lines, occasionally crossing through the printed rows. The alignment seems to channel stress along narrow paths, increasing fracture predictability but also brittleness.	**Row direction**: The breaks are more chaotic, frequently passing diagonally through the printed areas. Misalignment between circles and load direction may have created zones of uneven rigidity and localised failure.
	
SSC – Small Staggered Circles	
Column direction: Cracks appear fragmented and irregular, often bypassing dense print areas. The staggered configuration appears to better diffuse mechanical stress, leading to distributed rather than concentrated rupture.	**Row direction**: Jagged tears cut across the interspersed print pattern, and multiple samples show complex, branching failure lines. This suggests higher ductility or delayed intention to failure in the weft direction for this pattern.

QUALITATIVE ANALYSIS OF THE FAILURE MODE OF THE SAMPLES	
	
LAC – Large Aligned Circles	
Column direction: Several breaks occur through or around large circles, with clear stress risers near the printed edges. In some samples, minor delamination between PLA and tulle fabric is visible.	**Row direction**: Breakage often propagates between adjacent rows of circles, especially at lower printing density. The directionality of the aligned print may have acted like fault lines under stress.
	
LSC – Large Staggered Circles	
Column direction: Breaks follow less predictable paths than LAC. The staggered layout appears to distribute stress more evenly, but it still leaves weak points in overlapping zones.	**Row direction**: Tearing occurs in dispersed zones across the mesh. In some samples, the failure does not cut directly through the centre but follows less obvious load paths, likely due to the interaction between mesh and print.

In conclusion, it can be said that column direction testing (left) consistently yields straighter, more defined fracture lines, emphasising the natural stiffness and limited extensibility of the warp threads, whilst the row direction testing (right) results in more variable and complex break patterns, highlighting the deformability of the weft and how print geometries interact with a more compliant base. Denser, more regular geometries (e.g., aligned circles) tend to promote brittle, concentrated fractures, whereas staggered, less constrained layouts delay failure and encourage more distributed rupture behaviour. Visual evidence of partial PLA delamination or localised detachment was occasionally observed in more rigid geometries, especially LAC and LSC.

Analysis of stress-strain curves

As the graphs illustrate, for the 0 – Control Samples (Column/Warp Direction), the curves exhibit a steep initial slope, indicating high stiffness and low initial deformation, characteristic of warp threads which are more tightly tensioned during weaving. In the linear elastic region, most curves exhibit a linear rise at the beginning, typical of elastic behaviour before yield. Maximum load (peak force) is significantly higher in this direction, consistent with the numerical data (e.g., ~270 N). A sharp drop after the peak is evident, and a sudden rupture is observed, suggesting brittle-like failure in the warp direction. The curves are consistent across samples, indicating high repeatability and uniform mechanical behaviour of the unprinted tulle in this direction. Regarding the failure mode, the graph suggests that failure occurs when the material reaches its maximum load-bearing capacity, accompanied by minor plastic deformation.

For the 0 – Control Samples (Row/Weft Direction), these curves are generally more gradual, with shallower slopes, reflecting higher extensibility and lower stiffness than in the warp direction (figure 8). The samples exhibit greater extension before rupture; they stretch farther before failure, which is consistent with the elongation data (e.g., ~85% strain). The graph shows lower peak forces; the maximum load is significantly lower (~100 N), which aligns with the

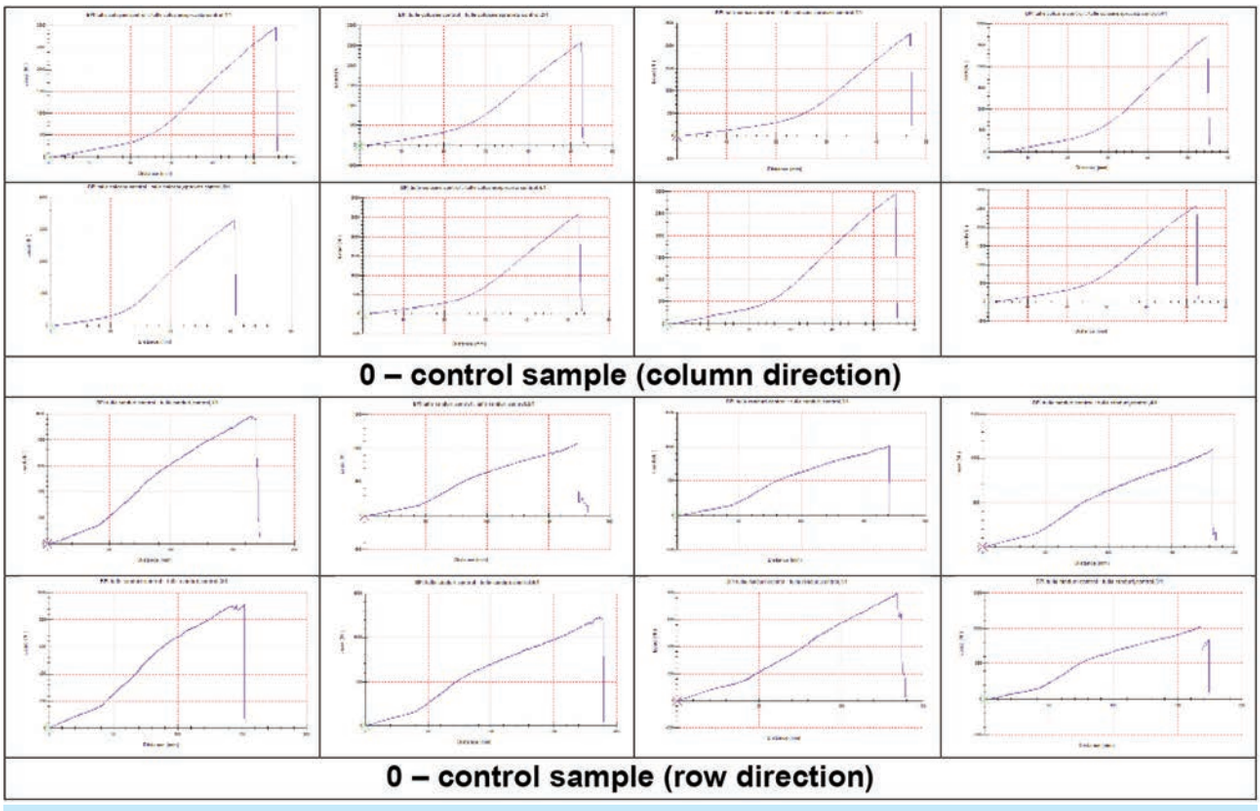


Fig. 8. The load-distance (force-extension) graphs for the 0 – Control samples (column/ row direction)

weft's structural properties (less-dense yarns, more open mesh). Some curves exhibit nonlinear behaviour early in the test, likely due to gradual thread engagement or mesh deformation. The post-yield region is more visible in some samples, with a plateau or slow increase before rupture, suggesting more ductile behaviour. Small fluctuations in the curves before failure (zigzag or dips) might be due to mesh deformation, thread slipping or reorientation before total rupture.

Overall, the unprinted tulle material behaves differently in each principal direction due to the anisotropic nature of woven fabrics. In the warp (column) direction, the structure is stronger and stiffer, bearing more load but failing more abruptly. In the weft (row) direction, the material is more deformable, stretching considerably before failure but unable to withstand high forces. These baseline behaviours help evaluate the reinforcement or degradation introduced by the 3D-printed patterns in later sample sets.

The curves for the SAC – Small Aligned Circles (Column Direction) are moderately steep, with a noticeable elastic region followed by a distinct peak, similar to the control column samples but with lower slopes, indicating reduced stiffness (figure 9). The maximum force is generally higher than the control, confirming the reinforcing effect of the 3D-printed pattern along the column (warp) direction. All samples demonstrate abrupt drops after the peak, characteristic of brittle-like rupture, despite the added 3D material. Compared to the control, the curves show slightly more gradual rises, indicating some loss in rigidity, but overall stronger peak values, consistent with previously reported average maximum forces (~328 N). The small, 3D-printed aligned circles act as load-bearing elements, transferring stress across the tulle and enhancing its resistance to force until rupture. The consistent peak and rupture across samples imply good repeatability and suggest the aligned pattern works well in the warp direction.

The curve for SAC – Small Aligned Circles (Row Direction) shows a more gradual slope and fewer sharp peaks, indicating lower stiffness and more ductile behaviour than in the column direction. There is a notable variation in post-peak behaviour; some curves drop sharply, while others show jagged, irregular fluctuations, possibly indicating progressive local failure, filament delamination, or cracking in the print. Despite lower stiffness, maximum forces are slightly higher than those of the unprinted control (e.g., ~105 N vs. 101 N), consistent with earlier quantitative results. Overall, the SAC pattern improves load-bearing capacity but also introduces heterogeneous stress concentrations, especially where the alignment doesn't align with the load path. The non-smooth post-peak behaviour suggests complex failure modes, likely a combination of tulle thread breakage and partial delamination or failure of the printed PLA.

The SAC geometry performs best in the column direction, where its alignment reinforces the warp threads. In the row direction, while there is some mechanical benefit, the alignment of small circles does not follow the primary strain path, leading to less efficient reinforcement and more complex failure behaviour. Overall, this pattern offers a balanced

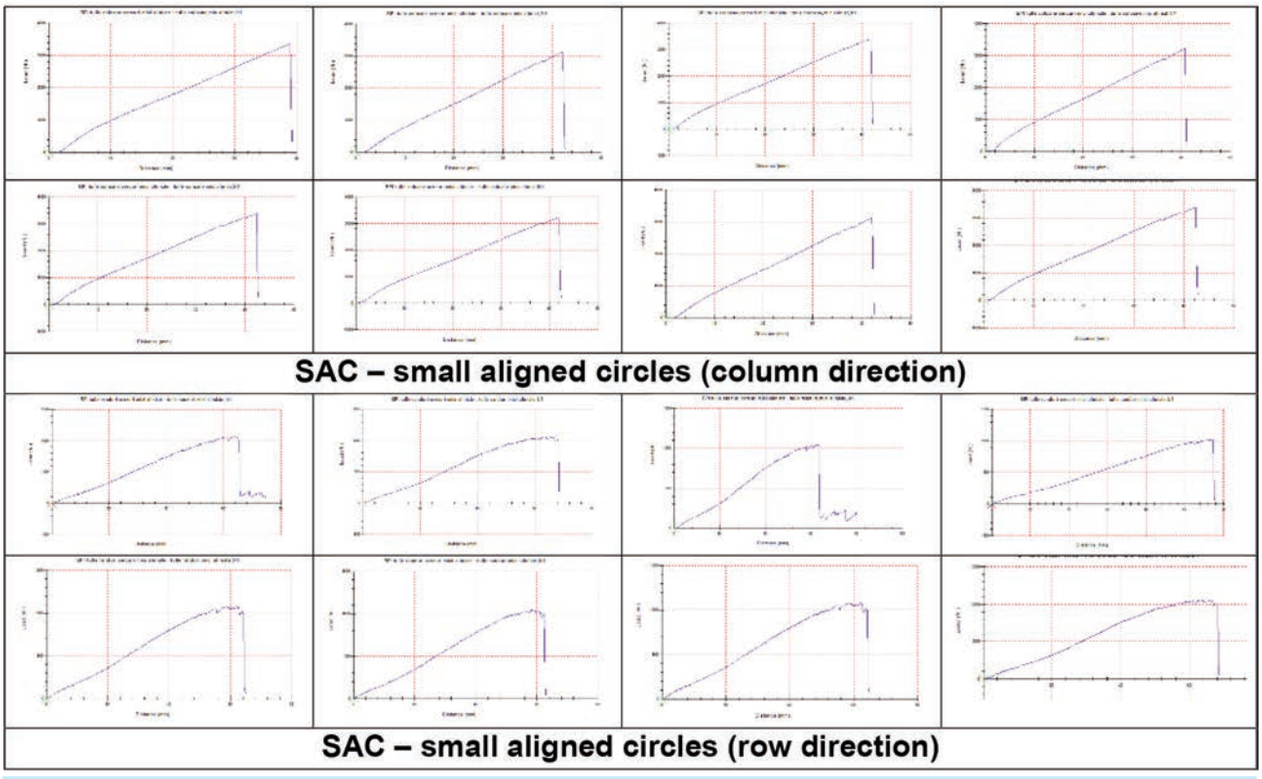


Fig. 9. The load-distance (force-extension) graphs for the SAC – Small Aligned Circles samples (column/ row direction)

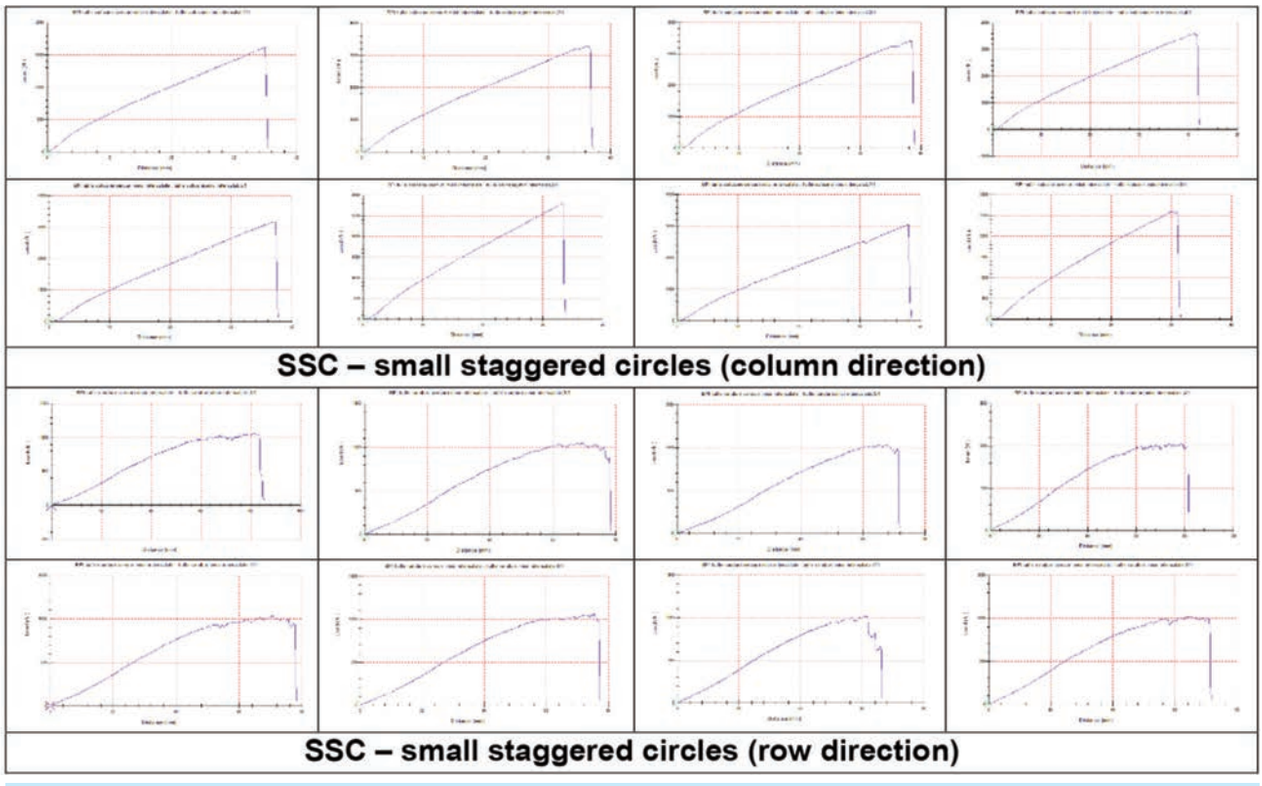


Fig. 10. The load-distance (force-extension) graphs for the SSC – Small Staggered Circles samples (column/row direction)

trade-off between reinforcement and flexibility, with better results when aligned with the principal load direction.

For the SSC – Small Staggered Circles (column direction), the force–extension curves for this geometry are consistent and highly repeatable, with linear increases followed by abrupt drops, indicating clear fracture points (figure 10). The slopes are similar to those observed in SAC (aligned circles), but slightly steeper in some cases, suggesting greater stiffness in the intercalated geometry. The maximum load appears comparable to or somewhat lower than

SAC, but remains higher than the control, confirming that the printed pattern strengthens the structure in the warp direction. Rupture occurs suddenly and consistently across all samples, which reflects uniform material response. The staggered arrangement of small circles contributes to homogeneous stress distribution, reducing the chance of premature failure along single filament lines. Compared to SAC, SSC might better distribute forces laterally, explaining slightly more consistent slopes and rupture points. The structure reinforces without excessively compromising deformability, which is favourable in high-load warp-oriented applications.

The curve behaviour for the SSC – Small Staggered Circles (row direction) shows greater elongation before failure and more complex post-peak behaviour, including plateaus, jagged declines, and progressive drops. The force–distance curves are flatter, indicating lower stiffness in the column direction. Several samples exhibit non-linear, gradual failures, likely reflecting a ductile-like progression, with staggered geometry delaying complete rupture. Compared to the SAC row curves, SSC exhibits slightly smoother transitions and possibly better energy absorption, as indicated by a wider curve. The staggered layout improves load redistribution, reducing the likelihood of abrupt failures. The gradual loss of load-bearing capacity post-peak suggests delamination or cracking of the PLA pattern before rupture of the tulle thread. While overall force values are still lower than those in the column direction, SSC performs relatively better than SAC in the row direction, likely due to the offset pattern reinforcing more cross-threads.

In the column direction, SSC samples demonstrate reliable mechanical strength with consistent performance, reinforcing the idea that intercalated geometries enhance structural continuity. In the row direction, the geometry enables controlled failure and better deformation tolerance, providing superior ductility and resilience compared to SAC. Overall, SSC represents a balanced configuration that enhances both strength and flexibility depending on load orientation, making it suitable for applications requiring durability and controlled deformation.

The load–distance graphs for the LAC – Large Aligned Circles (column direction) show a linear-elastic region followed by a clear peak and a sudden drop, consistent with brittle-type rupture (figure 11). Compared to SAC and SSC, the curves here tend to have slightly lower slopes, suggesting a moderate reduction in stiffness. Maximum loads are high and quite consistent, with very little dispersion among samples, indicating that the large aligned circles provide strong structural support in the warp direction. Rupture occurs abruptly, indicating uniform stress build-up followed by rapid failure, likely along the printed ring outlines. The large aligned circles act as rigid printed zones that transfer and concentrate loads, allowing the sample to resist significant force until a critical failure point is reached. While this improves maximum force capacity, it may compromise ductility, as seen in the sudden, sharp rupture profiles. This geometry is effective at strengthening tulle in the warp/column direction, though with reduced elasticity.

For the LAC – Large Aligned Circles (row direction), these graphs are more irregular, with plateau-like

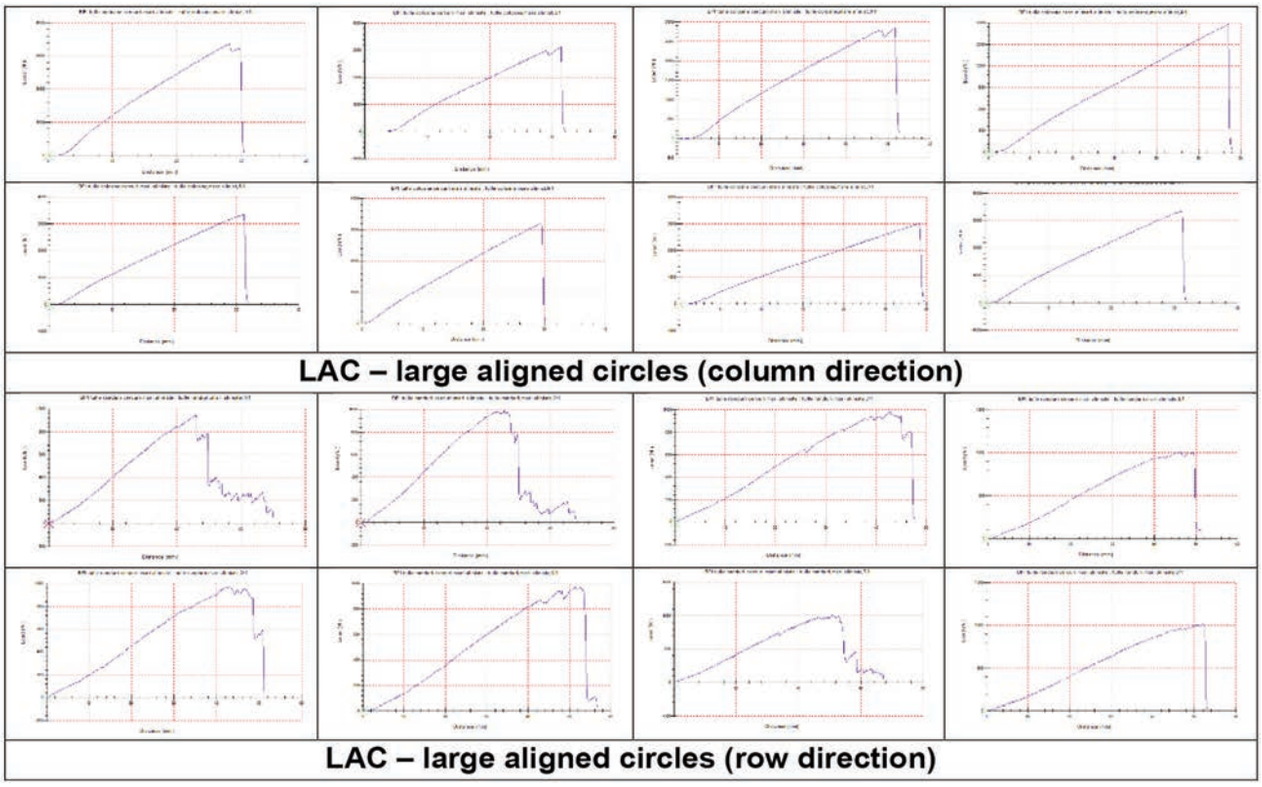


Fig. 11. The load-distance (force-extension) graphs for the LAC – Large Aligned Circles samples (column/ row direction)

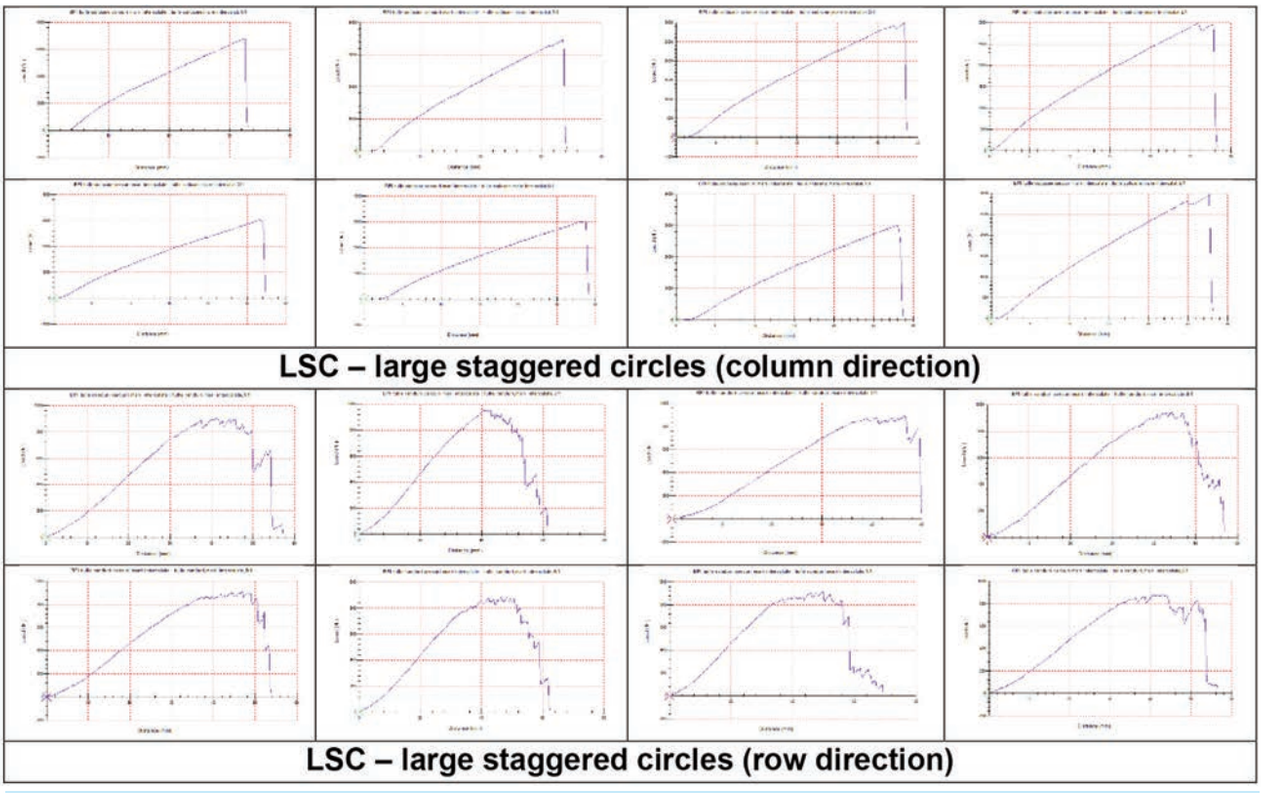


Fig. 12. The load-distance (force-extension) graphs for the LSC – Large Staggered Circles samples (Column/row direction)

behaviour and jagged descent patterns, suggesting progressive fibre and bond failures. Post-peak regions are more fragmented than in SAC or SSC, with multiple load drops, indicating micro-failure events and partial detachment or tearing within the printed pattern. The curves show lower slopes, indicative of lower stiffness and greater elongation in the column direction, but are more variable than SSC. The large ring pattern does not perform as well in the row direction, possibly due to misalignment between the load paths and the ring orientation, leading to localised stress concentrations. Fracture progression is more ductile, but less controlled, with evidence of crack propagation through the PLA network and tulle backing. The broader openings between rings may lead to stress localisation at fewer contact points, accelerating failure under crosswise strain.

LAC performs strongly in the warp direction, offering high strength but reduced ductility due to rigid geometric constraints. In the weft direction, the exact geometry becomes a structural weakness, as larger printed gaps and a mismatch in ring orientation hinder uniform force transfer. Compared to SAC and SSC, LAC is best used where directional strength is prioritised over overall flexibility.

All the LSC, Large Staggered Circles (column direction), curves show a relatively linear elastic phase, followed by a sharp peak and sudden drop, indicative of brittle-like failure (figure 12). Compared to small-circle models, the slope is more moderate, reflecting lower stiffness. Despite the reduced modulus, maximum load values remain high and consistent across samples. Minimal fluctuation in the post-peak region suggests a clean rupture without progressive tearing or delamination. The staggered pattern provides a balanced stress distribution, even in large-circle geometry, helping to delay rupture under uniaxial tensile force. However, the lower elastic modulus means deformation occurs more easily, which may be favourable for applications that need moderate flexibility with enhanced load capacity. The clean fracture profile indicates that while deformation occurs, the rupture is sudden and decisive, likely along predictable stress paths created by ring alignment.

For the LSC – Large Staggered Circles (row direction), the curves show a gradual rise to a peak, followed by a jagged, noisy decline, with many exhibiting plateau regions and stepped drops. This is characteristic of progressive micro-failure events, where the structure fails gradually rather than catastrophically. Slight undulations before the peak suggest internal redistribution of stress as some bonds yield before total rupture. The maximum force is lower than in the column direction, but relatively high compared to other row-direction models. In the weft direction, the large, staggered circles allow localised deformation and energy absorption, explaining the ductile behaviour observed in the force–distance graphs. The staggered layout helps to avoid abrupt stress concentrations, contributing to more controlled failure progression. This pattern shows promise in transverse reinforcement, where distributed performance and damage tolerance are needed.

Overall, the LSC geometry achieves a good compromise between strength and flexibility. It behaves predictably in the warp direction (sudden, high-load

rupture) and gracefully in the weft direction, where its staggered layout buffers crack propagation. This configuration may be best suited for applications requiring resilience and progressive energy dissipation, especially in multi-axial load environments.

The experimental results demonstrate a clear reinforcement effect induced by the 3D-printed circular patterns. Compared to unmodified tulle samples, all printed configurations exhibited increased maximum force and breaking strength, confirming effective stress transfer between the polymeric elements and the textile substrate.

This behaviour is consistent with findings reported in previous studies on textile–polymer hybrid structures, in which the printed material acts as a reinforcing phase [5, 16]. The adhesion between the polymer and textile enables load redistribution, leading to improved tensile performance.

However, the increase in strength is accompanied by a reduction in elongation at break, particularly in the weft direction. This effect can be attributed to the restriction of yarn mobility caused by the printed patterns, which limit the inherent deformability of the textile structure. Similar trade-offs between stiffness and flexibility have been observed in comparable additive manufacturing applications on textiles.

The results obtained in this study highlight the potential of additive manufacturing for the functional customisation of textile materials. By varying the size, spacing, and arrangement of printed elements, it is possible to locally tailor the mechanical properties of fabrics.

The ability to control stiffness and strength through geometric parameters enables the development of hybrid structures with spatially differentiated behaviour. This is particularly relevant in applications requiring localised reinforcement without compromising the overall flexibility of the material.

CONCLUSION

This study investigated the mechanical behaviour of a 3D-printed polymer layer deposited on a tulle fabric substrate, focusing on the influence of pattern geometry (aligned vs. staggered circles, small vs. large) and loading direction (warp vs. weft). Through uniaxial tensile tests and detailed visual and graphical analysis, several meaningful insights were drawn regarding the composite's structural performance.

Firstly, the presence of a 3D-printed pattern notably modified the mechanical properties of the tulle substrate. While the control samples (unprinted tulle) exhibited the highest elasticity and Young's modulus, especially in the weft direction, most printed samples showed reduced elongation and stiffness, indicating that the printed layer constrains the native deformability of the textile mesh. Despite this reduction in flexibility, all printed configurations demonstrated higher maximum force and breaking strength than the control, particularly in the column (warp) direction. This reveals the reinforcing effect of the polymeric overlay, which shares the tensile load and delays failure.

Among the printed geometries, small aligned and staggered circles (SAC and SSC) proved more effective in maintaining balanced mechanical performance, offering moderate flexibility while significantly improving strength. In contrast, large patterns, particularly those aligned (LAC), although providing higher force resistance, induced stress concentration zones at the edges, which occasionally led to premature and irregular failure, especially in the row (weft) direction. The staggered large-circle configuration (LSC) displayed interesting ductile behaviour with multiple load peaks before rupture, suggesting progressive failure mechanisms and partial energy dissipation within the network.

The fracture zones of most samples occurred near the clamping edge, an expected deviation for highly porous textiles like tulle, due to localised stress concentrations and mesh deformation under pressure. This phenomenon was observed consistently across all specimen types and directions, reinforcing the validity of relative comparisons across sample groups.

Force-elongation curves further confirmed these conclusions: control samples exhibited smooth, long curves indicating elastic deformation, while printed samples demonstrated sharper transitions, sudden drops (linked to partial delamination or rupture of the printed layer), and shorter extension paths, consistent with their reduced ductility.

In sum, 3D printing directly on textiles creates a new class of hybrid materials whose mechanical behaviour can be finely tuned by adjusting pattern geometry and orientation. The directionality of the textile plays a crucial role, as the warp (column) direction inherently offers higher stiffness and load-bearing capacity. The study confirms the potential of fused deposition modelling (FDM) to enhance or customise the performance of lightweight fabrics such as tulle, paving the way for applications in wearable technology, smart textiles, and functional garment engineering.

The findings of this study demonstrate that 3D-printed circular patterns can effectively modify the tensile behaviour of lightweight textile substrates such as tulle. The influence of pattern size and arrangement plays a critical role in determining the balance between strength and flexibility.

These results open new perspectives for applications in:

- fashion design, where structural reinforcement can be integrated into garments;
- technical textiles, requiring localised mechanical enhancement;
- wearable technologies, where printed elements can support embedded components;
- medical textiles, including customised orthotic and support systems.

Future work will focus on multi-material printing, adaptive geometries, and the integration of functional elements to further enhance the performance of textile–polymer composite systems.

Future research could explore the use of different filament materials (flexible or conductive), multilayered patterns, or multi-material strategies to optimise both mechanical and functional characteristics in line with specific end-use requirements.

ACKNOWLEDGEMENT

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Using a 3D virtual clothing system to develop bottom patterns for South Korean women in their 40s

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EOM RANI PARK A-MI

ABSTRACT – REZUMAT

Using a 3D virtual clothing system to develop bottom patterns for South Korean women in their 40s

This study aimed to analyse the lower body characteristics of South Korean women in their 40s and propose bottom patterns, such as for skirts or pants, using a 3D virtual clothing system. The lower body characteristics of South Korean women in their 40s were identified by comparing them with those of women in their 20s using the Mollison relational deviation line. The CLO software was employed to examine the bottom fits of South Korean women in their 20s and 40s and to analyse pressure points and clothing pressure. The pattern-drafting method was also suggested for South Korean women in their 40s. South Korean women in their 40s had lower height-related body measurements and larger circumference-related body measurements than South Korean women in their 20s. Therefore, the traditional drafting method of using clothing patterns for skirts and pants, such as using only the body measurements of women in their 40s, leads to inadequate fit. When designing bottom patterns for this demographic, the waist, abdomen, hip area, and hip length must be considered. For pants patterns, the crotch, thigh area, and pants silhouette should also be considered. This study is meaningful in that it analysed virtual clothing fit when designing bottom patterns for South Korean women in their 40s.

Keywords: *middle-aged South Korean women, body characteristics, clothing fit, 3D virtual clothing system, pattern making*

Utilizarea unui sistem virtual de îmbrăcăminte 3D pentru dezvoltarea tiparelor de articole vestimentare pentru partea inferioară a corpului, destinate femeilor sud-coreene în vârstă de 40 de ani

Acest studiu a urmărit analiza caracteristicilor părții inferioare a corpului femeilor sud-coreene în vârstă de 40 de ani și propunerea unor tipare pentru fuste și pantaloni utilizând un sistem virtual de îmbrăcăminte 3D. Caracteristicile părții inferioare a corpului femeilor sud-coreene cu vârsta cuprinsă între 40 și 49 de ani au fost identificate prin compararea acestora cu cele ale femeilor cu vârsta cuprinsă între 20 și 29 de ani, folosind linia de deviere relațională Mollison. Software-ul CLO a fost aplicat pentru a examina potrivirea, punctele de presiune și presiunea exercitată de îmbrăcăminte. Rezultatele au indicat faptul că femeile de 40 de ani prezintă valori mai mici ale dimensiunilor legate de înălțime și circumferințe mai mari decât femeile de 20 de ani. În consecință, utilizarea exclusivă a măsurătorilor corporale în construcția tradițională a tiparelor conduce la o potrivire insuficientă. La proiectarea tiparelor de articole vestimentare pentru partea inferioară a corpului pentru această grupă de vârstă, este necesară luarea în considerare a taliei, abdomenului, zonei șoldurilor și lungimii șoldurilor, iar pentru pantaloni, a zonei inghinale, coapselor și siluetei pantalonilor. Acest studiu este relevant prin faptul că analizează potrivirea virtuală a îmbrăcămintei la proiectarea tiparelor de pantaloni pentru femeile sud-coreene în vârstă de 40 de ani.

Cuvinte-cheie: *femei sud-coreene de vârstă mijlocie, caracteristici corporale, potrivirea îmbrăcămintei, sistem virtual de îmbrăcăminte 3D, construcția tiparelor*

INTRODUCTION

South Korean women often leave the labour market around childbearing age [1], with some re-entering in their 40s after marriage, childbirth, or childrearing. Women in this age group are therefore actively engaged in society. However, these life events and ageing lead to body shape changes, including reduced breast elasticity, back and posture issues, increased abdominal and hip girth, and decreased height, prompting many women to adjust their skirts and pants to fit their current measurements and social roles. The fashion industry has turned to using a 3D virtual clothing system to consider these patterns. This system allows the creation of virtual bodies without the hassle of scanning a body and creating virtual clothing by drafting clothing patterns [2]. As the system can quickly verify creative designs [3], clothing patterns can be modified by examining virtual fitting images [4]. This system can minimise time and financial losses from producing actual clothing samples. Additionally, it can analyse the pressure on clothing, allowing for an objective assessment of the effects of different clothing designs [5–7]. Currently, many women's fashion brands in South Korea plan clothing products that primarily target women in their 20s rather than those in their 30s and older, and their pattern-drafting methods are generally based on the standard body measurements of

women in their 20s. Hence, developing pattern-drafting methods that reflect the body shapes of South Korean women in their 40s while referencing the fit of women in their 20s can help fashion brands produce better-fitting garments. Accordingly, this study used a 3D virtual clothing system to identify the key body-shape characteristics of South Korean women in their 40s and to propose skirt and pants drafting methods suitable for this age group.

RESEARCH METHOD

The body measurement data for South Korean women in their 20s (hereinafter referred to as "the 20s") and South Korean women in their 40s (hereinafter referred to as "the 40s") were obtained from the 8th Size Korea [8], which provides data on the body measurements of South Koreans. Avatars were then modelled using CLO software based on these measurements. To compare body shapes between age groups, the Mollison relational deviation line was employed using the body measurements of the CLO avatars and calculated as shown in the following formula. A previous study [9] has used virtual fitting software, such as Israel's Optitex, Japan's i-Designer, and South Korea's CLO, to model avatars based on body types and compare virtual fitting results with actual garment fitting. The study reported that virtual fittings using normal-body-type avatars in CLO closely approximate real-world fit. Based on this evidence, CLO was used to model avatars and conduct virtual fittings for women in their 20s and 40s.

$$\text{Relational deviation} = (A-B)/C$$

A: Reference group measurement (20s)

B: Comparison group measurement (40s)

C: Reference group standard deviation (women in their 20s)

The CLO software was also used for pattern design and virtual fit analysis. A book on drafting women's clothing patterns was used as a reference for comparative patterns [10]. This reference book, *Industrial Pattern Design*, provides pattern templates for both custom-made and ready-to-wear garments, following pattern-drafting methods commonly used in Korea. The pattern drafting method is shown in table 1. Patterns were drafted from the book using the waist circumference (W) and lower hip circumference (H) of women in their 20s and 40s. In South Korean women in their 20s to 40s, the actual hip length generally exceeds 20.0 cm [8]. However, in Korean pattern drafting practices, this measurement is not directly reflected in the pattern dimensions. Instead, a shorter hip length is often used to create a visually higher hip line and achieve a more aesthetically preferred silhouette. Additionally, in Korea, cases in women's apparel pattern drafting have also been reported in which a fixed hip length of 18.0 cm is applied across all sizes for convenience and consistency [11]. Reflecting these conventions, the present study fixed the hip length at 18.0 cm, following the specifications provided in the pattern reference book. Therefore, while modifying the patterns to improve fit, the hip length was fixed at 18.0 cm in accordance with standard Korean drafting practice. Next, the drafted skirt and pants patterns were applied to avatars representing women in their 20s and 40s to generate virtual garments and conduct virtual fitting simulations. In CLO, virtual garment silhouettes, contact point maps, and clothing pressure vary depending on the specified fabric properties, enabling detailed visual analysis [12]. Because CLO provides highly realistic fit simulations based on fabric characteristics and supports objective visual evaluation, the present study analysed and refined patterns using these three components. By using CLO's "Show Pressure Points" tool, the body's contact areas were identified, and the corresponding points on the garment were marked with blue indicators. This tool highlights regions where the garment touches the avatar, with a greater distribution of contact points indicating reduced fabric flexibility [12]. It allows for visual assessment of garment-to-avatar fit and is particularly useful for comparing multiple pattern variations [13]. In this study, the tool was used to visually evaluate the silhouette and fit of both the comparative and developed patterns. Additionally, the "Stress Map" tool was employed to assess clothing pressure. The virtual fabric chosen for pattern evaluation was "Muslin_28×36", as it is commonly used for experimental garments in real-world fit assessments [14]. The physical characteristics of the muslin provided by CLO are shown in table 2. Clothing pressure was measured at points where the skirt or pants closely contact the body, based on previous studies [15]. Table 3 lists the areas for clothing pressure measurement. In CLO, clothing pressure is visualised with colours, and numerical values are also provided. In previous studies, the same avatar and garment were simulated five times to calculate fabric deformation [16]. Following this approach, in the present study, measurements were performed five times in each area, yielding five numerical values for analysis. This process highlighted considerations for 40s women's bottom patterns. Previous research [17] has shown that garment fit must balance ease: excessive fabric can restrict movement and reduce comfort, while insufficient ease can cause tightness, high-pressure zones, and limited mobility. This principle was therefore applied when adjusting the pattern dimensions to ensure both comfort and proper fit. After pattern adjustments, fit was re-evaluated. Clothing pressure was measured five times per pattern, with the mean and standard deviation calculated and compared using a t-test performed with SPSS Statistics 29.0 software.

RESULTS

Table 4 presents the results of the Mollison relational deviation line analysis. Height-related measurements for women in their 40s ranged from –0.2σ to –0.4σ, generally lower than those of women in their 20s, with low hip height and inseam height showing the

Table 1

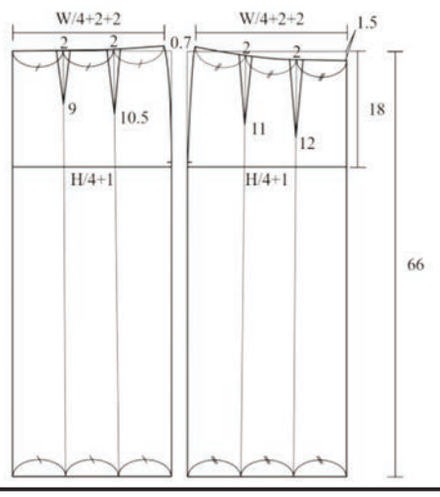
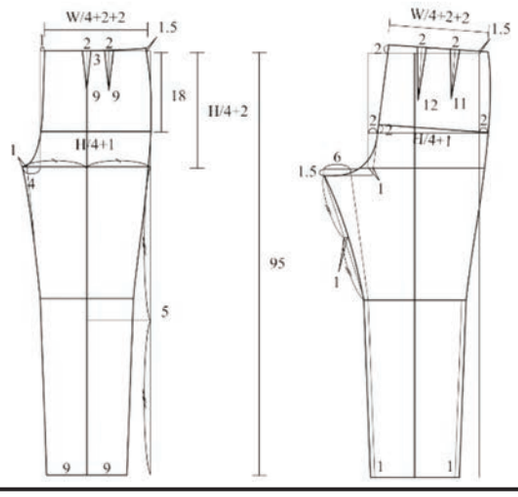
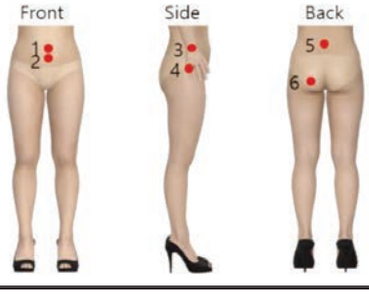
REFERENCE PATTERN DRAFTING METHODS (UNIT: cm)	
Skirt	**Pants**
	

Table 2

PHYSICAL PROPERTIES OF FABRIC IN CLO			
Mechanical properties of fabric	**Value**	**Mechanical properties of fabric**	**Value**
Weft stretch	58.0	Bias bending (right, left)	47.0
Warp stretch	56.0	Internal damping	1.0
Shear stretch (right, left)	18.0	Density	11.0
Weft bending	45.0	Friction	3.0
Warp bending	48.0	Thickness	0.4 mm

Note: No units, except for thickness

Table 3

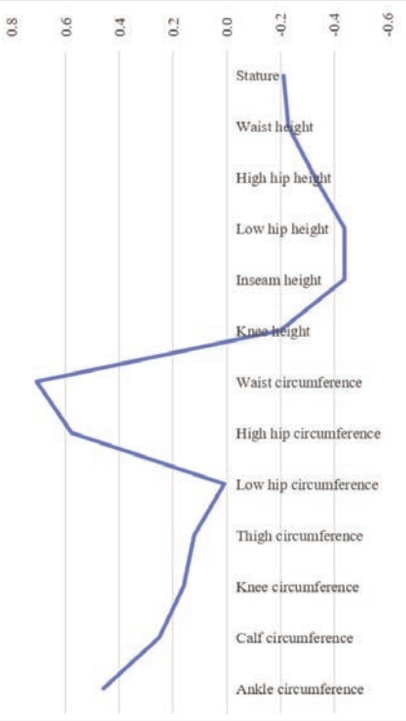
MEASURING POINTS OF CLOTHING PRESSURE		
Measurement point		
1	Front waist	
2	Front abdomen	
3	Side waist	
4	Side hip	
5	Back waist	
6	Back hip	

largest decreases (–0.4σ). Circumference-related measurements ranged from 0.0σ to 0.7σ, indicating larger girths in the 40s group, particularly in the waist (0.7σ), hip (0.6σ), and ankle (0.5σ). The difference between waist and lower hip circumferences was 24.9 cm for women in their 20s and 19.6 cm for women in their 40s, showing that a larger waist in the 40s group reduced the waist–hip differential.

Table 5 presents the results of the contact point analysis from virtual fitting of the comparative skirt patterns. The fit differed between women in their 20s and 40s. The 40s group showed wider contact points around the abdominal area and gaps at the waist due to horizontal wrinkles near the hips. Skirt length was also longer for women in their 40s. Fitting issues in women in their 40s can be attributed to morphological changes identified in the body measurement analysis. Table 4 shows that they had larger waist and high-hip circumferences than women in their 20s. The reduced waist–lower-hip difference indicates a less pronounced waist–hip contour, leading to insufficient skirt anchoring and gaps at the back

Table 4

BODY SIZES OF THE 20s AND 40s (UNIT: cm, σ)

	Item	20s	40s	Mollison relational deviation	Mollison relational deviation line
Height	Stature	162.0	160.9	–0.2	
	Waist height	100.5	99.6	–0.2	
	High hip height	89.2	88.0	–0.3	
	Low hip height	79.1	77.5	–0.4	
	Inseam height	74.2	72.6	–0.4	
	Knee height	43.1	42.7	–0.2	
Circumference	Waist circumference	70.4	75.9	0.7	
	High hip circumference	86.6	90.8	0.6	
	Low hip circumference	95.3	95.5	0.0	
	Thigh circumference	57.3	57.9	0.1	
	Knee circumference	35.5	35.9	0.2	
	Calf circumference	35.0	35.7	0.3	

during virtual fitting. Increased high-hip circumference also concentrates tension around the hips, creating horizontal wrinkles and pushing the garment away from the waistline. These waist gapping and hip wrinkles align with the body shape characteristics identified via the Mollison relational deviation analysis.

Based on these findings, several factors must be considered when drafting skirt patterns for women in their 40s. The 40s group exhibited a back waist area that tended to lift away from the body due to the smaller difference between the waist and lower hip circumferences, tightness around the abdominal area due to a larger waist circumference, wrinkles around the hip area due to fabric tension, and a longer skirt length that made the legs appear shorter.

Accordingly, the pattern was modified as follows: the back waistline was reduced by 0.8 cm to prevent the skirt from lifting away from the body; the front and back waistlines, hip lines, and hemlines were extended by 1.0 cm to provide more room in the abdominal and hip areas; and the skirt length was shortened by 1.0 cm to achieve an appropriate length. Figure 1 shows the revised skirt pattern. Table 6 presents the contact point analysis using virtual fitting on a 40s avatar. The number of contact points decreased overall, and the issues observed in the comparative pattern, including lifting at the back waist, tightness

Table 5

CONTACT POINTS OF THE COMPARATIVE SKIRT FOR THE 20s AND 40s

Front		Side		Back	
20s	40s	20s	40s	20s	40s
					

around the abdomen and hips, and excessive skirt length, were resolved. Table 7 shows that the clothing pressures of the developed skirt pattern were significantly lower than those of the comparative skirt pattern for women in their 40s across all measured areas, indicating improved fit.

Table 8 presents the results of the contact point analysis from virtual fitting of the comparative pants patterns. The fit differed between women in their 20s and 40s. The 40s group showed wider contact points in the abdominal and thigh areas, a tight crotch, and a waistline that appeared steeply sloped from the side view. The pants were longer, creating wrinkles along the legs and a deviated leg silhouette.

Based on these findings, several factors must be considered when drafting pants patterns for women in their 40s. The 40s group exhibited a steeply sloped waistline, tightness in the crotch, pressure in the front thigh area, longer pants length, and a deviated leg silhouette. Accordingly, the pattern was modified as follows: the back waistline was lowered by 1.7 cm to level the waist; the front rise was extended by 0.5 cm, the back rise by 1.0 cm, and the crotch point raised

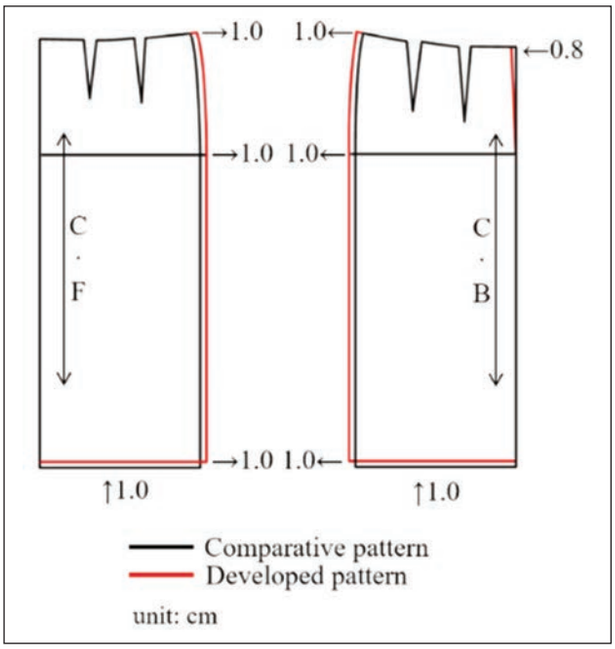


Fig. 1. Overlap of comparative skirt pattern and developed skirt pattern

Table 6

CONTACT POINTS OF THE COMPARATIVE SKIRT AND DEVELOPED SKIRT FOR THE 40s

Front		Side		Back	
Comparative pattern	Developed pattern	Comparative pattern	Developed pattern	Comparative pattern	Developed pattern
					

Table 7

CLOTHING PRESSURE OF COMPARATIVE SKIRT AND DEVELOPED SKIRT FOR THE 40s (UNITS: kPa)

Measurement point	Comparative pattern		Developed pattern		t-value	p-value
	M	S.D	M	S.D		
Front waist	43.6	0.4	30.0	0.0	61.060	0.000
Front abdomen	20.9	0.3	1.6	0.2	89.501	0.000
Side waist	45.7	0.0	4.6	0.0	6164.000	0.000
Side hip	5.5	0.1	1.7	0.4	15.309	0.000
Back waist	37.1	0.0	33.0	1.2	5.628	0.005
Back hip	10.2	0.3	7.4	2.0	4.814	0.009

by 0.5 cm to relieve abdominal and crotch pressure. This adjustment was made because a higher crotch point results in better-fitting pants [18]. The front knee line and hemline were extended by 1.0 cm, the back knee line by 0.5 cm to improve thigh fit, and the pants length was shortened by 1.0 cm to prevent wrinkles. When the lower body circumference is large, extending the knee line and hemline helps improve the fit;

Table 8

CONTACT POINTS OF COMPARATIVE PANTS FOR THE 20s AND 40s

Front		Side		Back	
20s	40s	20s	40s	20s	40s
					

however, unnecessary ease was not added to the back panel to avoid overfitting the front thighs. Additionally, 0.2 cm was added to the mid-hip line between the waistline and hip line to create a more natural line for the back panel's outseam. Figure 2 shows the revised pants pattern. Table 9 presents the contact point analysis using virtual fitting on a 40s avatar. The number of contact points decreased overall, and the issues observed in the comparative pattern were resolved, including a levelled waistline, improved crotch and thigh ease, appropriate length, and an undistorted silhouette. Table 10 shows that the clothing pressures of the developed pattern were generally lower than those of the comparative pants pattern for women in their 40s, indicating improved fit.

CONCLUSIONS

This study aimed to identify bottom patterns suitable for the body shapes of South Korean women in their 40s. Compared with women in their 20s, women in

Table 9

CONTACT POINTS OF COMPARATIVE PANTS AND DEVELOPED PANTS FOR THE 40s

Front		Side		Back	
Comparative pattern	Developed pattern	Comparative pattern	Developed pattern	Comparative pattern	Developed pattern
					

Table 10

CLOTHING PRESSURE OF COMPARATIVE PANTS AND DEVELOPED PANTS FOR THE 40s (UNITS: kPa)

Measurement point	Comparative pattern		Developed pattern		t-value	p-value
	M	S.D	M	S.D		
Front waist	49.0	3.5	36.3	4.4	3.918	0.017
Front abdomen	47.1	0.7	27.1	1.9	17.387	0.000
Side waist	51.4	5.0	35.1	4.3	4.298	0.013
Side hip	24.3	3.4	24.3	3.4	0.000	1.000
Back waist	41.4	2.8	39.4	0.2	1.173	0.360
Back hip	13.5	2.8	7.4	0.1	3.786	0.063

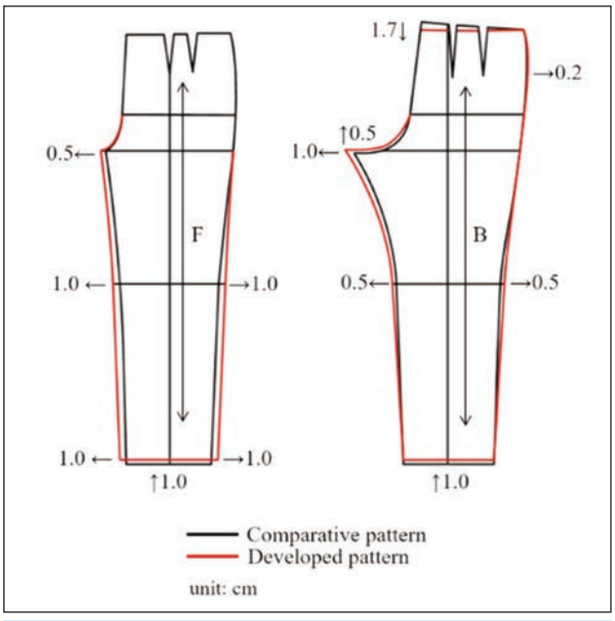


Fig. 2. Overlap of comparative pants pattern and developed pants pattern

their 40s had lower height-related measurements and larger circumference-related measurements, which can result in inadequate fit if traditional drafting methods are applied. Based on these findings, it is proposed that skirt patterns be adjusted by reducing the back waist panel to prevent lifting, adding ease along the side seams to relieve abdominal pressure and prevent hip-area wrinkles, and shortening the length to avoid disproportionate proportions. For pants, it is proposed that the back waistline be lowered to prevent lifting, the crotch and thigh areas be widened to relieve tightness, and the length be shortened to maintain proper proportions and prevent wrinkles, ensuring a straight silhouette from waist to ankle. This study is limited in that all analyses were based on a single average avatar and virtual simulations, and the hip length was fixed during pattern design; physical prototyping and human fitting are needed to confirm real-world validity. Using one representative body form also cannot capture the diversity of somatotypes among women in their 40s, so future research should develop and evaluate pattern blocks for multiple body-shape groups.

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The impact of equity structure on technological innovation efficiency in China's listed textile firms

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ABSTRACT – REZUMAT

The impact of equity structure on technological innovation efficiency in China's listed textile firms

Technological innovation efficiency is a pivotal metric for assessing a firm's innovation capability, and equity structure is a key determinant shaping it. This study investigates this relationship within China's listed textile sector (Shanghai and Shenzhen A-share markets, 2013–2024). To isolate the true managerial performance, we employ an integrated three-stage Data Envelopment Analysis (DEA) model that purges the effects of external environmental factors and statistical noise. Subsequently, a Tobit regression is used to test the impacts of distinct equity governance mechanisms. The main findings are: (1) External environmental factors significantly inflate initial efficiency measurements; after purification, the overall decline is primarily driven by reduced pure technical efficiency, highlighting managerial practices as the critical bottleneck. (2) The adjustment reveals divergent paths: state-shareholding firms show improved efficiency mainly through scale efficiency, whereas non-state-shareholding firms exhibit a decline due to deficiencies in pure technical efficiency. (3) Regarding equity structure, ownership concentration, equity checks and balances, and institutional ownership all significantly promote technological innovation efficiency. In contrast, the mere presence of state shareholding exerts no statistically significant direct effect. These findings underscore that internal governance mechanisms, rather than ownership labels, are decisive for driving innovation efficiency in traditional manufacturing industries transforming.

Keywords: *technological innovation efficiency, equity structure, corporate governance, textile industry, listed companies, three-stage DEA, Tobit model*

Impactul structurii capitalului propriu asupra eficienței inovării tehnologice în cadrul companiilor textile cotate la bursă din China

Eficiența inovării tehnologice reprezintă un indicator esențial pentru evaluarea capacității de inovare a unei întreprinderi, iar structura capitalului propriu este un factor determinant cheie care o modelează. Prezentul studiu analizează această relație în cadrul sectorului textil cotat la bursă din China (piețele de acțiuni de tip A din Shanghai și Shenzhen, perioada 2013–2024). Pentru a izola performanța managerială reală, a fost utilizat un model integrat de Data Envelopment Analysis (DEA) în trei etape, care elimină efectele factorilor de mediu externi și ale zgomotului statistic. Ulterior, se utilizează o regresie Tobit pentru a testa impactul diferitelor mecanisme de guvernanță a capitalului propriu. Principalele concluzii sunt: (1) Factorii de mediu externi umflă în mod semnificativ măsurătorile inițiale ale eficienței; după eliminare, scăderea generală este determinată în principal de reducerea eficienței tehnice pure, ceea ce evidențiază practicile manageriale ca fiind principalul obstacol. (2) Ajustarea relevă traiectorii divergente: întreprinderile cu capital de stat prezintă o eficiență îmbunătățită în principal prin eficiența de scară, în timp ce întreprinderile fără capital de stat înregistrează o scădere din cauza deficiențelor în ceea ce privește eficiența tehnică pură. (3) În ceea ce privește structura capitalului propriu, concentrarea proprietății, mecanismele de control și echilibrul acționariatului, precum și deținerea instituțională, acestea promovează în mod semnificativ eficiența inovării tehnologice. În schimb, simpla prezență a acționariatului de stat nu exercită niciun efect direct semnificativ din punct de vedere statistic. Aceste concluzii subliniază faptul că mecanismele interne de guvernanță, mai degrabă decât etichetele de proprietate, sunt decisive pentru stimularea eficienței inovării în industriile manufacturiere tradiționale aflate în plin proces de transformare.

Cuvinte-cheie*: eficiența inovării tehnologice, structura capitalului propriu, guvernanța corporativă, industria textilă, societăți cotate la bursă, DEA în trei etape, modelul Tobit*

INTRODUCTION

China's textile industry, a cornerstone of the national economy, stands at a critical juncture. After decades of rapid expansion fueled by labour-cost advantages, the sector now grapples with the erosion of the "demographic dividend" and rising production costs [1], prompting the relocation of many firms to Southeast Asia. To sustain competitiveness, the industry must transition from factor-driven growth to innovation-led development, a strategic priority underscored by the 2024 Government Work Report and the Action Outline for the Construction of a Modern Textile Industry System (2022–2035).

In the knowledge-based economy, technological innovation efficiency, reflecting a firm's capability to transform R&D inputs into valuable outputs, has become pivotal for maintaining competitive advantage. However, innovation is inherently characterised by long cycles, high risk, and substantial investment, making it particularly susceptible to principal-agent problems arising from the separation of ownership and control [2]. As a fundamental element of corporate governance, equity structure directly shapes incentive alignments and agency costs, thereby critically influencing managerial decisions on innovation resource allocation [3]. Understanding this nexus is essential for unlocking the innovation potential within traditional manufacturing sectors like textiles.

Extant literature offers valuable insights yet remains inconclusive. Debates persist regarding the impact of ownership concentration [4], the moderating role of ownership checks and balances [5], the influence of institutional investors [6], and the effect of state shareholding [7]. Furthermore, a significant methodological gap exists: many studies measuring innovation efficiency fail to adequately account for external environmental factors and statistical noise, potentially leading to biased estimations. This study aims to address these gaps by investigating how equity structure affects the true technological innovation efficiency of China's listed textile firms, after rigorously purging the influence of the operating environment.

To achieve this objective, we employ an integrated empirical framework. First, we apply a three-stage Data Envelopment Analysis (DEA) model to a sample of 60 A-share listed textile companies (2013–2024) to derive innovation efficiency scores net of environmental and random disturbances. Subsequently, we use a Tobit regression model to test our hypotheses concerning the relationships between key equity structure variables, concentration, balance, institutional ownership, and state shareholding, and the adjusted innovation efficiency.

The remainder of this paper is structured as follows. The 2nd section reviews the relevant literature and formally develops the research hypotheses. The 3rd section details the research design, including the specification of the three-stage DEA and Tobit models, variable definitions, and data sources. The 4th section presents the empirical results, comprising the efficiency analysis and regression findings, followed by robustness checks. The 5th section provides an in-depth discussion, comparing the results with existing literature and elucidating the study's theoretical contributions and practical implications. Finally, the 6th section concludes by summarising the key findings, synthesising the managerial and policy insights, and outlining limitations and future research directions. An overview of the entire research framework is visually presented in figure 1 to guide the reader.

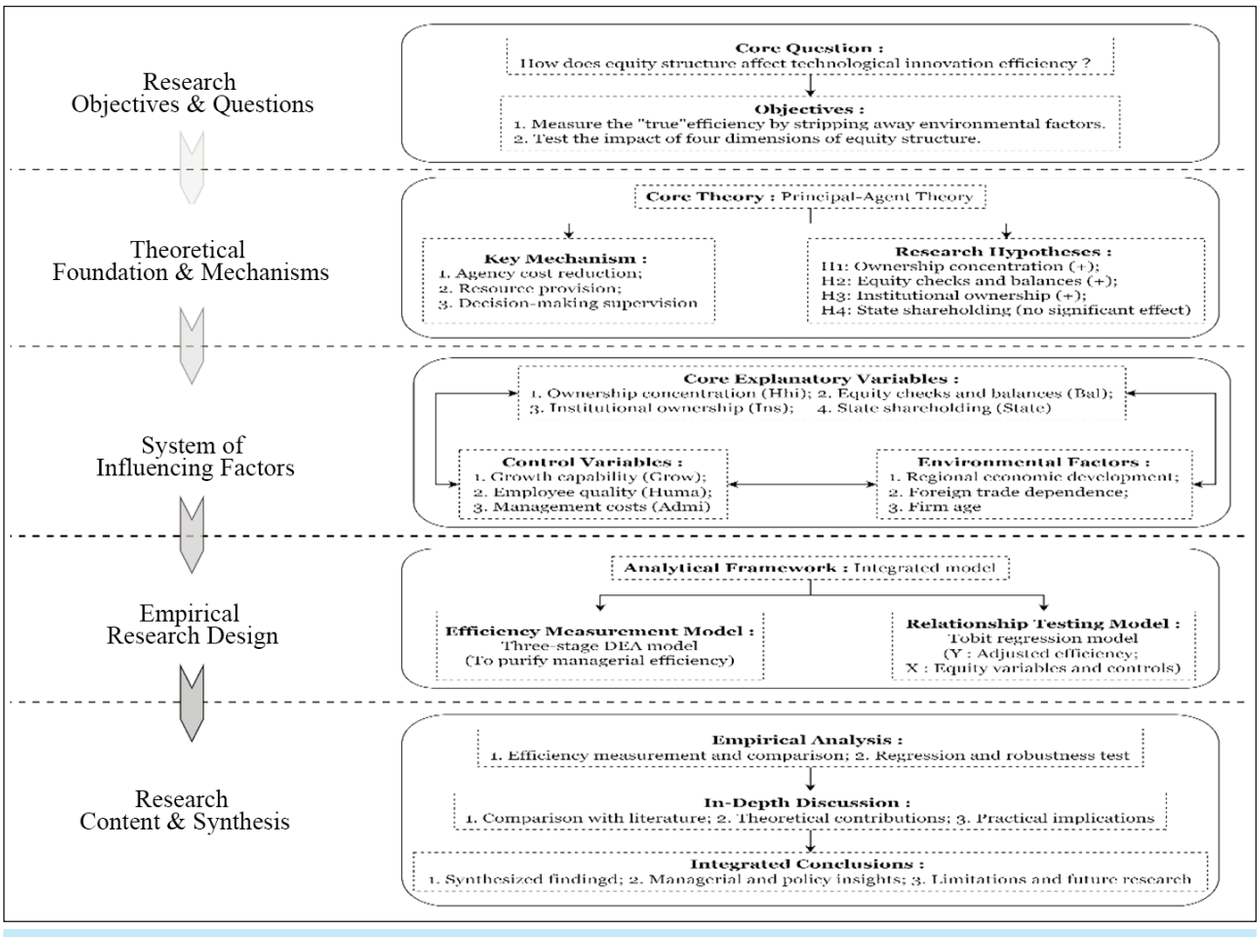


Fig. 1. Research framework

The schematic outlines the conceptual and analytical framework developed for this study.

LITERATURE REVIEW

Technological innovation is the cornerstone for the transformation and upgrading of traditional manufacturing industries. For China's textile sector, which is grappling with the loss of the demographic dividend and rising global competition, improving innovation efficiency is not merely a strategic choice but a necessity for survival and high-quality development [8, 9]. Recent studies continue to highlight the generally low level of green technology [8] and overall technological innovation efficiency [10] within the industry, underscoring the persistent urgency of this issue. At the micro-firm level, innovation efficiency is fundamentally shaped by corporate governance structures, with equity arrangement being a primary determinant [11]. The principal-agent conflict arising from the separation of ownership and management remains a central theoretical lens for understanding innovation decisions [12]. Equity structure influences the intensity of these conflicts and the consequent allocation of resources to long-term, high-risk innovative activities. However, empirical findings on the nature of these relationships are mixed and context-dependent, warranting a focused examination within the specific institutional and industrial setting of China's textile sector.

Ownership concentration and innovation efficiency: a contingent relationship

The impact of ownership concentration on innovation is theoretically ambiguous and empirically contested. Concentrated ownership can mitigate Type I agency problems (manager-shareholder) by enhancing monitoring and aligning interests, potentially fostering a long-term orientation conducive to innovation [13]. Conversely, excessive concentration may lead to Type II agency problems (controlling vs. minority shareholders), where the controlling shareholder expropriates resources or avoids risky innovation to secure private benefits [14].

Recent studies reflect this complexity. Some find a negative or inhibitory effect, suggesting that highly concentrated control may stifle innovation by limiting managerial discretion and promoting risk aversion [10, 15]. Others propose a non-linear, inverted U-shaped relationship, where moderate concentration is optimal [16]. This study posits that, given the relatively dispersed ownership structure prevalent among many listed textile firms in China [10], a higher degree of concentration in the current stage may help overcome managerial short-termism and provide the stable oversight needed for sustained R&D investment. Therefore, we hypothesise that in the context of China's textile industry:

H1: Ownership concentration is positively correlated with technological innovation efficiency.

The governance role of equity checks and balances and institutional investors

Beyond the largest shareholder, the distribution of power among other major shareholders and equity checks and balances plays a critical governance role. A balanced equity structure can restrain the controlling shareholder's self-serving behaviour, protect minority interests, and encourage more transparent, value-maximising decisions, including innovation [17, 18]. Recent evidence strongly supports this view, showing that equity restriction mechanisms significantly promote innovation quality and efficiency by incentivising R&D investment and improving decision-making processes [17, 19].

Institutional investors, with their professional expertise and monitoring capabilities, represent another key governance force. Their involvement can reduce information asymmetry, alleviate managerial myopia, and provide essential resources for innovation [20]. Studies confirm that institutional shareholding, particularly by long-term and independent institutions, improves corporate innovation quality and efficiency through enhanced supervision and resource provision [20, 21]. This is especially relevant for traditional industries like textiles seeking external expertise for upgrading. Thus, we propose:

H2: Equity checks and balances promote technological innovation efficiency in textile enterprises.

H3: Institutional ownership helps improve technological innovation efficiency in textile enterprises.

The evolving role of state shareholding

The impact of state shareholding on innovation is profoundly shaped by institutional transitions. While early literature often highlighted the inefficiencies and political burdens associated with state-shareholding enterprises (SOEs), the ongoing mixed-ownership reform in China has reconfigured this relationship [22]. State shareholding can facilitate access to critical resources, policy support, and long-term capital for innovation, especially in strategic sectors [23]. However, it may also introduce non-commercial objectives and bureaucratic inertia.

Contemporary research suggests that the net effect is increasingly nuanced and may be non-significant in competitive markets. The positive effects of state shareholding are often conditional or mediated by other governance improvements, such as the introduction of heterogeneous blockholders [22] or equity diversification [11]. In the textile industry, which is highly market-oriented, the potential advantages of state backing (e.g., subsidies) may be offset by governance rigidities [8]. Consequently, we expect that in the current market environment:

H4: State shareholding has no significant impact on the technological innovation efficiency of textile enterprises.

Table 1

VARIABLE DESCRIPTION FOR THE THREE-STAGE DEA MODEL			
Category		**Name (unit)**	**Calculation method**
Inputs	Productive	Fixed assets (CNY)	Book value of fixed assets
		Total employees (Persons)	Number of employees at year-end
	Operational	Operating costs (CNY)	Total operating costs
		Accounts receivable (CNY)	Book value of accounts receivable
	R&D	R&D expenditure (CNY)	Total R&D expenditure capitalised and expensed
Outputs	Profitable	Net profit (CNY)	Net profit for the fiscal year
		Operating income (CNY)	Total operating revenue
	Technical	Intangible assets (CNY)	Book value of intangible assets
Environment variables	Internal factors	Shareholding ratio of the largest shareholders (%)	Percentage of shares held by the largest shareholder
		Firm age (Years)	(Observation year – establishment year) + 1
	External factors	Regional GDP per capita (CNY)	GDP per capita of the province where the company is registered
		Regional trade dependence (%)	(Total imports + exports) / GDP of the Company's region

Note: Variable definitions are constructed based on the innovation input-output framework and prior studies [10]. Data sources for these variables are detailed in the 3rd section.

Methodological advancements: isolating managerial efficiency

Accurately measuring technological innovation efficiency is crucial for valid inference. Traditional single-stage DEA models are often criticised for conflating managerial inefficiency with the effects of external environmental factors and statistical noise. The three-stage DEA model addresses this by using Stochastic Frontier Analysis (SFA) to strip away these exogenous influences, yielding a purer measure of managerial performance [24]. This method has gained traction in efficiency analysis across sectors, including energy [25] and, pertinently, textile innovation [10]. Its application ensures that the subsequently analysed relationship between equity structure and innovation efficiency is not confounded by regional disparities, macroeconomic conditions, or random shocks.

Synthesis and research positioning

In summary, while the literature establishes a clear link between equity governance and innovation, the specific mechanisms and outcomes within China's textile industry require further empirical clarification. Recent studies provide updated evidence and more sophisticated methodological tools. This study aims to contribute by: (1) applying the rigorous three-stage DEA model to isolate the true innovation efficiency of listed textile firms; and (2) employing a Tobit regression analysis to empirically test the four hypotheses concerning equity structure, thereby providing contemporary evidence grounded in the industry's specific context.

RESEARCH DESIGN

Three-stage DEA model variables

This study focuses on the micro-level technological innovation efficiency of enterprises. Inputs are categorised into productive inputs, operational inputs, and R&D inputs. Outputs are similarly divided into profit-oriented outputs and technology-oriented outputs. Under the premise of satisfying the "separability assumption", environmental influencing factors were selected from both internal and external aspects. A detailed description of each indicator is provided in table 1.

Tobit model and its variables

Technological innovation is characterised by long cycles, substantial investment, and high risk, resulting in a lagged effect of R&D investment. To capture this dynamic, we construct a one-period lagged Tobit model (Model 1), with the three-stage DEA-measured innovation efficiency of listed textile firms as the dependent variable and its one-period lagged value as an independent variable. To validate the suitability of the explanatory and control variables, using ownership concentration as an example, two additional Tobit models (Models 2 and 3) are established. Based on the validation outcomes from these models, we formulate the final multivariate linear regression Tobit model with a one-period lagged dependent variable (Model 4). β_1^T

$$Effect_{it} = \beta_0 + \beta_1^T Effect_{it-1} + \varepsilon_{it} \quad (1)$$

$$Effect_{it} = \beta_0 + \beta_1^T Effect_{it-1} + \beta_2^T Hhi_{it} + \varepsilon_{it} \quad (2)$$

$$Effect_{it} = \beta_0 + \beta_1^T Effect_{it-1} + \beta_2^T Hhi_{it} + \\ + \beta_m^T Controls_{it} + \varepsilon_{it} \quad (3)$$

Table 2

VARIABLE DEFINITIONS FOR THE TOBIT MODEL			
Type	**Name**	**Symbol**	**Measurement / Definition**
Dependent variable	Technological innovation efficiency	Effect	Efficiency score derived from the three-stage DEA model
Independent variables	Ownership concentration	Hhi	Sum of the squared shareholding of the top five shareholders
	Equity checks and balances	Bal	Sum of shareholding percentages of the 2ndto the10th largest shareholders
	Institutional ownership	Ins	Total shareholding percentage of funds, brokers, insurers and QFIIs
	State shareholding (Dummy)	state	A dummy variable that equals 1 if the firm has state-owned shareholders, and 0 otherwise
Control variables	Growth capability	Grow	Year-on-year growth rate of operating revenue
	Employee quality	Huma	Percentage of employees with a college degree or above
	Management costs	Admi	Ratio of administrative expenses to total operating revenue

Note: See table 1 for input-output variable definitions. The construction of governance and control variables follows common practices in corporate finance literature. Data sources are provided in the 3rd section.

$$Effect_{it} = \beta_0 + \beta_1^T Effect_{it-1} + \beta_n^T Explanation_{it} + \\ + \beta_m^T Controls_{it} + \varepsilon_{it} \quad (4)$$

This study primarily examines the impact of equity structure on technological innovation efficiency from the perspective of internal corporate governance. The explanatory and control variables are as detailed in table 2.

Data sources and processing

This study focuses on listed companies in the textile industry in the Shanghai and Shenzhen A-share markets from 2013 to 2024. This period was selected to capture the dynamic changes in the technological innovation efficiency of the textile industry amid the disappearance of the "demographic dividend" and evolving global economic conditions. Despite the limited sample size, we believe that the data from this period accurately reflect the technological innovation efficiency of the listed companies in the textile industry. After the screening process, we identified 60 sample companies that met the criteria. Input and output indicator data are sourced from the Choice database, whereas data on environmental variables came from the annual reports of listed companies, the National Bureau of Statistics, and the statistical bureau websites of various provinces. Data processing for the three-stage DEA model was conducted using DEAP 2.1 and Frontier 4.1, whereas processing for the Tobit model was performed using Stata 17.0.

EMPIRICAL RESULTS

Three-stage DEA model results

Prior to applying the three-stage DEA model, we conducted a statistical description and Pearson correlation test on the model indicators. The tests confirmed that all indicators meet the required criteria, allowing further construction of the DEA model.

Using DEAP 2.1 and the DEA-BCC model, comprehensive efficiency (TE), pure technical efficiency (PTE), and scale efficiency (SE) were calculated for the 60 listed companies in the textile industry for each year. The annual industry average values were calculated, and the efficiency values from the first-stage DEA-BCC model are presented in figure 2, *a*. Using the adjusted input variables from the second stage alongside the original output variable data, the DEA-BCC model was reapplied to recalculate TE, PTE, and SE for listed companies in the textile industry, excluding environmental factors. The results are presented in figure 2, *b*.

Based on the results presented in figure 2, *a* and *b*, the following conclusions can be drawn.

Technological innovation efficiency is a comprehensive indicator reflecting a firm's ability to utilise and transform relevant resources. From 2013 to 2024, the TE of listed textile companies averaged 0.9, showing a fluctuating downward trend. The PTE ranged between 0.899 and 0.957, with an overall mean of 0.928, while SE fluctuated between 0.925 and 0.989, averaging 0.968, indicating that SE values were generally higher than PTE. Companies with state shareholding had an average innovation efficiency of 0.893, compared to 0.902 for those without, suggesting no significant difference in TE, PTE, or SE between the two, preliminarily supporting the hypothesis that state shareholding does not significantly affect innovation efficiency in this sector. However, as these initial results included the influence of random noise and environmental factors, a second-stage SFA was employed to mitigate these exogenous influences. After adjustment, the TE, PTE, and SE all decreased compared to the first-stage results, indicating that innovation efficiency had been previously overestimated due to external environmental factors. During 2013–2024, the TE fluctuated between 0.845 and 0.96, generally declining after an initial upward trend. The TE peaked in 2016,

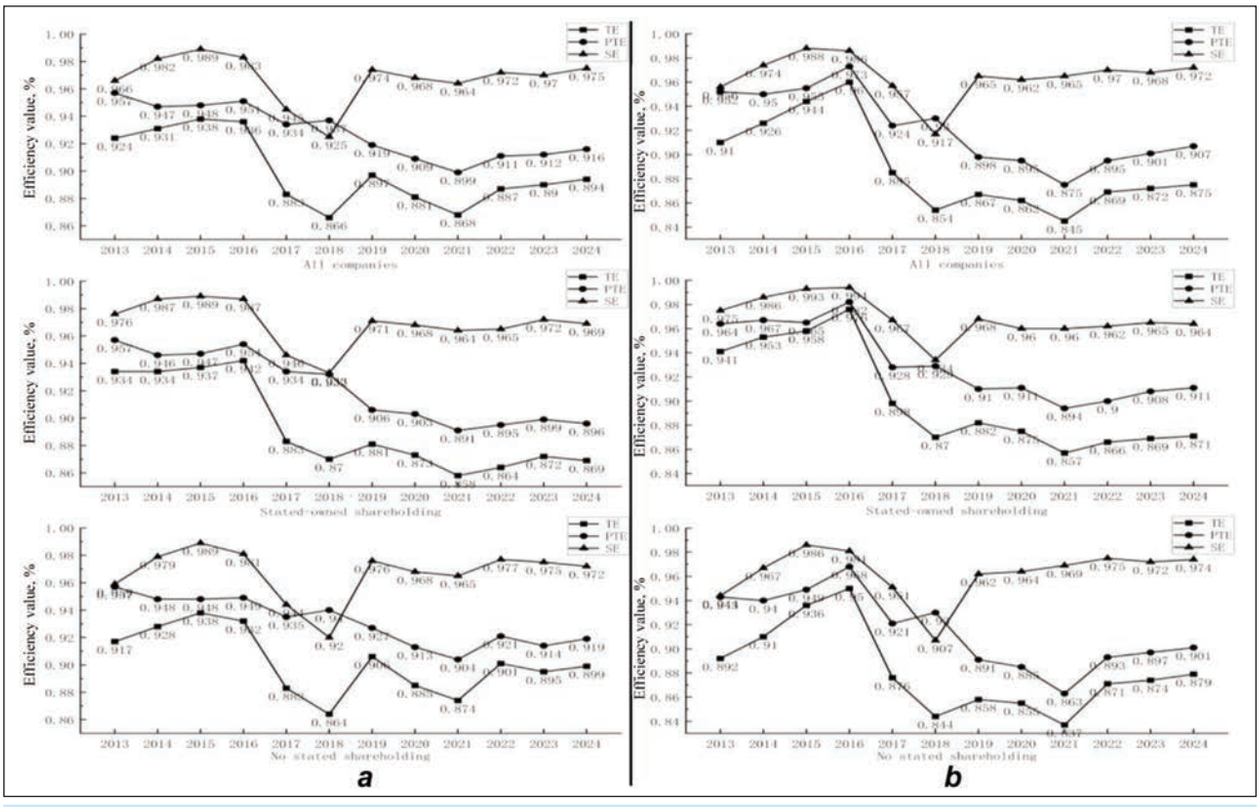


Fig. 2. Average technological innovation efficiency over the years:
a – the first-stage DEA-BCC model; *b* – the second-stage DEA-BCC model

later declining due to national supply-side reforms and Sino-U.S. trade disputes, rebounded briefly in 2018, and fell again during the COVID-19 pandemic. After controlling for environmental factors, innovation efficiency in firms with state shareholding improved, primarily driven by increased SE, with a slight rise in PTE, suggesting that adverse external conditions had previously constrained their efficiency. In contrast, firms without state shareholding showed a significant decline in innovation efficiency, mainly due to reduced PTE, indicating that their efficiency had been overestimated before environmental adjustments.

Tobit model results

Descriptive statistics were obtained for each explanatory variable included in the Tobit model. To avoid multicollinearity, testing revealed that the variance inflation factor (VIF) values for all explanatory variables are less than 5, confirming the absence of multicollinearity in the model, which does not affect the accuracy of the regression results.

In the Tobit model analysis, Model (1) is used to verify the effect of one-period lagged technological innovation efficiency on current technological innovation efficiency. Models (2) and (3) are used to test the suitability of the explanatory and control variables in the Tobit model with a one-period lagged dependent variable, using ownership concentration as the explanatory variable example.

From table 3, it can be seen that Model (1) provides strong evidence that one-period lagged technological innovation efficiency has a positive impact on current technological innovation efficiency. This finding indicates that the technological innovation of listed

Table 3

REGRESSION RESULTS OF MODELS (1), (2), AND (3)

Variable	Hhi	Effect$_{it-1}$	Grow	Huma	Admi	_cons	Sigma_U	Sigma_E	N	Rho
Model (1)		0.815*** (15.907)				18.227*** (3.931)	4.207*** (5.403)	7.677*** (25.821)	660	0.231
Model (2)	0.125*** (2.677)	0.781*** (15.137)				19.069*** (4.230)	4.666*** (5.737)	7.533*** (25.593)	660	0.277
Model (3)	0.122** (2.630)	0.756*** (14.949)	0.032* (1.771)	0.075** (2.539)	–0.388** (–2.416)	22.271*** (4.604)	4.648*** (5.847)	7.408*** (25.522)	660	0.282

Note: Regression results are based on the authors' calculations using Tobit models. Data sources are provided in the 3rd section. ***, **, and * indicate that the model regression coefficients are significant at the 1%, 5%, and 10% significance levels, respectively. Z values corresponding to the regression coefficients are in parentheses.

companies in the textile industry has a lag effect and that the lag of the dependent variable should be considered when constructing the Tobit multivariate linear model. Moreover, the regression results from Models (2) and (3), which include a one-period lagged dependent variable, show that both explanatory and control variables are significant. This suggests that the Tobit model established in this paper, which includes a one-period lagged dependent variable, is robust and can effectively explain the factors affecting technological innovation efficiency.

By constructing a Tobit multivariate linear regression model with a one-period lagged dependent variable, this work explores the impact of equity structure on corporate technological innovation efficiency. This study controls for growth capability, employee quality, and management costs. The model's regression results are presented in table 4.

Based on the empirical results, ownership concentration, equity checks and balances, and institutional ownership all demonstrate significant positive effects on the technological innovation efficiency of listed textile companies, supporting H1, H2, and H3. Higher ownership concentration helps alleviate principal-agent conflicts, incentivises firms to increase R&D investment, and positively impacts innovation efficiency. This conclusion reflects that, among the sampled textile firms, moderate ownership concentration effectively mitigates agency conflicts between shareholders and management, creating a stable environment conducive to long-term R&D investment. This finding resonates with recent studies suggesting that ownership concentration can exert a positive monitoring effect under specific circumstances [10, 16]. Stronger equity checks and balances can constrain the controlling power of the largest shareholder and mitigate conflicts of interest among shareholders, thereby enhancing innovation efficiency. This suggests that effective oversight by other major shareholders over the controlling shareholder can curb potential expropriation behaviours and safeguard corporate resources allocated for innovation. This finding aligns with the current literature asserting that equity constraints can improve innovation quality by strengthening corporate governance [17, 19].

Moreover, Institutional investors further promote corporate innovation by providing financial support, professional expertise, and market-oriented strategic guidance–particularly valuable for traditional manufacturing sectors like textiles, which rely on innovation-driven transformation and upgrading. Recent studies also highlight the dual role of institutional

Table 4

REGRESSION RESULTS OF MODEL (4)

Variable	Model (4-1)	Model (4-2)	Model (4-3)	Model (4-4)	Model (4-5)	Model (4-6)
Hhi	0.122** (2.630)	0.122** (2.635)				
Hhi×State		–0.009 (–0.151)				
Bal			0.116** (2.726)	0.123*** (2.844)		
Bal×State				–0.051 (–1.415)		
Ins					0.262** (2.095)	0.264** (2.112)
Ins×State						–0.041 (–1.137)
$Effect_{it-1}$	0.756*** (14.949)	0.757*** (14.916)	0.772*** (15.562)	0.773*** (15.657)	0.790*** (15.624)	0.793*** (15.708)
Grow	0.032* (1.771)	0.032* (1.758)	0.028 (1.513)	0.026 (1.450)	0.026 (1.377)	0.025 (1.337)
Huma	0.075** (2.539)	0.076** (2.540)	0.076** (2.644)	0.079*** (2.726)	0.066** (2.293)	0.068** (2.356)
Admi	–0.388** (–2.416)	–0.391** (–2.417)	–0.413** (–2.621)	–0.429*** (–2.724)	–0.405** (–2.545)	–0.416** (–2.623)
_cons	22.271*** (4.604)	22.277*** (4.606)	20.077*** (4.162)	20.278*** (4.242)	21.232*** (4.202)	21.385*** (4.254)
Sigma_U	4.648*** (5.847)	4.640*** (5.826)	4.159*** (5.569)	4.222*** (5.640)	4.128*** (5.345)	4.154*** (5.389)
Sigma_E	7.408*** (25.522)	7.408*** (25.520)	7.484*** (25.771)	7.459*** (25.777)	7.524*** (25.700)	7.510*** (25.713)
N	660	660	660	660	660	660
Rho	0.282	0.282	0.236	0.243	0.231	0.234

Note: Data sources and variable symbols are consistent with those described in table 3.

investors in enhancing corporate innovation quality through both governance oversight and resource provision [20, 21].

In contrast, state shareholding shows no statistically significant impact on technological innovation efficiency, which aligns with H4. Although state involvement may offer advantages such as policy support and resource allocation, it may also introduce social responsibilities and administrative burdens that offset potential innovation benefits. This, to some extent, corroborates the academic observation that, under the current context of mixed-ownership reform, the direct impact of ownership type itself has become increasingly complex [11, 22]. Additionally, other control variables, including growth capability and employee quality, show positive correlations with innovation efficiency, whereas management costs exhibit a significant negative relationship. This suggests that stronger development capacity, higher human capital, and reduced administrative friction all contribute to enhanced innovation performance.

Robustness tests

To enhance the reliability of the empirical findings, this study conducted the following robustness checks: (1) Sample period adjustment. To mitigate potential short-term effects from the 2019 U.S.–China trade friction and the 2020 COVID-19 pandemic, the model was re-estimated by excluding data from 2019, 2020, or both. The results show that the coefficients and significance levels of the core equity structure variables remain consistent with the baseline model. (2) Subsample analysis. Considering regional disparities in economic development and policy support, firms headquartered in central and western regions were excluded. Regression results using the subsample of firms from the eastern region confirm the stability of the key explanatory variables in both sign and statistical significance. (3) Sensitivity analysis. The robustness of the main explanatory variable – ownership concentration (Hhi) – was tested by applying a ±10% variation to its measurement. Additional checks include altering model specifications by introducing or omitting other potential control variables, such as firm size and market competition intensity. The positive relationship between ownership concentration and technological innovation efficiency remained robust throughout these tests.

DISCUSSION

This section provides a comprehensive interpretation of the empirical findings, positioning them within the broader scholarly conversation on corporate governance and innovation. We first compare and contrast our results with existing literature, then elucidate the specific theoretical contributions of this study, and finally summarise its practical implications, which are detailed in the subsequent chapter.

Comparative analysis with existing literature

Our findings offer nuanced confirmations and extensions to the ongoing debate on how equity structure shapes corporate innovation.

Regarding ownership concentration, our results demonstrate a significant positive linear relationship with technological innovation efficiency. This aligns with the view that concentrated ownership can mitigate Type I agency problems by enhancing monitoring and incentivising long-term R&D investment [13]. However, it appears to contrast with studies proposing an inverted U-shaped relationship [16], where excessive concentration becomes detrimental. This divergence may be context-specific. For the listed textile firms in our sample, characterised by relatively dispersed ownership and facing intense transformation pressure, a higher degree of concentration may not yet have reached the threshold where entrenchment and expropriation (Type II agency problems) outweigh its monitoring benefits. Thus, our finding likely captures the upward-sloping segment of the curve, highlighting that the optimal ownership structure is contingent on industry dynamics and initial governance conditions.

Concerning equity checks and balances and institutional ownership, our results strongly corroborate recent empirical work. The positive effect of equity checks and balances supports the argument that restraining the controlling shareholder's power protects innovation resources and fosters more balanced decision-making [17, 19]. Similarly, the positive role of institutional ownership resonates with literature emphasising their dual function of providing superior monitoring and valuable external resources, which are particularly crucial for innovation in traditional industries [20, 21]. Our study reinforces that these governance mechanisms are effective not only in high-tech sectors but also in traditional manufacturing like textiles, where upgrading depends critically on efficient resource use and external knowledge.

The most striking finding pertains to state shareholding. The statistically insignificant coefficient for State aligns with an emerging strand of literature that questions the deterministic role of formal ownership type in a competitive market [7, 22]. While traditional views posited clear advantages (e.g., resource access) or disadvantages (e.g., bureaucratic inertia) for state-shareholding enterprises, our result suggests a more complex reality shaped by China's mixed-ownership reforms. The insignificance may indicate that the presence of state capital is less impactful than the governance quality and commercial orientation it is embedded within. Potential benefits (e.g., policy support) and costs (e.g., social objectives) may offset each other, making internal governance mechanisms like ownership concentration and equity checks and balances more salient determinants of innovation efficiency. This finding shifts the focus from a binary "state vs. private" debate to a more granular analysis of governance arrangements within different ownership forms.

Theoretical contributions

This study makes several distinct contributions to the theoretical discourse on corporate governance and innovation.

First, it advances methodological rigour in measuring the dependent variable. By employing the three-stage DEA model to purge environmental and statistical noise from the innovation efficiency scores, we provide a cleaner test of governance theories. Much of the prior ambiguity in the literature may stem from the conflation of managerial inefficiency with external factors. Our approach isolates the "managerial" component of efficiency, thereby offering a more precise estimate of how internal governance mechanisms, such as equity structure, actually influence a firm's capacity to transform inputs into innovative outputs.

Second, it contextualises and enriches principal-agent and resource-based theories. The results demonstrate that classic agency theory retains strong explanatory power in a traditional industry setting, but its manifestations are nuanced. The positive effects of both ownership concentration (addressing manager-shareholder conflicts) and equity checks and balances (addressing shareholder-shareholder conflicts) confirm the multi-faceted nature of agency problems in innovation. Furthermore, the positive role of institutional ownership integrates the resource-based view, highlighting that certain shareholders are not just monitors but also vital sources of information and expertise. Our study thus presents a more integrated theoretical framework where governance structures simultaneously mitigate agency costs and facilitate resource provision to drive innovation efficiency.

Third, it deepens the understanding of ownership reform in transitional economies. The non-significant finding for state shareholding, coupled with the significant results for other governance variables, contributes to the literature on China's mixed-ownership reforms. It suggests that reform efforts should look beyond mere changes in ownership labels and focus intensively on cultivating high-quality, professional, and balanced internal governance mechanisms. The theoretical implication is that governance quality mediates the relationship between ownership type and firm outcomes like innovation.

Implications for practice

The findings translate into clear directives for corporate managers, investors, and policymakers, which are elaborated in detail in the 6th section. In essence, they collectively argue for a shift in focus:

For boards and controlling shareholders. Prioritise the construction of an effective internal equity governance mix, balancing appropriate concentration with checks and balances and attracting long-term institutional investors, over reliance on ownership type alone.

For policymakers. Design support mechanisms that incentivise good internal governance practices and innovation management efficiency, rather than favouring firms based solely on ownership. Fostering industry-level collaborative platforms can help diffuse best practices, especially among non-state-shareholding firms.

This discussion synthesises how our context-specific empirical results refine theoretical expectations and guide actionable strategies. The following conclusion chapter will now integrate these insights into a final, overarching synthesis.

CONCLUSIONS AND IMPLICATIONS

Synthesised conclusions and scholarly contribution

This study rigorously examines the nexus between corporate governance and innovation productivity in a traditional yet vital industry. By applying a three-stage DEA model to strip away environmental distortions, we reveal the "true" managerial efficiency in technological innovation among China's listed textile firms. The central conclusion is that internal equity governance mechanisms exert a more decisive influence on innovation efficiency than external ownership labels. Specifically, we conclude that:

First, governance efficacy over ownership form. While ownership concentration, equity checks and balances, and institutional ownership are all significant positive drivers, the mere presence of state shareholding is not. This underscores that how ownership is structured and exercised (governance) is more critical than who owns it (ownership nature) in fostering innovation efficiency within a competitive market environment.

Second, the primacy of managerial practices. The post-adjustment decline in efficiency, primarily attributed to pure technical inefficiency, points to internal management and resource allocation processes, rather than scale or external factors, as the key bottleneck. This shifts the focus for improvement from seeking external advantages to optimising internal innovation management systems.

Third, contextualised understanding of equity roles. The findings contribute to a more nuanced theoretical understanding. They suggest that in industries undergoing pressured transformation like textiles, concentrated ownership can provide necessary commitment, while balanced ownership and professional institutional investors introduce essential oversight and expertise. This context-dependent efficacy enriches principal-agent theory and resource-based views in a specific industrial setting.

These conclusions collectively advance the theoretical discourse by demonstrating that established governance theories hold significant explanatory power in traditional sectors, provided the measurement of the dependent variable (technological innovation efficiency) is purified, and the institutional context is carefully considered.

Integrated managerial and policy implications

The preceding conclusions translate into direct implications for practice, forming a bridge from theoretical insight to actionable strategy. These implications are

structured to guide different stakeholders in the innovation ecosystem.

(1) Strategic and governance-level implications for innovation

The findings offer actionable insights for corporate owners and governors to architect an equity structure and incentive system that catalyses innovation.

First, design dynamic equity governance for long-term innovation. Merely adjusting the level of ownership concentration is insufficient. Governance bodies should focus on cultivating a high-quality equity mix. This involves actively introducing long-term-oriented institutional investors (e.g., technology-focused funds, ESG investors) who can provide not only capital but also strategic oversight and market access, aligning with their positive role identified in this study. Furthermore, in line with the ongoing mixed-ownership reform trends, firms, especially state-shareholding ones, should consider diversifying their shareholder base with heterogeneous blockholders from complementary industries (e.g., new materials, digital platforms). This can inject fresh perspectives and mitigate the risk of strategic myopia, directly addressing the core agency problem in innovation investment.

Second, implement innovation-aligned incentives with ESG and digital metrics. To counteract managerial short-termism, compensation committees must move beyond traditional financial metrics. A portion of long-term incentives (e.g., restricted stock units) for executives and R&D leaders should be explicitly tied to innovation output quality and sustainability. Metrics should include the green attributes of patents (e.g., energy-saving processes, recyclable materials), linking managerial rewards directly to the firm's ESG performance and sustainable transition. Concurrently, firms should invest in digital R&D management platforms to track project milestones and resource efficiency in real-time. This data-driven approach not only improves "pure technical efficiency" but also provides transparent, objective bases for incentive payouts, operationalising the potential of digital technology for governance and knowledge management.

(2) Operational and policy-level implications for ecosystem development

The results also provide guidance for internal process optimisation and the design of industry-level innovation policies.

First, streamline internal processes with a focus on green and digital transformation. To elevate pure technical efficiency, firms must scrutinise and re-engineer their innovation value chains. A critical step is establishing dedicated "green innovation" pipelines with streamlined approval processes and cross-functional teams. Additionally, reducing administrative friction ("management costs") requires leveraging digital collaborative tools to automate reporting and facilitate communication between R&D, production, and marketing, thereby enhancing the fluidity of ideas and resources.

Second, fostering an enabling external innovation ecosystem. Policymakers should transition from blanket subsidies to efficiency-based and mission-oriented support. Public funding (e.g., R&D subsidies, innovation funds) could be partially allocated through matching mechanisms that favour firms with higher adjusted innovation efficiency, thus rewarding effective governance and management.

Furthermore, to help the entire industry overcome technological bottlenecks and improve scale efficiency, governments and industry associations should spearhead the creation of shared "Textile 4.0" innovation infrastructures. These could include open-access labs for circular economy technologies, industry cloud platforms for supply chain data pooling, and skill-building programs in AI and data analytics for textile engineers. Such ecosystems lower the innovation threshold for SMEs and foster spillover effects, addressing the industry-wide efficiency challenges highlighted in this study.

Limitations and trajectory for future research

Recognising the boundaries of this study not only clarifies its scope but also illuminates productive paths for further inquiry. The main limitations, and the research opportunities they unveil, are threefold.

First, regarding methodological scope. The three-stage DEA model, while effective in purging environmental noise, is inherently static and non-parametric. Our analysis captures efficiency at specific points in time but does not fully model the dynamic adjustment processes of innovation activities. Future studies could employ dynamic DEA models, panel vector autoregression (PVAR), or system dynamics simulation to explore how equity structure influences innovation efficiency trajectories and the feedback effects over time.

Second, concerning the research context and variables. Our focus was on traditional dimensions of equity structure. However, the modern business environment introduces new, interactive governance factors. For instance, how digital transformation level or ESG (Environmental, Social, and Governance) commitments moderate the identified relationships remains an open question. The rise of hybrid ownership forms, including equity participation by core customers or supply chain partners, also warrants investigation. Furthermore, extending the analysis from firm-level to intra-firm levels (e.g., the efficiency of specific R&D projects) or inter-firm levels (e.g., innovation efficiency within textile industry clusters or supply networks) could yield richer insights.

Third, about the industry sample. Although concentrating on the textile industry enhances internal validity, it may limit the generalizability of our findings to other sectors with different technological regimes (e.g., high-tech or service industries). Comparative studies across multiple traditional manufacturing industries would help distinguish industry-specific effects from universal governance principles.

In conclusion, addressing these limitations would not only validate and extend our findings but also contribute to a more nuanced and comprehensive understanding of corporate governance and innovation management in the era of industrial upgrading and sustainable development.

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Optimisation study of female suit product design based on the Kano-HOQ model

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ABSTRACT – REZUMAT

Optimisation study of female suit product design based on the Kano-HOQ model

This study adopts the Kano-HOQ method to address the gap between the consumption demands of female suit consumers and the market supply, improving the satisfaction of female suit consumers and the precision of market response. Firstly, 20 product demand factors influencing the consumption decisions of female suit consumers are extracted, classified and analysed according to Kano attributes. Then, based on the importance of each demand factor to the users, the comprehensive satisfaction of each consumption demand is calculated. The consumption demands of female suit consumers are transformed into 4 primary design requirements and 16 secondary design requirements. These are then input into the House of Quality (HOQ) model to determine the correlation between user demand factors and design requirements. Finally, by calculating the matrix, the weight values of each design requirement were determined, and they were ranked accordingly. The study summarised the consumer demand items and product design technical elements that should be prioritised for improvement in the female suit product design process. The research indicates that priority should be given to aesthetic appeal on the visual level in the design process of female suits, such as style, structure, colour, and patterns. At the same time, attention should also be paid to the personalised characteristics of the product, ensuring that it matches the individual demands of users. This approach aims to enhance user satisfaction and better fulfil consumer demands.

Keywords: *female suit, user demands, Kano model, House of Quality, design requirement*

Studiu de optimizare a proiectării costumelor de damă pe baza modelului Kano-HOQ

Prezentul studiu adoptă metoda Kano-HOQ pentru a aborda discrepanța dintre cerințele de consum ale femeilor care achiziționează costume și oferta de pe piață, îmbunătățind astfel satisfacția acestor consumatoare și precizia răspunsului pieței. În primul rând, sunt identificați, clasificați și analizați 20 de factori de cerere ai produsului care influențează deciziile de consum ale femeilor care achiziționează costume, în conformitate cu atributele Kano. Apoi, pe baza importanței fiecărui factor de cerere pentru utilizatoare, se calculează nivelul de satisfacție globală asociat fiecărei cerințe de consum. Aceste cerințe sunt transformate în 4 cerințe de proiectare primare și 16 cerințe de proiectare secundare. Acestea sunt apoi integrate în modelul „House of Quality" (HOQ) pentru a determina corelația dintre cerințele utilizatorilor și cerințele de proiectare. În final, prin calcularea matricei, au fost determinate valorile ponderale ale fiecărei cerințe de proiectare, iar acestea au fost clasificate în consecință. Studiul a sintetizat aspectele legate de cerințele consumatoarelor și elementele tehnice de proiectare a produsului, care ar trebui să fie prioritizate în vederea îmbunătățirii procesului de proiectare a costumelor de damă. Studiul indică faptul că în procesul de proiectare a costumelor de damă ar trebui să se acorde prioritate aspectelor estetice la nivel vizual, precum stilul, structura, culoarea și modelele. În același timp, ar trebui să se acorde atenție și caracteristicilor personalizate ale produsului, asigurându-se că acesta corespunde cerințelor individuale ale utilizatorilor. Această abordare are ca scop sporirea satisfacției și o îndeplinire mai bună a cerințelor utilizatorilor.

Cuvinte-cheie*: costum de damă, cerințele utilizatorilor, modelul Kano, modelul House of Quality, cerințe de proiectare*

INTRODUCTION

As China's apparel industry soft power grows [1], market competition intensifies [2]. Consumers demand greater personalisation in garment designs [3]. Market drivers now blend fashion, individuality, and varied aesthetics [4], replacing utility-focused priorities. Designers must analyse consumer needs meticulously, innovate concepts to create styles that align with market demands, bridging supply-demand gaps through optimal design [5].

Existing research on market supply and demand has perspective-driven limitations in China. From enterprise/designer viewpoints, studies emphasise apparel structure, styling, patterns, colours, and fabric functions, but over-reliance on individual philosophies creates design-consumer disconnects. Song et al. [6]. Taking geometric patterns of different forms and basic cheongsam styles as the research objects, this paper analyses the perceptual evaluations generated by the combination of different geometric patterns and cheongsam styles. Zhang [7], taking the dress as an example, realised the digital construction of the clothing style database through the quantification of clothing styles. Shen [8] analysed the four

major relationships between clothing styling design and fabric, and put forward effective suggestions for guiding clothing styling design and promoting fabric research and development. User-centric research focuses on perceptual needs while insufficiently addressing market-demand alignment [9–11]. This duality creates supply-demand gaps impacting satisfaction and competitiveness.

In the highly competitive women's clothing sector, female suits have a large market share, and it continues to grow. However, traditional female suit products suffer from severe homogenization, making it difficult to meet the diverse demands of contemporary women for female suits. Based on this, this article focuses on the Chinese clothing market and takes female suits as the research object, identifying market-consumer imbalance points and satisfaction-impacting design elements. Using Kano-HOQ [12–14], it prioritises design requirements to enhance supply-demand alignment, providing apparel enterprises with theoretical and practical guidance for improving user satisfaction.

METHODOLOGY

Research on the consumer demands of female suit users

This article selects the styles of women's suits with lapel structures as the research objects based on the morphological classification of women's suits, and does not impose restrictions on the silhouettes and lapel classifications of women's suits. The basic style of women's suits is shown in figure 1. Based on the existing research results on women's suit product design and user needs [2, 15–16], the consumer demand elements of women's suit users are refined,



Fig. 1. Basic women's suit styles

and on this basis, the questionnaire is designed and investigated. To ensure the representativeness of the research sample, this study employs a combination of stratified sampling and quota sampling to select respondents. First, stratification is conducted based on the tier levels of Chinese cities (first-tier, second-tier, third-tier, and below). Within each tier, quotas are set according to two key demographic variables: age and monthly income, to ensure that the sample structure aligns with the basic characteristics of the core consumer group for women's suits (referencing data from the National Bureau of Statistics and industry consumption reports). Ultimately, 150 respondents were selected for semi-structured interviews, including sales personnel from women's suit brands (30%) and consumers with over five years of experience in purchasing and wearing women's suits (70%). All respondents provided informed consent and voluntarily participated in this study. This approach aims to

Table 1

CONSUMER DEMAND ELEMENTS OF FEMALE SUIT USERS

Primary demand elements	Secondary demand elements	Primary demand elements	Secondary demand elements
Aesthetic elements (A)	Aesthetic design (A_1)	Personality elements (C)	Professional image (C_1)
	Proper structure & cut (A_2)		Flexible pairing (C_2)
	Concealing figure flaws (A_3)		*Print/embroidery craft* (C_3)
	Beautiful patterns (A_4)		Fashionable flair (C_4)
	Coordinated colors (A_5)		Personality accent (C_5)
	Aesthetic variety I (A_6)		Unique accessories (C_6)
Quality elements (B)	Excellent workmanship (B_1)		Gender-specific traits (C_7)
	Exquisite detail design (B_2)		Identity recognition (C_8)
	Soft, fine texture (B_3)	Cultural elements (D)	Reflect ethnic styles (D_1)
	Durable and thick fabric (B_4)		Chinese elements (D_2)
	Extra parts included (B_5)		Brand narrative and cultural embodiment (D_3)
	Easy to wash and maintain (B_6)	Functional elements (E)	Suitable for multiple occasions (E_1)
	Reflect brand value (B_7)		Comfortable and convenient to wear (E_2)
	Eco-friendly fabric (B_8)		Multifunctional design (E_3)
	Durable fabric (B_9)		Adjustable size (E_4)

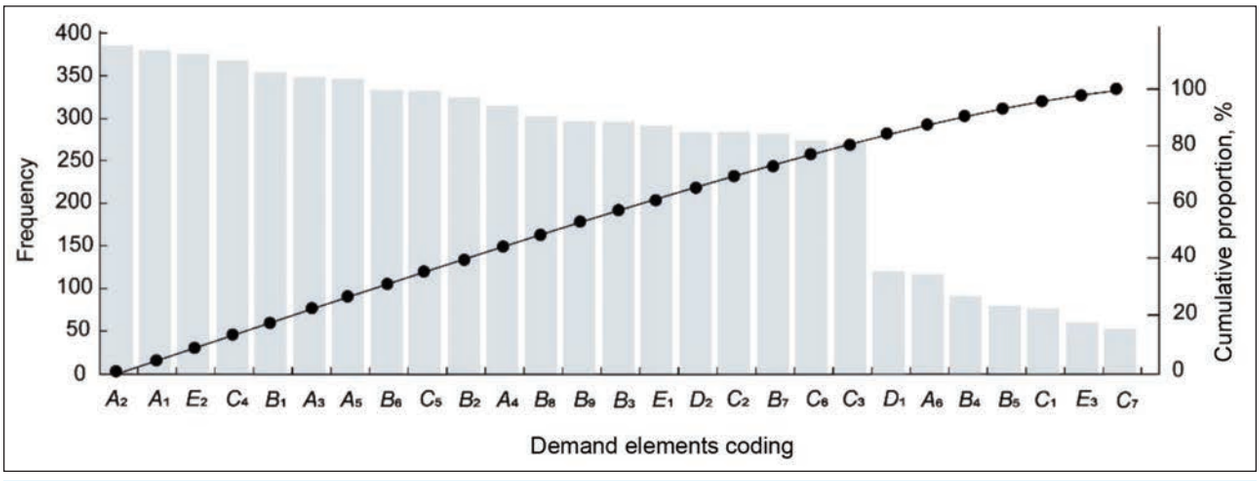


Fig. 2. Female suit products consumer demand key elements of the Pareto figure

comprehensively capture user needs from both supply (sales) and demand (consumption) perspectives, enhancing the representativeness of the sample and the external validity of the research findings. Moreover, the number of participants meets the common scale for market research and can be compared with past results. It complies with the basic requirements of statistical validity and principles of statistical analysis, fulfilling the capacity requirements for samples in such surveys [17]. Semi-structured interviews explored background, preferences, usage, purchasing, and market feedback. Data analysis categorised results into 5 primary demand elements and 30 secondary elements (table 1).

Based on a preliminary survey of 150 respondents, participants selected prioritised attributes from table 1. Three least-selected primary attributes (<10 selections) were excluded, leaving 27 demand elements. A questionnaire assessed user expectations for these elements, with optional non-essential attributes. Applying the Pareto principle (2:8 rule) [18], critical factors were identified by 80% cumulative selection frequency, visualised in figure 2.

Figure 2 shows 20 key attributes, including proper structure & cut (A_2), aesthetic design (A_1), comfortable and convenient to wear (E_2), and fashionable flair (C_4), covering 79.88% of responses. These were redefined as primary demand attributes (table 2), while seven lower-priority attributes were excluded.

Analysis of the gap between market supply and user demands

Users form varied expectations based on consumption needs, influencing purchase decisions. Gap values correlate with satisfaction: negative gaps indicate excess demand fulfilment, positive gaps reflect unmet needs, and zero gaps signify alignment.

This study applies Expectation Confirmation Theory (ECT) [19] to link consumer demands and satisfaction for female suits. A 5-point Likert Scale [20] assessed discrepancies between expectations and perceived satisfaction for each attribute. Participants were female, with demographics detailed in table 3.

Table 2

FEMALE SUIT CONSUMER DEMAND SYSTEM TABLE

Primary demand elements	Secondary demand elements	Primary demand elements	Secondary demand elements
Aesthetic elements (A)	Aesthetic design (A_1)	Personality elements (C)	Flexible pairing (C_1)
	Proper structure & cut (A_2)		*Print/embroidery craft* (C_2)
	Concealing figure flaws (A_3)		Fashionable flair (C_3)
	Beautiful patterns (A_4))		Personality accen (C_4)
	Coordinated colors (A_5)		Unique accessories (C_5)
Quality elements (B)	Excellent workmanship (B_1)	Cultural elements (D)	Chinese elements (D_1)
	Exquisite detail design (B_2)	Functional elements (E)	Suitable for multiple occasions (E_1)
	Soft, fine texture (B_3)		Comfortable and convenient to wear (E_2)
	Easy to wash and maintain (B_4)		
	Reflect brand value (B_5)		
	Eco-friendly fabric (B_6)		
	Durable fabric (B_7)		

SPSS analysis of questionnaire data (table 4) revealed that all demand elements exhibited P<0.05 [21], highlighting intergroup discrepancies.
Expectations consistently exceeded market satisfaction, with current offerings falling short of user needs. This gap underscores significant market optimisation potential.

Principles of the Kano model

The Kano model is a demand analysis model that can conduct qualitative analysis and attribute classification of demands, and is often used to study users' personalised demands. This model is frequently applied in fields such as product design, interaction design, and service design [22]. Its advantage lies in

Table 3

TARGET AUDIENCE FOR THE QUESTIONNAIRE					
Dimension	**Category**	**Percentage**	**Dimension**	**Category**	**Percentage**
Age	20–29 years old	20%	Region	First-tier cities	30%
	30–39 years old	25%		Second-tier cities	40%
	40–49 years old	25%		Third-tier and below cities	30%
	50–59 years old	20%	Purchasing frequency	High frequency (at least once per quarter)	60%
	60+ years old	10%		Low frequency (half a year or less)	40%
Occupation	White-collar/public staff	50%	Monthly income	Below 5,000 RMB	30%
	Freelancers	30%		5,001–10,000 RMB	40%
	Students	10%		Above 10,000 RMB	30%
	Others	10%			

Table 4

RESULTS OF THE SIGNIFICANT DIFFERENCE ANALYSIS							
Primary demand elements	**Secondary demand elements**	**Expectation**		**Satisfaction**		***T*-value**	***P*-value**
		Mean value	**Rank**	**Mean value**	**Rank**		
Aesthetic elements (*A*)	Aesthetic design (A_1)	4.82	1	3.72	6	4.75	0.000*
	Proper structure & cut (A_2)	4.76	2	4.41	2	4.69	0.000*
	Concealing figure flaws (A_3)	4.68	3	3.85	10	4.15	0.000*
	Beautiful patterns (A_4)	4.65	4	4.19	4	3.72	0.000*
	Coordinated colors (A_5)	4.57	5	4.00	8	4.28	0.025*
Quality elements (*B*)	Excellent workmanship (B_1)	4.55	6	3.82	11	3.79	0.000*
	Exquisite detail design (B_2)	4.48	7	4.52	1	4.70	0.032*
	Soft, fine texture (B_3)	4.43	8	4.38	3	4.28	0.000*
	Easy to wash and maintain (B_4)	4.39	9	4.02	7	3.66	0.000*
	Reflect brand value (B_5)	4.26	10	3.78	12	3.38	0.000*
	Eco-friendly fabric (B_6)	4.18	11	4.06	5	3.81	0.000*
	Durable fabric (B_7)	4.12	12	3.96	9	4.39	0.000*
Personality eements (*C*)	Flexible pairing (C_1)	4.08	13	3.38	19	2.87	0.000*
	Print/embroidery craft (C_2)	4.05	14	3.57	15	3.19	0.018*
	Fashionable flair (C_3)	3.96	15	3.41	18	2.58	0.000*
	Personality accent (C_4)	3.92	16	3.5	16	2.13	0.000*
	Unique accessories (C_5)	3.88	17	3.62	14	3.02	0.000*
Cultural elements (*D*)	Chinese elements (D_1)	3.81	18	3.46	17	1.99	0.000*
Functional elements (*E*)	Suitable for multiple occasions (E_1)	3.72	19	3.66	13	2.26	0.000*
	Comfortable and convenient to wear (E_2)	3.75	20	3.36	20	2.31	0.006*

Note: * indicates a p-value less than 0.05, indicating significant differences.

its ability to effectively and clearly illustrate the relationship between product demand elements and user satisfaction, precisely dissect users' demand levels, and provide a clear basis for product decision-making [23]. Based on the links, it classifies elements into five attributes: Must-be (M), One-dimensional (O), Attractive (A), Indifferent (I), and Reverse (R) [3, 24]. To design the Kano questionnaire, target users were invited to assign importance scores to the secondary demand factors listed in table 2. The scoring criteria were as follows: Satisfied (5 points), Should be (4 points), Neutral (3 points), Barely Acceptable (2 points), and Disliked (1 point). To ensure the reliability and validity of the results from the Kano questionnaire, reliability and validity tests were conducted. Cronbach's α coefficient was used to assess the internal consistency of the survey. The overall α coefficient of the questionnaire was calculated to be 0.892, and the α coefficients for each primary demand element were all greater than 0.7, indicating a high level of reliability. In terms of validity, exploratory factor analysis (EFA) was performed on the 20 secondary demand factors using principal component analysis, with the maximum variance method applied for rotation. Ultimately, 3 common factors were extracted, with a cumulative variance contribution rate of 88.45%. Additionally, this indicates that the questionnaire possesses good structural validity and can effectively measure the consumption demand structure of women's suit users [3].

To prevent misclassification, Better-Worse coefficients (equations 1–2) refined prioritisation and weighting.

$$Better = (A + O) / (A + O + M + I) \quad (1)$$

$$Worse = -1 \times (O + M) / (A + O + M + I) \quad (2)$$

Kano attribute classification

Following the Kano model, 20 female suit demand elements were categorised using Better-Worse coefficients (table 5) [22]. Must-be attributes centred on aesthetics, highlighting users' priority for fashionable design to drive purchase intent. One-dimensional attributes were quality-focused, indicating users' dual expectations for aesthetics and durability. Attractive and indifferent attributes showed scattered distribution, reflecting diverse yet consistent needs.

Attractive attributes enhance satisfaction but are non-essential, while indifferent attributes garner minimal attention. Notably, no reverse attributes were identified, avoiding potential user aversion.

Comprehensive user demand satisfaction calculation

User satisfaction for each demand element was determined via Kano model analysis. The satisfaction index T_i was calculated using equation 3.

$$T_i = \max(|Better|, |Worse|) \quad (3)$$

Table 5

THE KANO ATTRIBUTE CLASSIFICATION OF THE CONSUMER DEMAND ELEMENTS OF FEMALE SUIT USERS

Primary demand elements	Secondary demand elements	Percentage/%					Kano attribute	Better coefficient	Worse coefficient
		M	O	A	I	R			
Aesthetic elements (*A*)	A_1	68.22	22.10	8.03	1.33	0.32	M	0.302	–0.906
	A_2	55.97	31.82	7.14	3.88	1.28	M	0.394	–0.888
	A_3	25.16	45.82	13.16	12.86	3.00	O	0.608	–0.732
	A_4	32.68	25.27	20.97	13.61	7.47	M	0.500	–0.626
	A_5	49.72	34.65	8.63	6.96	0.04	M	0.433	–0.844
Quality elements (*B*)	B_1	52.04	31.04	12.27	3.08	1.07	M	0.443	–0.845
	B_2	25.58	31.72	22.39	17.92	2.39	O	0.554	–0.587
	B_3	25.80	36.52	16.98	19.68	1.02	O	0.541	–0.630
	B_4	30.01	47.28	16.05	4.02	2.64	O	0.650	–0.794
	B_5	19.08	43.28	21.02	13.05	3.57	O	0.667	–0.647
	B_6	5.63	23.64	52.93	14.69	3.11	A	0.790	–0.302
	B_7	21.85	22.32	10.09	44.68	1.06	I	0.328	–0.446
Personality elements (*C*)	C_1	27.28	29.57	18.63	20.04	4.48	O	0.505	–0.595
	C_2	13.86	12.46	10.39	56.31	6.98	I	0.246	–0.283
	C_3	59.18	23.91	10.22	3.28	3.41	M	0.353	–0.860
	C_4	28.48	39.82	10.65	18.32	2.73	O	0.519	–0.702
	C_5	15.29	28.66	39.72	10.87	5.46	A	0.723	–0.465
Cultural elements (*D*)	D_1	4.56	4.51	3.34	27.53	60.06	I	0.197	–0.227
Functional elements (*E*)	E_1	7.56	28.06	43.27	20.11	1.00	A	0.721	–0.360
	E_2	55.68	33.64	3.37	4.27	3.04	M	0.382	–0.921

Table 6

SCORE OF EACH INDEX OF CONSUMER DEMAND FACTORS OF FEMALE SUIT USERS											
Demand elements	H_i	T_i	V_i	k	Z_i	**Demand elements**	H_i	T_i	V_i	k	Z_i
A_1	4.49	0.91	0.30	0.5	1.84	B_6	3.66	0.79	0.03	1.5	0.26
A_2	4.53	0.89	0.05	0.5	0.33	B_7	3.19	0.45	0.04	0	0.13
A_3	4.28	0.73	0.22	1	1.59	C_1	3.35	0.60	0.21	1	1.11
A_4	3.89	0.63	0.11	0.5	0.72	C_2	2.98	0.28	0.13	0	0.40
A_5	4.27	0.84	0.14	0.5	0.82	C_3	4.26	0.86	0.16	0.5	0.94
B_1	4.39	0.84	0.19	0.5	1.14	C_4	4.02	0.70	0.12	1	0.82
B_2	3.45	0.59	0.02	1	0.09	C_5	3.95	0.72	0.07	1.5	0.64
B_3	3.64	0.63	0.01	1	0.07	D_1	2.76	0.23	0.10	0	0.28
B_4	4.51	0.69	0.09	1	0.70	E_1	3.38	0.72	0.02	1.5	0.13
B_5	4.10	0.67	0.13	1	0.87	E_2	4.65	0.92	0.12	0.5	0.75

An adjustment coefficient k (I=0, M=0.5, O=1, A=1.5) [25] was integrated to quantify the relationship between satisfaction and attributes. Let S_1 = "satisfaction", S_0 = "expectation", and V_i = "improvement rate", derived from equation 4.

$$V_i = \frac{S_0 - S_1}{S_1} \quad (4)$$

Target users from the preliminary survey were invited to rate the importance (H_i) of each demand element on a 5-point scale: Extremely Important (5 points), Moderately Important (4 points), Neutral (3 points), Moderately Unimportant (2 points), and Extremely Unimportant (1 point). The ratings are summarised in table 6. A comprehensive importance score (Z_i) was established, as presented in equation 5.

$$Z_i = H_i \times (1 + T_i)^k \times V_i \quad (5)$$

All values of H_i, T_i, S_0, S_1, V_i, and Z_i are presented in table 6.

RESULTS AND DISCUSSION

Establishment of the design requirement framework

The House of Quality (HOQ), as the core analytical tool of Quality Function Deployment, can create a systematic mapping of 'customer needs – technical characteristics – process parameters – quality control' through a visual matrix structure, effectively transforming vague requirements into quantifiable technical indicators. By quantifying customer importance and analysing the correlation of technical characteristics, it supports product development decisions, thereby reducing production costs, shortening the research and development cycle, and enhancing the market adaptability of the final output [26]. This article combines the application of the Kano model and the HOQ model. It can not only precisely classify the core demands of female suit users through the Kano model, but also quantitatively map user demands to design requirements with the help of the HOQ model, scientifically determining the priority order for improvement of each design requirement. Thus, through the combined application of these two technical models, it can not only avoid the waste of resources by the supply side of female suits in undifferentiated demands, but also precisely match the differentiated demands of users for female suits, efficiently narrowing the gap between supply and demand.

Design requirements must align with consumer demands through human-centred approaches [27]. Thirty female suit designers refined requirements via expertise and market analysis, retaining features with over 80% consensus. Four primary requirements emerged: D_1 (Visual Design), D_2 (Quality Design), D_3 (Emotional Design), D_4 (Functional Design), with 16 secondary ones (table 7).

Construction of the HOQ matrix model

Consumer demand requirements were input into the HOQ model to determine relevance (γ_{ij}) between user demands and design requirements. The HOQ ceiling represents product design requirements, while the left wall lists user demands. Substituting Z_i and γ_{ij} into equation 6 calculated weight values for design requirements, ranked by importance. To ensure the objectivity and accuracy of the correlation scores (γ_{ij}) between user demands and design requirements in the Quality House, this study formed an evaluation panel consisting of 15 experienced women's suit product designers and 15 experts in the field of garment engineering. Before the evaluation, all experts were given a detailed explanation of the correlation scoring criteria (strong correlation 9 points; moderate correlation 5 points; weak correlation 1 point). Subsequently, the experts independently scored the correlation between 20 user demands and 16 design requirements. The Kendall's W coefficient was calculated for each group's scores to assess the consistency of expert opinions, resulting in a W value of 0.813 ($p < 0.001$), indicating a high level of consistency among the expert ratings. The quality house model is constructed accordingly, as shown in figure 3. Figure 3 illustrates the female suit HOQ model,

Table 7

DESIGN REQUIREMENTS FOR FEMALE SUIT PRODUCTS			
Primary design requirements		**Secondary design requirements**	
No.	**Name**	**No.**	**Design requirement description**
D_1	Visual Design	D_{11}	Monitor fashion trends and maintain sensitivity to trend changes
		D_{12}	Consider characteristics of different figure types
		D_{13}	Develop colour schemes based on popular colours
		D_{14}	Design attractive and fashionable patterns
		D_{15}	Create unique accessories that complement the apparel
D_2	Quality Design	D_{21}	Use eco-friendly materials and prioritise sustainability
		D_{22}	Refine design for craft precision
		D_{23}	Prioritise washability & durability to cut maintenance
D_3	Emotional Design	D_{31}	Consider appropriate occasions for the apparel
		D_{32}	Feature logos/elements for brand recognition
		D_{33}	Fuse brand narratives to convey values
		D_{34}	Personalised design options with distinct styles
		D_{35}	Employ traditional Chinese elements for cultural depth
D_4	Functional Design	D_{41}	Optimise patterns for ergonomic comfort
		D_{42}	Prioritise performance fabrics for comfort/function
		D_{43}	Design versatile styles for easy mixing

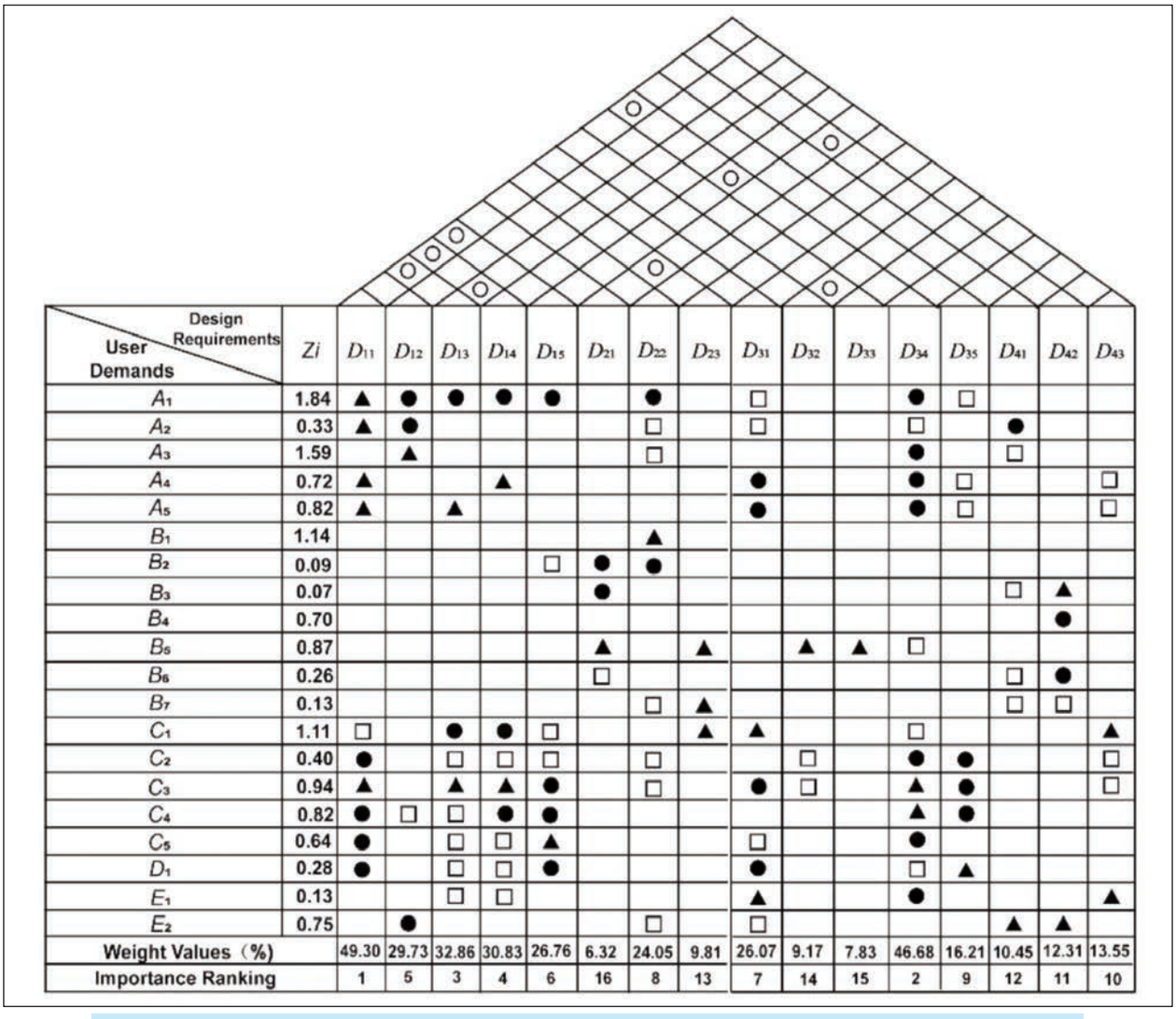


Fig. 3. Female suit product quality house model

with symbols ▲, ●, and □ indicating strong, medium, and weak correlations scored as 9, 5, and 1 points.

$$W_j = \sum_{i=1}^{m} Z_i \times \gamma_{ij} \quad (j = 1, 2, ..., n) \qquad (6)$$

Equation 6 defines γ_{ij} as the relevance between *No.* $_i$ user demand and *No.* $_j$ design requirement.

Correlations among technical requirements were assessed: "○" denotes positive mutual enhancement, while "×" indicates negative trade-offs. Figure 3 shows that no negative correlations exist among design requirements.

The HOQ analysis reveals the importance ranking of female suit design requirements: $D_{11} > D_{34} > D_{13} > D_{14} > D_{12} > D_{15} > D_{31} > D_{22} > D_{35} > D_{24} > D_{43} > D_{42} > D_{41} > D_{23} > D_{32} > D_{33} > D_{21}$. Implementation should prioritise these levels. The top ranks cluster under visual design, indicating consumer priorities have shifted from functionality to aesthetics, reflecting a "visual appeal-driven" market. Among secondary requirements, personalised customisation holds extreme weight, signalling a demand for self-expression. The HOQ ceiling correlations show no negative impacts between design requirements, ensuring holistic improvement.

This study, via HOQ model analysis, concludes that female suit design should focus on fashion trends (D_{11}) and personalised customisation (D_{34}). Digital systems and modular platforms integrate colours (D_{13}), patterns (D_{14}), and fit (D_{12}) into dynamic units. Traditional elements (D_{35}) are redesigned via parametric methods while improving precision (D_{22}), forming a "trend-driven, function-fit, cultural-added" path. This ensures comfort (D_{41}, D_{42}) and enhances product competitiveness and cultural value, bridging consumer-market gaps effectively.

CONCLUSIONS

To address the supply-demand gap and imbalance between user consumption demands and market supply in female suit products, this study integrates user demands, comprehensive evaluation, and design requirements. By integrating the Kano-HOQ methodology, a user-oriented optimisation model for female suit design is proposed, achieving precise alignment between demand elements and design requirements. The conclusions are as follows:

Research shows that there is a comprehensive supply-demand gap in the Chinese women's suit market; user expectations for all demand factors are significantly higher than their satisfaction levels, and the gap exhibits 'layered characteristics'. The supply-demand difference is greatest for Aesthetic elements (A_1 Aesthetic design, A_2 Appropriate structure and version) and Personality elements (C_3 Fashionable flair, C_4 Highlight personal temperament), with average expectation levels above 4.5 and average satisfaction levels below 3.7. This finding challenges the common perception that 'users only care about appearance' and reveals that the dual demand gap of 'aesthetic necessity + individuality enhancement' is the core contradiction limiting market satisfaction, thus pinpointing a precise direction for design optimisation.

Based on the model analysis results, we broke through the traditional design logic of female suits and created a three-dimensional collaborative path of "trend-driven – personalised adaptation – cultural value-added":

Trend-driven layer: With the core of responding to D_{11} fashion trends, a conversion mechanism of "fashion data – design parameters" is constructed to address the gap in aesthetic demands.

Personalised adaptation layer: Based on the high weight of D_{34} personalised customisation, a modular design platform is developed to meet the value-added demands of C_1 Flexible matching capabilities and C_4 Highlight personal temperament.

Cultural value-added layer: Integrate the traditional cultural elements of D_{35} into visual design to avoid waste caused by attribute generalisation. Its feasibility has been verified through the positive correlation of design requirements, which can directly guide enterprises to carry out precision development and reduce trial-and-error costs.

This study shows the Kano-HOQ correlation effectively converts user demands into design requirements, aligning products with consumer expectations. Among 16 secondary requirements, top criteria emphasised visual/emotional design and personalisation. Thus, female suits should prioritise aesthetics (style, colour, pattern) and individualised features.

However, there are still some limitations. Approaches to the acquisition of user consumption demands can be further explored. For example, semantic analysis of user comments, feedback on online platforms(e.g., Taobao, Douyin, livestreams) and fan messages on official brand websites could be employed to capture deeper consumer insights. These limitations will be tackled in future research.

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The impact of the need for uniqueness on counterfeit luxury apparel consumption: an attitude-based mediation model

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ABSTRACT – REZUMAT

The impact of the need for uniqueness on counterfeit luxury apparel consumption: an attitude-based mediation model

Economic and technological developments in recent years have facilitated the introduction of counterfeit products into the market. The spread of counterfeit luxury apparel has brought on both legal and economic challenges for the global textile industry. This study examines the mediating role of attitude in the relationship between consumers' need for uniqueness (NFU) and their purchase intentions for counterfeit luxury apparel products in Türkiye, a country with a high circulation of counterfeit products. Data from 365 Turkish participants collected via an online survey were analysed using Structural Equation Modelling (SEM). The findings indicate that the NFU significantly increases positive attitudes toward counterfeit apparel, and these attitudes are a strong predictor of purchase intentions. The lack of a significant direct relationship between the NFU and purchase intentions suggests a full mediating effect of attitude. These findings explain why individuals purchase counterfeit luxury apparel and suggest an argument for promoting ethical and sustainable luxury products.

Keywords: *need for uniqueness, counterfeit products, luxury apparel, consumer behaviour, textile industry, apparel*

Impactul nevoii de unicitate asupra consumului de articole vestimentare de lux contrafăcute: un model de mediere bazat pe atitudine

Evoluțiile economice și tehnologice din ultimii ani au facilitat introducerea pe piață a produselor contrafăcute. Răspândirea articolelor vestimentare de lux contrafăcute a generat provocări atât de natură juridică, cât și de natură economică pentru industria textilă globală. Prezentul studiu examinează rolul de mediator al atitudinii în relația dintre nevoia consumatorilor de unicitate și intențiile lor de cumpărare a articolelor vestimentare de lux contrafăcute în Turcia, o țară cu o circulație ridicată a produselor contrafăcute. Datele colectate de la 365 de participanți turci prin intermediul unui sondaj online au fost analizate utilizând modelarea ecuațiilor structurale (SEM). Rezultatele indică faptul că nevoia de unicitate (NFU) crește semnificativ atitudinile pozitive față de articolele de îmbrăcăminte contrafăcute, iar aceste atitudini constituie un predictor puternic al intențiilor de cumpărare. Lipsa unei relații directe semnificative între NFU și intențiile de cumpărare sugerează un efect de mediere complet al atitudinii. Aceste rezultate explică motivul pentru care indivizii achiziționează articole de îmbrăcăminte de lux contrafăcute și oferă un argument în favoarea promovării produselor de lux etice și durabile.

Cuvinte-cheie: *nevoia de unicitate, produse contrafăcute, îmbrăcăminte de lux, comportamentul consumatorilor, industria textilă, îmbrăcăminte*

INTRODUCTION

In recent years, developments in the apparel industry and increased access to information have highlighted variations in consumers' apparel preferences. Although many consumers are aware of fast fashion's environmental harms, others continue to buy luxury apparel to express their identities in social contexts. It is frequently discussed in the literature that consumers buy many products for their symbolic and social value rather than their functional value [1]. Since individuals construct their social identities through possessions [2], luxury goods become powerful indicators of status and personal identity [3]. In this context, understanding the fundamental psychological mechanisms underlying luxury consumption behaviour is crucial. The perception of luxury as a status symbol is driven by the "Need for Uniqueness" (NFU), which is defined as individuals' desire to distinguish themselves from others by owning rare products [4]. Owning unique products allows people to feel more valued and privileged and to reflect their differences [5, 6]. Consequently, this search for uniqueness leads people to adopt new things, challenge traditions, and seek out rare and unusual objects [7]. Therefore, it is not surprising that exclusive luxury products, which are produced in limited quantities and are not affordable to everyone, respond to consumers' search for uniqueness.

While each luxury product category has its own unique benefits, what they all have in common is that they are all defined by elements such as rarity, quality, and originality [8]. Consequently, luxury fashion brands in particular face a growing threat from counterfeits of original products [9]. Technological

advances have expanded counterfeiters' capacity to imitate original products with minimal constraints. As a result, imitations have become common even before the original product is introduced to the market. Although it is difficult to measure the exact volume of counterfeit goods trade, its actual size is estimated to far exceed official estimates [10]. Global trade in counterfeit products reached an estimated value of US$467 billion in 2021, representing about 2.3% of all world imports. During 2020–2021, Türkiye was the second-largest provenance economy, after China, for counterfeit goods seized on their way to the European Union, accounting for approximately 22% of seizures [11]. The rapid rise of counterfeiting is causing economic losses to legitimate brand owners and damaging brand reputations [12]. In Türkiye, a country with a high rate of counterfeit apparel, it is crucial to investigate the factors that influence consumers' purchases of counterfeit luxury apparel over originals. Counterfeit apparel production and circulation rely heavily on consumer demand. Therefore, this study aims to shed light on this growing global problem by examining how consumers' need for uniqueness influences their attitudes and purchase intentions toward counterfeit luxury apparel.

LITERATURE

Counterfeit luxury apparel

Luxury product lines are typically characterised by rarity, superior quality, aesthetic appeal, and premium pricing. Therefore, consumers purchase luxury apparel not only for its functional benefits, such as quality and design, but also for the prestige and social status it provides [13–15]. Thus, the luxury apparel sector, with its strong symbolic and hedonic appeal, has become a prime target for counterfeiting [16]. Counterfeiting is defined as the illegal production of products protected by legal means such as trademarks, copyrights, or patents [17]. It covers a wide range of industries, including fashion, accessories, and electronics. These unlicensed imitations often copy the trademarks of legitimate companies and offer lower-quality copies that resemble the original products [18]. Accordingly, consumers purchase counterfeit products to attain social status and identity associated with genuine luxury brands. They do so without paying a high price, especially during periods of economic hardship [19–22]. In contrast, Fiza et al. [23] found that economic attitudes, subjective norms, and perceived behavioural control significantly influence intentions to purchase counterfeit textiles, while hedonic attitudes have no significant effect.

Linking NFU to counterfeit consumption: hypothesis development

The Need for Uniqueness (NFU) is an individual's drive to differentiate themselves from others by acquiring, using, or disposing of products and varies across individuals and situations [4, 5]. Individuals with a high NFU prefer to buy unusual, distinctive, unique, and luxury products to strengthen their self-identity and avoid being perceived as an ordinary person by those around them [7, 24, 25]. Social identity theory suggests that consumers gravitate toward products that enable them to express their distinctiveness, a tendency often amplified by social media dynamics [26, 27]. Individuals with a strong NFU are typically early adopters of innovative products and designs. Their pursuit of distinctiveness can enhance brand preference and foster loyalty toward brands perceived as exclusive or exceptional [28]. The hypothesis based on these arguments is as follows:

H1: Consumers' need for uniqueness positively and significantly affects their attitudes towards counterfeit luxury apparel.

The central argument of this study is that NFU may paradoxically encourage consumers to purchase counterfeit luxury apparel. While genuine luxury apparel often satisfies this need [5], financial constraints and high prices may make counterfeit apparel attractive to individuals seeking status and uniqueness [29]. Luxury brands inherently embody attributes such as rarity, exceptional quality, visual appeal, personalisation, prestige, and exclusivity, and can satisfy NFU [5, 8, 14]. Consumers exhibiting a high NFU generally place greater value on items that signal scarcity and evoke a sense of exclusivity [30]. Previous studies have shown that NFU is strongly linked to status-motivated consumption and has a significant impact on purchase intentions [31, 32]. The hypothesis based on these arguments is as follows:

H2: Consumers' need for uniqueness positively and significantly affects their purchase intention toward counterfeit luxury apparel.

Consumers with high NFU may view counterfeit luxury apparel as a mechanism to show their uniqueness and gain social recognition [33]. Studies show that status-focused consumption, closely linked to NFU, has a significant impact on developing positive attitudes and purchase intentions toward counterfeit goods [34, 35]. Furthermore, consumers who are price-sensitive but still seek uniqueness may choose counterfeit brands to differentiate themselves without incurring high costs [36]. This tendency is especially evident among young, fashion-oriented consumers who perceive counterfeit goods as an affordable means of expressing uniqueness [37, 38]. Previous research has well documented the positive link between consumer attitudes toward counterfeit goods and purchase intentions [34, 39–41]. Attitude is a person's tendency to evaluate an object positively, negatively, or neutrally and is generally an indicator of behavioural intentions [42]. Consumers who purchase counterfeit goods exhibit positive attitudes and are satisfied as long as these products meet their expectations and needs [43]. This positive attitude is likely to trigger repeat purchases. Therefore, it is predicted that consumers' attitudes toward counterfeit luxury apparel will also influence their purchase intentions. Furthermore, the conceptual framework presented thus far suggests that a consumer's NFU fosters a more positive attitude toward counterfeit

luxury apparel, which in turn drives purchase intentions. Based on these arguments, the hypotheses are as follows:

H3: Consumers' attitudes toward counterfeit luxury apparel positively and significantly influence their purchase intentions.

H4: Consumers' attitudes toward counterfeit luxury apparel mediate the relationship between their NFU and purchase intentions.

The research model, established to determine the relationships among variables based on past research and research hypotheses, is presented in figure 1.

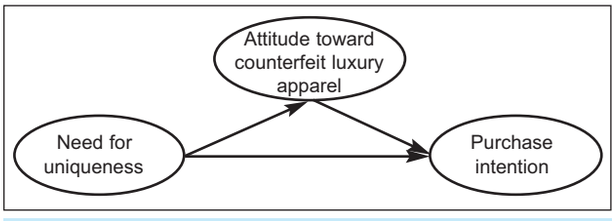


Fig. 1. Research model

METHODOLOGY

Data collection methods and techniques

Research data were collected through an online survey from volunteers using a convenience sampling method. Designed using Google Forms to ensure accessibility and clarity, the survey was pretested with a small pilot group before being applied to the main sample. Participants were contacted through social media, email, and online groups. Participants were fully informed about the study's purpose and data confidentiality, and their consent was obtained. Participants were not offered any incentives to provide unbiased responses. This approach facilitated broad participation and maintained ethical research standards.

Description of the instruments

This study used an online questionnaire to collect data. The survey consisted of two main sections. The first section included questions aimed at identifying NFU, attitude, and purchase intentions of participants. The second section contained demographic details, such as the respondents' age, gender, and educational qualifications.

Scales previously validated in international studies were adapted for use in Türkiye through a process of translation and back-translation. All items, except demographic characteristics, were rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). Three variables were examined in the study: need for uniqueness, attitude towards counterfeit luxury apparel, and purchase intention. The NFU was measured using the 8-item scale developed by Lynn and Harris [44] ($\alpha = 0.78$). To measure consumers' attitudes toward counterfeit apparel, the 6-item scale by Huang et al. [45] ($\alpha = 0.85$) was used. Purchase intention toward counterfeit apparel was measured using five items adapted from Ang et al. [39] ($\alpha = 0.92$) and Phau and Teah [34] ($\alpha = 0.93$).

Sample description

Convenience sampling, a non-random sampling method, was used in this study due to its speed, practicality, and cost-effectiveness. The sample consisted of 365 volunteer participants. The sample size was calculated using the formula by Bartlett et al. [46]. As a result, complete and reliable data collected from 365 participants were found to be sufficient at a 95% confidence level. Demographic characteristics of the participants are presented in table 1.

Table 1

PARTICIPANTS' CHARACTERISTICS			
Criterion		**Value**	**Percentage**
Gender	Female	185	50.7
	Male	180	49.3
Education	Primary School	4	1.1
	High School	50	13.7
	Associate degree	44	12.1
	Bachelor's degree	155	42.5
	Postgraduate	85	23.3
	PhD	27	7.4
Age	18–24	115	31.5
	25–34	163	44.7
	35–49	63	17.3
	50–64	24	6.6
n=365			

RESULTS

Normality test

A normality test was conducted to determine whether the data followed a normal distribution. As seen in table 2, all skewness and kurtosis values fall within the range of –1.5 to +1.5 [47]. This confirms that the data meet the normality assumption and allows the

Table 2

NORMALITY TEST					
Scales	**N**	**Mean**	**S.D.**	**skewness**	**kurtosis**
Need for Uniqueness (NFU)	365	2.8976	0.83586	0.313	–0.588
Attitude (A)	365	2.3032	0.95520	0.684	–0.333
Purchase intention (P)	365	2.2460	1.04233	0.659	–0.452

use of parametric statistical techniques in further analyses.

Validity and reliability of the measurement model

Within structural equation modelling, the measurement model specifies construct indicators and enables the assessment of construct validity [48]. To assess the construct validity of the research scales, Confirmatory Factor Analysis (CFA) was performed using AMOS.

The CFA results revealed that the obtained loadings ranged from 0.549 to 0.886 and were statistically significant (table 3). According to Hair et al. [48], factor loadings above 0.50 are considered acceptable, indicating that the variables demonstrate satisfactory construct validity. To establish construct validity, both convergent and discriminant validity must be ensured. Convergent validity indicates a strong correlation among the variables within the model. According to Fornell and Larcker [49], it is achieved when AVE exceeds 0.50 and CR exceeds 0.70, though an AVE of 0.40 may be acceptable in social sciences. As shown in table 3, AVE values ranged from 0.451 to 0.713 and CR values from 0.866 to 0.925, confirming adequate convergent validity.

Discriminant validity, which indicates how distinct the factors in a model are from one another, must also be established to confirm construct validity. According to Fornell and Larcker [49], this validity is achieved when the square root of each construct's AVE exceeds its correlations with other constructs. As shown in table 4, the AVE square roots were greater than the inter-construct correlations, confirming that the model demonstrates adequate discriminant validity.

Alongside validity, assessing reliability is also crucial. Reliability refers to the consistency of results obtained from repeated measurements using the same method within similar samples. Cronbach's Alpha values above 0.70 indicate acceptable internal consistency [50]. As shown in table 3, all scales in the study had Alpha values exceeding this threshold, demonstrating strong reliability.

Table 3

RELIABILITY AND CONVERGENT VALIDITY

Factors	Items	Loading*	AVE	CR	Cronbach Alpha
Need for Uniqueness (NFU)	NFU1	0.591	0.451	0.866	0.865
	NFU2	0.595			
	NFU3	0.772			
	NFU4	0.591			
	NFU5	0.726			
	NFU6	0.627			
	NFU7	0.702			
	NFU8	0.737			
Attitude (A)	A1	0.731	0.557	0.881	0.876
	A2	0.784			
	A3	0.723			
	A4	0.816			
	A5	0.837			
	A6	0.549			
Purchase intention (P)	P1	0.840	0.713	0.925	0.925
	P2	0.886			
	P3	0.854			
	P4	0.793			
	P5	0.847			

Note: *All standardised factor loadings are significant at the 0.001 level.

Table 4

CORRELATIONS AMONG VARIABLES AND DISCRIMINANT VALIDITY

Factors	Mean	S.D.	NFU	A	P	√AVE
NFU	2.8976	0.83586	-	0.211	0.225	0.672
A	2.3032	0.95520	0.211	-	0.711	0.746
P	2.2460	1.04233	0.225	0.711	-	0.845

Note: * $p<0.001$.

Table 5

GOODNESS OF FIT STATISTICS OF THE RESEARCH MODEL [48]					
Goodness of fit values	**χ^2/df**	**GFI**	**CFI**	**NFI**	**RMSEA**
Research model	2.037	0.924	0.964	0.933	0.053
Good fit	≤3	≥ 0.95	≥ 0.95	≥ 0.95	≤ 0.05
Acceptable fit	≤ 5	≥ 0.90	≥ 0.90	≥ 0.90	≤ 0.08

Table 6

PARAMETER ESTIMATES OF THE STRUCTURAL MODEL					
Paths	**Path coefficients**	**Standard error**	**t-value**	**p-value**	**R^2**
NFU → A	0.240	0.067	3.769	<0.001	0.058
A → P	0.882	0.115	10.512	<0.001	0.808
NFU → P	0.063	0.051	1.776	0.076	

As shown in table 5, the research model demonstrates an acceptable overall fit to the data.

Structural equation model

Structural equation modelling was used to measure the significance of the relationships between the research variables. Table 6 presents parameter estimates for the structural model, including path coefficients, standard errors, t-values, and p-values. The structural model results indicate that the need for uniqueness has a significant positive effect on attitude toward counterfeit products ($\beta = 0.240$, $p < 0.001$). Attitude, in turn, strongly influences purchase intention ($\beta = 0.882$, $p < 0.001$). However, the direct effect of need for uniqueness on purchase intention is not statistically significant ($\beta = 0.063$, $p > 0.05$). These findings suggest that attitude mediates the relationship between need for uniqueness and purchase intention. Therefore, while H1 and H3 are supported, H2 is not supported.

The mediation effect of attitudes toward counterfeit luxury apparel was tested using the modern approach [51] based on the bootstrap technique, as it provides more valid and reliable results than the traditional causal steps method [52]. In the modern approach, the primary focus is to calculate the indirect and direct effects and to make inferences from these values. According to the modern approach, if the indirect effect of the independent variable on the dependent variable is significant as a result of the bootstrap test, the mediation model is confirmed [53]. The analysis, conducted in AMOS with 5,000 bootstrap samples, revealed significant indirect effects, confirming the mediation model. Standardised direct, indirect, and total effects are presented in table 7.

The analysis shows that the indirect effect of need for uniqueness on purchase intention through attitude ($\beta = 0.212$, $p < 0.001$) is significant, while the direct effect ($\beta = 0.063$) is not. This indicates that attitude fully mediates the relationship between need for uniqueness and purchase intention. Therefore, H4 is supported.

Table 7

MEDIATION ANALYSIS (TOTAL, DIRECT, AND INDIRECT EFFECTS)				
Paths	**Direct effect**	**Indirect effect**	**Total effect**	**p-value for the indirect effect**
NFU → A → P	0.063	0.212	0.274	<0.001

CONCLUSION AND DISCUSSION

Although the rising incidence of counterfeiting in the luxury apparel market creates financial concerns, buyers usually prefer these items because of the prestige and social status that they offer. The goal of this study is to investigate the mediating role of attitude in the influence of customers' NFU on purchase intentions for counterfeit luxury items. The first major result of the study is that the NFU has a statistically significant positive influence on attitudes toward counterfeit luxury apparel. This finding suggests that individuals' desire to distinguish themselves from others leads them to develop positive attitudes toward counterfeit luxury products as much as toward original products. As Snyder and Fromkin [4] demonstrated, individuals with high NFU prefer to buy unusual and rare products. While luxury goods are a natural way to satisfy this desire for originality [5], counterfeit apparel can offer a comparable social signal at a reduced cost. This appeals to customers who do not have access to these products or who face financial restrictions [29, 36]. Therefore, counterfeit luxury apparel carries a symbolic value that satisfies individuals' desire to appear "different", which in turn leads to the formation of a positive attitude.

Another important finding of the study is that positive attitudes toward counterfeit luxury apparel have a strong and significant positive effect on purchase intention. This result is in full agreement with the previous counterfeiting studies [34, 39, 42]. The more positively consumers evaluate a counterfeit product, the more likely they are to purchase it. As long as these products meet basic expectations and satisfy social needs (status, identity expression), consumers

can derive satisfaction from their counterfeit product purchasing behaviour [43].

One of the most notable findings is the absence of a significant direct relationship between NFU and purchase intention. This shows that the effect of NFU on purchase intention is not direct, but entirely indirect. The bootstrap analysis revealed that the attitude variable plays a full mediating role in this relationship. In other words, a high level of NFU does not, by itself, drive a consumer to purchase counterfeit apparel; rather, it creates a positive attitude toward these products, which then translates into purchase intention [29, 33, 34]. This finding contributes to a more nuanced understanding of consumer behaviour. NFU, a psychological need, can be transformed into a concrete behavioural intention only through a cognitive and emotional evaluation process (attitude).

The relatively low mean values of attitude (M = 2.3032) and purchase intention (M = 2.2460) toward counterfeit luxury apparel indicate that respondents' overall interest in counterfeit luxury products is not particularly high in Türkiye. A primary possible reason for this situation may be the increased ethical awareness of Turkish customers regarding the negative impacts of counterfeit products. Sustainability and ethical sensitivity have become widespread, particularly among younger generations, and the importance given to concepts such as fair trade, sustainable consumption, and ethical consumption has increased. The influence of religious and cultural norms on consumer behaviour in Türkiye may also support these findings. Values such as "halal consumption" or "honesty" (avoiding waste, unjust enrichment, and deception) may have negatively impacted attitudes towards counterfeit products. Furthermore, the increase in customs and police inspections in recent years is also an important legal requirement that deters consumers from purchasing counterfeit luxury apparel. In addition to increased customs inspections, recent legal regulations concerning intellectual property rights and how these have been covered in the media may have increased consumer awareness and risk perception.

Another possible reason for low averages is that the use of counterfeit luxury apparel brings social risks to consumers. Firstly, since luxury apparel is a status symbol, wearing counterfeit versions can create an image of unreliability or low status. This also increases the risk of social stigma; using counterfeit apparel may be perceived as unethical, against the rules, or opportunistic. Because luxury brand communities value authenticity, individuals who use counterfeit luxury apparel may face the risk of exclusion. Finally, interpreting the preference for counterfeit products as a sign of financial inadequacy or lack of status can negatively impact an individual's social self-perception. These risks indicate that counterfeit luxury apparel consumption involves substantial social consequences beyond economic considerations. Moreover, participants may have also exhibited social desirability bias. They may have reported more negative attitudes toward counterfeit products than they hold, driven by concerns about maintaining a socially acceptable image. Indeed, communication factors such as the increase in marketing content for genuine luxury brands on social media, influencers promoting original luxury apparel, and the discrediting of counterfeit apparel may have influenced these results.

Furthermore, considering the prices of genuine luxury apparel, the low propensity for counterfeit luxury apparel may be related not only to ethical or social risks, but also to alternative consumption patterns such as the development of the "second-hand luxury" market or the proliferation of "affordable luxury" brands. In addition, the risks associated with product performance, such as poor quality, lack of durability, or aesthetic shortcomings, associated with counterfeit luxury apparel may also have lowered attitudes. This includes not only social but also functional risks. However, despite low absolute means, SEM analysis has shown that there is a statistically significant and positive relationship between "NFU and attitude" and between "attitude and intention to purchase". This supports the validity of the research model. The low overall tendency does not obscure the existence and structure of the relationship. On the contrary, it shows that individuals with high NFU have significantly more positive attitudes, even with a low overall tendency, and that this fully mediates intention.

The results of the present research provide major contributions to both theoretical and practical fields. Theoretically, this research expands the knowledge on psychological variables that drive counterfeit luxury consumption. It does so by identifying the full mediating role of attitude in the relationship between NFU and purchase intention. Furthermore, the fact that it was conducted in Türkiye, which is both a source and market for counterfeit apparel, enhances the validity and originality of the findings. The results of the research have various real-world implications for both fashion companies and regulatory agencies. Luxury fashion brand managers should be mindful that consumers' NFU might paradoxically drive demand for counterfeit items, and they ought to attempt to alter their favourable attitudes towards counterfeits. Therefore, marketers should prioritise genuine brand value and individualised customer experiences when creating their promotional activities. The usage of product traceability technologies, such as digital labels and blockchain-based verification, can dramatically improve brand legitimacy. Furthermore, fashion companies should provide education on awareness that emphasises the negative ethical, social, and quality constraints associated with counterfeit items while also improving their brand image. Policymakers might also create awareness campaigns for young customers, who are more inclined to perceive counterfeit luxury products as a means of expressing their sense of self.

This study has various shortcomings that may lead to further research. First, the convenience sampling approach reduces the findings' generalizability to the

entire Turkish population. Furthermore, the study concentrated primarily on the luxury apparel category. Future studies should include larger, more probabilistic samples from several product categories (accessories, cosmetics, and electronics). Finally, the use of self-reported measurements raises the possibility that social desirability bias impacted the results. Future studies could overcome these limitations by employing more diverse, cross-cultural samples and longitudinal or experimental designs to trace the evolution of attitudes toward counterfeits. Furthermore, incorporating other variables that may influence counterfeit consumption, such as cultural norms, ethical perception, brand loyalty, or social media influence, into the model would provide a more comprehensive understanding of this complex behaviour. Furthermore, the study's dataset may be considered a "low-involvement sample" due to low average attitude and intention values. Therefore, future research with different segments exhibiting stronger intentions may yield different results. Future research could highlight the importance of the cultural-economic context by comparing attitudes and behaviours towards counterfeit luxury apparel in developing countries like Türkiye or in European countries. Ultimately, this study establishes that the pursuit of uniqueness, when mediated through attitude, is a pivotal factor in understanding the consumption of counterfeit luxury apparel. Addressing this underlying psychological motivation offers a strategic pathway for the textile and fashion industries to reduce counterfeiting and promote sustainable consumption.

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Design and characterisation of silica-reinforced nonwoven agricultural fabrics for plant protection and agricultural production

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ABSTRACT – REZUMAT

Design and characterisation of silica-reinforced nonwoven agricultural fabrics for plant protection and agricultural production

Agricultural textiles protect crops from detrimental weather and pests while promoting sustainable agriculture. This research introduces an innovative nonwoven polypropylene (PP) fabric directly incorporated with silicon dioxide (silica) to diminish pesticide application. Silica acts as a physical insecticide by disrupting pests' protective wax coatings, offering an alternative to chemical pesticides that harm the environment and human health. UV-stabilized and non-stabilised polypropylene textiles were treated with silica at concentrations of 2%, 3%, and 5%. Essential qualities were evaluated, encompassing air permeability, tensile and tear strength, ageing resistance, and thermal stability (FTIR, DSC, TGA). SEM and EDS studies validated the presence and dispersion of silica. The findings indicated that silica diminished air permeability, thereby aiding in the retention of soil moisture and safeguarding plants. Although tensile and tear strength experienced minor reductions (up to 11% and 25%, respectively), the textiles continued to perform satisfactorily. Thermal investigations revealed slight alterations in decomposition temperatures. SEM–EDS showed that silica was evenly spread out but decreased a bit after ageing, suggesting that better fixing is needed for longer use. This direct incorporation of silica enhances pest control efficacy and UV resistance without dependence on chemical pesticides. The method promotes sustainable agriculture by improving crop protection and mitigating environmental hazards. Future research should concentrate on enhancing silica retention and conducting tests in actual field settings to create more robust agricultural textiles.

Keywords: *agricultural textiles, silica, non-woven, fabric, UV ageing*

Proiectarea și caracterizarea materialelor nețesute armate cu silice pentru agricultură destinate protecției plantelor și producției agricole

Agrotextilele protejează culturile de condițiile meteorologice nefavorabile și de dăunători, contribuind în același timp la promovarea agriculturii durabile. Acest studiu prezintă un material nețesut inovator din polipropilenă (PP), în care este încorporată silicea, cu scopul de a reduce necesitatea utilizării pesticidelor. Silicea acționează ca un insecticid fizic prin compromiterea straturilor protectoare de ceară ale dăunătorilor, oferind o alternativă la pesticidele chimice care sunt dăunătoare pentru mediu și sănătatea umană. Materialele textile din polipropilenă, atât cele stabilizate, cât și cele nestabilizate la radiații UV, au fost supuse unor tratamente cu concentrații de silice de 2%, 3% și 5%. Au fost evaluate proprietățile esențiale, printre care permeabilitatea la aer, rezistența la tracțiune și la rupere, rezistența la îmbătrânire și stabilitatea termică (FTIR, DSC, TGA). Analizele SEM și EDS au confirmat prezența și modul de dispersie a silicei. Rezultatele au indicat că silicea a redus permeabilitatea la aer, contribuind astfel la menținerea umidității solului și la protejarea plantelor. Deși rezistența la tracțiune și la rupere a înregistrat reduceri minore (de până la 11%, respectiv 25%), materialele textile și-au păstrat performanțele la un nivel satisfăcător. Analizele termice au relevat ușoare modificări ale temperaturilor de descompunere. Analiza SEM–EDS a arătat că silicea era distribuită uniform, dar a scăzut ușor după procesul de îmbătrânire, sugerând că este necesară o fixare mai bună pentru o utilizare pe termen lung. Această încorporare directă a silicei îmbunătățește eficacitatea combaterii dăunătorilor și rezistența la radiațiile UV fără a depinde de pesticide chimice. Această metodă promovează agricultura durabilă prin îmbunătățirea protecției culturilor și atenuarea riscurilor de mediu. Studiile viitoare ar trebui să se concentreze pe îmbunătățirea retenției de silice și pe efectuarea de teste în condiții reale de teren, pentru a crea agrotextile mai rezistente.

Cuvinte-cheie*: agrotextile, silice, materiale nețesute, țesătură, îmbătrânire sub acțiunea razelor UV*

INTRODUCTION

Agricultural textiles, classified as technical textiles, possess the capability to safeguard plants and products from external influences, including adverse weather, harmful insects, and various environmental factors. In 1948, the United States pioneered the use of agricultural textiles by enveloping small greenhouses with a transparent, thin paper known as cellophane. Since 1948, agricultural textiles have established a market presence, utilising various materials such as polypropylene, nylon, polyester, polyethylene, jute, and wool [1]. The agricultural textiles market is expanding and evolving daily in conjunction with population growth. In 2010, the agricultural textiles sector repre-

sented 6.4% of the technical textiles market, with sales estimated at 8.1 billion USD. This figure attained 10 billion USD in sales in 2014 and 14 billion USD in sales in 2022 [2, 3].

Contemporary agricultural textiles provide a straightforward yet efficient capacity for safeguarding against detrimental climatic factors, including hail, precipitation, wind, elevated temperatures, and ultraviolet radiation. These fabrics, because of their minute holes, establish optimal climatic conditions for plants while ensuring enough air permeability. These cloth constructions obstruct intense sunlight and, due to their capacity to reflect, absorb, and diffuse solar wavelengths, offer straightforward and efficient protection against detrimental ultraviolet (UV) radiation. In a world facing global warming, it is a fact that shade diminishes water requirements and reduces irrigation expenses [2, 4, 5].

The agricultural industry, of growing significance, employs numerous strategies to enhance product yield and diversity. The studies undertaken in the field of agricultural textiles are acquiring significant importance. Alongside technological advancements, the discovery of novel fibre materials has enhanced the diversity of fibres and the range of structures that may be constructed with these fibres. Consequently, advancements in agricultural textiles have proliferated, and these novel goods have begun to establish their presence in the market [6]. Agricultural textiles possess diverse and significant applications across the entire process, from pre-harvest to post-harvest, and continuing until the food reaches the end customer. Applications of agricultural textiles encompass moisture retention in soil, temperature regulation, nutrient loss reduction, surface greening, weed growth prevention, air permeability, germination facilitation, and the packing, shipping, and storage of agricultural products. The agricultural textiles used in these applications are expected to have key features, such as blocking sunlight and UV rays, holding water, reducing evaporation, protecting against outside conditions, being easy to transport, being affordable, and being good for the environment [7].

In recent years, there have been many new technologies in agricultural textiles, such as UV protective covers, antibacterial fabrics, pest-repellent materials with added scents or particles, and devices that generate electricity from movement.

Agricultural textiles can efficiently safeguard plants from crop pests. Their function as physical barriers renders the plants and crops they safeguard less vulnerable to assaults from birds, insects, parasites, and aphids. Pesticide spraying is presently the most recognised and often used technique for pest management in agriculture globally. Unfortunately, people still view pesticides as the traditional method of crop protection. Pesticides are chemical agents that are detrimental to undesirable organisms; they function by inhibiting the proliferation of dangerous species, repelling them, or exterminating them. In Germany, the yearly use of pesticides is estimated to be around nine kilograms per hectare [8]. Besides the detrimental impacts of pesticide application on water, soil, and beneficial organisms in agricultural regions, there are also harmful consequences on human health resulting from uncontrolled dosages and applications. Numerous studies have explored the correlation between pesticides and cancer in this domain [9, 10]. Globally, there remains a necessity for techniques that minimise pesticide usage while being environmentally sustainable and safeguarding human and animal health. Silica is also one of the primary materials used in this context. Research with silica-treated fibres is prevalent in this domain [11, 12, 13].

Research with silica seeks to offer an alternative to pesticides and diminish their application in agriculture. The term “silicate” in chemical literature denotes compounds composed of silicon and oxygen that include hydroxide ions and one or more metals, as well as silicon and silicate salts [14]. The insecticidal efficacy of silica powder relies on the absorptive dust mechanism [15]. This method suggests that the waxy layer on the outside of the insect interacts with silica dust, causing this layer to break down and be destroyed. Destruction of the protective layer that prevents desiccation in the insect leads to water loss by evaporation, ultimately resulting in the insect’s death from dehydration [14, 15, 16]. Silica powders cannot be directly applied to extensive regions due to their susceptibility to being displaced by meteorological phenomena such as wind and rain. As a result, researchers have developed diverse methodologies to integrate silica particles into textile materials [11, 17]. Unfortunately, these studies have only looked at adding silica to filament yarns, and it has been noted that using silica in these cases was also limited. Consequently, our study developed an agricultural textile by eliminating this constraint and directly integrating silica into the fabric. We assessed the benefits of the new material compared to existing materials using ageing, FTIR, TGA, SEM, and further tests. The innovative development of silica-integrated agricultural textiles represents a major milestone in the field of sustainable farming materials. By directly incorporating silica into the textile, this study overcomes the limitations associated with traditional methods of adding silica to filament yarns, paving the way for enhanced performance and durability. This approach not only enhances the functional properties of agricultural textiles but also contributes to more efficient resource use in agriculture, ultimately supporting the industry’s quest for sustainability and resilience in a changing climate.

MATERIALS AND METHODS

Materials

The study utilised non-woven polypropylene textiles with a basic weight of 32 g/m^2, including both UV-enhanced and UV-free variants. Silica, or Silicon dioxide, with the chemical formula SiO_2, a particle size of 100 microns, and the IUPAC designation “silicon dioxide”, was employed to deter agricultural

pests. The molar mass of silicon dioxide is 60.08 g/mol, the melting point is 1,710°C, the boiling point is 2,230°C, and the density is 2.65 g/cm³.

The printing paste was prepared using Tubivis VP 681 (ammonium salt of anionic carboxylic acid polymers, CHT, Turkey) as a synthetic thickener and Tubifast (CHT, Türkiye) as a fixative, together with a silicon dioxide additive. Table 1 below presents the abbreviations and their corresponding expansions for the samples utilised in the investigation.

Table 1

CODES AND DESCRIPTIONS FOR THE SAMPLES

Sample code	Sample description
N1	Silica-free and UV-added fabric
N2	Silica-free and UV-free fabric
N1-2	UV-added fabric with 2% silica
N1-3	UV-added fabric with 3% silica
N1-5	UV-added fabric with 5% silica
N2-2	UV-free fabric with 2% silica
N2-3	UV-free fabric with 3% silica
N2-5	UV-free fabric with 5% silica
B-N1-5	Pre-ageing, UV-added fabric with 5% silica
A-N1-5	Post-ageing, UV-added fabric with 5% silica
B-N2-5	Post-ageing, UV-free fabric with 5% silica
A-N2-5	Post-ageing, UV-free fabric with 5% silica

Air permeability

The Textest FX 3300 Air Permeability Tester III was employed to assess the air permeability values of all fabric samples. The tests were done according to ASTM D737-04. The air permeability value is determined by the volume of air traversing a designated region of the fabric sample within a specific time interval, influenced by the airflow between the fabric surfaces. Air permeability values of the fabric samples were measured from ten distinct regions of each sample.

Tensile strength and tear strength

The Lloyd LR5K Plus strength testing device was utilised to assess the tensile strength, percentage elongation, and tear strength of fabric samples exposed to a coating procedure based on the constant rate elongation (CRE) principle according to TS EN ISO 13934-2. Eight distinct samples were evaluated for tensile strength throughout ten repeated experiments. The specimens were fabricated to dimensions of 7×35 cm and evaluated in accordance with the specified standard, employing a pre-stress of 5.6 N and a jaw distance of 20 cm. The Elmatear Device was utilised to assess the tear strength of the fabric samples according to WSP 100.1. The testing procedure was conducted utilising the single-tear method. Eight distinct samples were evaluated for tear strength throughout ten repeated experiments. The samples were manufactured in dimensions appropriate for the B pendulum and evaluated in accordance with the specified standard. The tensile strength and tear strength tests were applied in the MD direction of nonwovens.

Ageing

The Q-LAB QUV/spray apparatus, equipped with a Solar Eye Irradiance Control Spectrophotometer, was utilised to assess the UV transmittance values of the fabric samples. Twenty distinct samples were produced following the operational parameters of the Q-LAB brand QUV/spray utilising the Solar Eye Irradiance Control Spectrophotometer apparatus. The samples created in accordance with the device's operational specifications were dispatched to the company, and the resultant data together with the post-test samples were returned. The experimental test methodology stipulates that it will be positioned in the Q-LAB QUV/spray apparatus equipped with the Solar Eye Irradiance Control Spectrophotometer. Each 24-hour ageing cycle comprises 12 hours of ultraviolet light exposure at 50°C (0.68 W/m^2, utilising an UltraViolet A [UVA] 340 lamp with a spectrum closest to sunshine) followed by 12 hours of water condensation at the same temperature.

FTIR

Fourier Transform Infrared Spectroscopy (FTIR) is an analytical technique employed to examine the chemical bonds within materials. FTIR works by measuring the spectrum created when infrared (IR) light interacts with the vibrations of the material's molecules. This spectrum serves as a distinctive fingerprint that conveys information regarding the chemical bonds of the material. Qualitative analyses of the samples were performed using a PerkinElmer Frontier FT-IR instrument within the wavelength range of 700 cm^{-1} to 4000 cm^{-1}. The results of the fabric sample tests were documented on a computer, and the acquired data were transformed into graphs.

DSC

Differential scanning calorimetry (DSC) is a thermal analysis method that quantifies the heat absorbed or released by a sample during heating or cooling processes. This approach involves heating the sample in comparison to a reference sample, during which the heat emitted or absorbed by the sample varies from that of the reference sample.

In DSC analysis, the sample is measured with a precision balance and subjected to heat flow as the temperature rises or falls. The sample and reference pans are fitted with heating elements and are kept at the same temperature. The thermal characteristics of the sample are depicted in the heat flow graph obtained during the temperature variation.

DSC analysis was performed in a nitrogen environment (80 ml/min) across a temperature range of 0°C to 500°C, maintaining a constant heating rate of 10°C/min with a PerkinElmer DSC 400 apparatus.

The samples were made with a mass ranging from 5 to 10 mg. The test results were documented by the computer and transformed into a graph.

TGA

Thermogravimetric Analysis (TGA) is a thermal analysis technique that investigates the variations in the weight of a material in response to a controlled rise or decrease in temperature. A sample is typically heated at a designated, consistent temperature. The chosen temperature protocol delivers precise information regarding the sample. TGA analysis was performed to assess the thermal stability of fabric samples. The study was performed in a nitrogen environment (200 mL/min) at temperatures ranging from 30°C to 600°C, with a constant heating rate of 10°C/min. The sample's weight was calibrated to range from 5 to 10 mg. The samples for the TGA test have been adjusted to suitable dimensions and masses.

SEM and EDS

The scanning electron microscope (SEM) is a laboratory instrument utilised for surface examination. This apparatus employs an electron beam to generate high-resolution pictures of sample surfaces. The signals produced when electrons interact with the sample provide information about the surface shape, chemical makeup, and crystal structure of the sample. Data is often gathered from a designated region of the sample surface, resulting in a two-dimensional image that illustrates spatial changes in these attributes. It was acquired with a QUANTA FEG 250 Scanning Electron Microscope (SEM). Energy Dispersive Spectroscopy (EDS) is a microanalytical method employed to identify and quantify the elements within a sample. When utilised alongside a scanning electron microscope (SEM) or a scanning transmission electron microscope (STEM), energy-dispersive spectroscopy (EDS) can provide elemental maps of samples.

RESULTS AND DISCUSSIONS

As stated in the Materials and Methods section, the following physical properties of coated and uncoated fabrics were examined before ageing and after being kept under standard conditions.

Air permeability

The air permeability metric is a crucial attribute in agricultural textiles. In agricultural textiles, the objective is to safeguard the plant while ensuring adequate moisture and oxygen supply. This is crucial for the plant's development.

Figure 1 displays the air permeability values of the fabrics with 2%, 3%, and 5% silica additions, alongside the unmodified reference fabrics, as determined by the air permeability equipment. The tests were performed with 10 repetitions for each sample, and the average was calculated.

The air permeability of fabrics is influenced by the fabric texture, fibre composition, yarn characteristics, ambient conditions, and the viscosity of substances applied to the fabric [18].

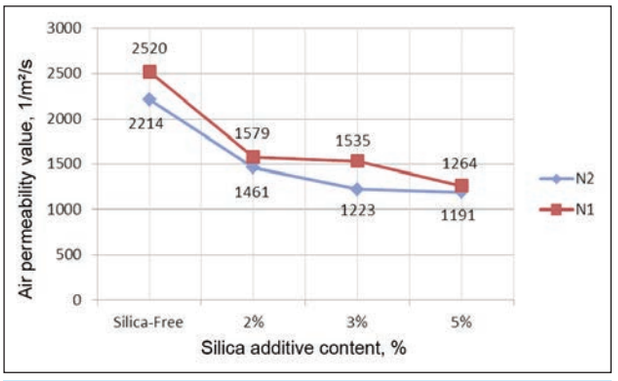


Fig. 1. Air permeability outcomes of untreated, 2%, 3%, and 5% silica-modified polypropylene fabrics

The UV-free cloth (N2), exhibiting identical qualities, possesses a reduced air permeability rating. This circumstance indicates that the fibre ratio or density employed in the N2 fabric may be elevated. Post-coating, the air permeability ratings of both fabrics diminish. A 2% coating on the N1 fabric led to a 37% decrease, whereas a 34% decrease was noted on the N2 fabric. A 3% coating on the N1 cloth resulted in a 2% reduction in air permeability, but the N2 sample exhibited a 16% reduction. The N1 sample exhibited a 17% reduction with a 5% coating, but the N2 sample demonstrated a 2.6% decrease. Once the coating surpassed 5%, no additional decrease in air permeability values was noted; hence, the coating rate was not augmented further. A reduction of roughly 50% in air permeability values was recorded in the N1 fabric, and a decrease of 46% in the N2 fabric, between the uncoated and 5% coated fabrics. This also demonstrates that the coating and the results are congruent.

The average air permeability values for samples N1 and N2 are presented in figure 1. Upon examining figure 1, it is evident that an increase in silica content in both sample types correlates with a decrease in air permeability. This issue, significant for agricultural textiles, aligns with the literature when compared to prior investigations.

Now, let's support these results with correlation and regression analyses. When we examine the data in the table and graph, the basis of our analyses is the Silica Ratio (Independent Variable – *X*) and the Average Air Permeability Value (Dependent Variable – *Y*).

N1 sample analyses

Correlation Analyses (Pearson r): The correlation coefficient (*r*) indicates the direction and strength of the relationship between two variables. The correlation coefficient (*r*) = –0.921. That value means there is a very strong and negative relationship. As the silica ratio increases, N1 values decrease significantly.

Regression Analysis: We use the equation $y = mx + c$ to model the linear relationship between the data. Slope (*m*) = –243.2, Intercept (*c*) = 2332.6, Regression

Equation: $y = -243.2x + 2332.6$, Coefficient of Determination (R^2) = 0.848.
The change in the silica ratio explains 84.8% of the change in N1 values. The model is reliable, but the sudden drop in the graph from 0 to 2 suggests that the relationship may not be fully linear (perhaps exponential).

N2 sample analyses

Correlation Analyses (Pearson r): The correlation coefficient (r) = –0.927. Similar to N1, that value indicates there is a very strong and negative correlation in the N2 sample.
Regression Analyses: Slope (m) = –205.9, Intercept (c) = 2036.9, Regression Equation: $y = -205.9x + 2036.9$, Coefficient of Determination (R^2) = 0.859.
The change in silica content explains 85.9% of the change in N2 values. Sample N2 fit the linear model slightly better than sample N1.
Table 2 summarises the statistical comparison between the two samples.
For both sample groups, increasing the silica content significantly reduces the test results (measured based on the number of replicates). The decrease is particularly sharp between 0% (Silica-Free) and 2%. After this point (2%, 3%, 5%), the decrease continues, but its momentum slows.
R^2 values above 0.80 indicate that the negative effect of the additive content on these values is statistically significant.

Tensile and tear strength

The tensile strength measurements of the fabric samples were performed using the Lloyd LR5K Plus strength tester, employing the constant rate elongation (CRE) method. A minimum of 10 tests were performed on each fabric sample, and the average of the findings was calculated.
The average tensile strength values for the N1 and N2 samples are presented in figure 2. Upon examination of figure 2, it is seen that the strength values

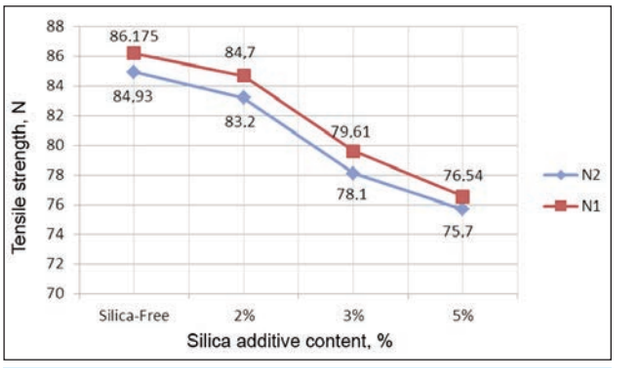


Fig. 2. Tensile strength outcomes of untreated, 2%, 3%, and 5% silica-modified polypropylene fabrics

of both fabric types exhibit a slight, if not significant, decline with increasing silica content.
In the N1 fabric, the overall strength reduction decreased by 11% compared to the initial value, while in the N2 sample, it also decreased by 11%. In the N1 sample, a 2% coating results in a strength reduction of 1.7%, but in the N2 sample, the loss is 2%. As the coating quantity increases, the data exhibit a slight decline; nonetheless, the overall percentage remains at 11% for both fabrics. This condition suggests that the coating process does not substantially diminish the strength values. This is an exceptionally advantageous circumstance.
The graph shows the distribution analyses of the tensile strength of the N1 and N2 samples based on the tensile strength (tensile strength) by changing the silica additives (0%, 2%, 3%, 5%) in line with the obtained data.
Table 3 below summarises the Pearson Correlation Coefficient (r), the Coefficient of Determination (R^2), and the Linear Regression Equation for both samples.
The correlation coefficient (r) for both samples is very close to –1 (–0.96 and –0.97). These data show that the tensile strength of the material decreases sharply and consistently as the silica addition ratio increases.
The R^2 values above 0.90 (93.5% for N1, 94.1% for N2) demonstrate that the resulting linear equations

Table 2

CORRELATION AND REGRESSION ANALYSES ABSTRACT BETWEEN SILICA CONTENT AND AIR PERMEABILITY			
Parameter	**Sample N1**	**Sample N2**	**Comment**
Correlation (r)	–0.921	–0.927	Both have a strong negative relationship.
Regression equation	$y = -243.2x + 2332.6$	$y = -205.9x + 2036.9$	The slope for N1 is steeper, meaning that the increase in silica affects N1 more severely.
R^2 Value	0.848	0.859	The data fit the model well.

Table 3

CORRELATION AND REGRESSION ANALYSES ABSTRACT BETWEEN SILICA CONTENT AND TENSILE STRENGTH			
Sample	**Correlation (r)**	**(R^2) Value**	**Regression equation ($y = mx + c$)**
N1	–0.967	0.935	$y = -2.05x + 86.88$
N2	–0.970	0.941	$y = -1.97x + 85.41$

are quite successful in explaining this data set. In other words, the decrease in tensile strength follows a largely linear trend. The coefficient of x (slope) in the regression equations shows how much strength is lost with each 1% silica increase. The N1 sample loses approximately 2.05 N strength with each 1% silica increase. The N2 sample loses approximately 1.97 N strength with each 1% silica increase. According to the graph and analyses, the silica additive in this composite structure negatively affects the tensile strength.

The tear strengths of both unprocessed and processed fabric samples were measured using the Elmendorf equipment from the James H. Heal brand. Figure 3 presents the average tear strength values for samples N1 and N2. Upon examining figure 3, it is evident that an increase in silica content in both fabric types correlates with a decrease in strength values. The initial and end tear strength values for the N1 and N2 samples are similar, with a total strength loss of 25% for both N1 and N2 textiles. In the 2% coating, the loss for the N1 sample is 11%, whereas for the N2 sample, it is 15%.

Analysis of the tensile and tear strength graphs reveals that, in both sample categories, strength values diminish with an increase in silica concentration. The reduction in strength values corresponding to the rise in silica content suggests that silica contributes to a deterioration of strength in the fibre structure. This scenario indicates that the infiltration of silica between the fibres may have diminished friction and created slight alterations in the chemical structure of the fibres. The deterioration of strength in the fibre structure has directly impacted the fabric's strength. The result obtained aligns with the literature [19, 20]. Table 4 below provides a statistical summary of the relationship between the tear strength of the samples and the silica additive ratio.

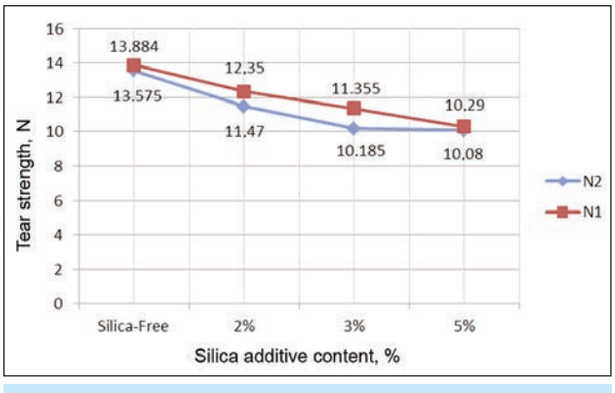


Fig. 3. Tear strength outcomes of untreated, 2%, 3%, and 5% silica-modified polypropylene fabrics

The calculated R^2 value for sample N1 is 0.995. This indicates that the data fit the generated regression line almost perfectly. Tear strength decreases very smoothly and linearly as the silica content increases. Each 1% addition decreases strength by approximately 0.73 N. Although the N2 sample also exhibits a generally negative trend (r = –0.909), the change between 3% and 5% is minimal (from 10.185 to 10.08). This indicates a "break" or "saturation" point in the graph. While linear regression for N2 shows a general decrease, the dataset is actually more prone to a curvilinear (polynomial) behaviour. After the 3% additive rate, the strength decrease almost ceased. In both samples, silica addition reduces tear strength. Sample N1 exhibited higher strength values than N2 at all concentration levels.

Ageing

The ageing processes of the fabric samples were conducted using the Q-LAB brand "QUV/spray with Solar Eye Irradiance Control Spectrophotometer Device". The procedure was conducted in the Paint and Colour Laboratories of MMK Metalürji San. Tic. ve Liman İşletmeciliği A.Ş. in Dörtyol, Hatay, adhering to TS EN ISO/IEC 17025 standards. The samples were created with dimensions of 7.5×15 cm, and the tests were executed. Subsequent to the testing, the sample specimens were collected for post-ageing analysis. Figure 4 presents comparative photos of the post-ageing N1-5 sample.

A pilot study using a 500-hour ageing cycle was conducted; however, upon completion, both sample types were entirely disintegrated. Consequently, it was determined to utilise 200- and 300-hour cycles



Fig. 4. Post-ageing images of non-woven fabric samples N1-5-4 (200 hours), N1-5-5 (300 hours), and N1-5-1 (500 hours)

Table 4

CORRELATION AND REGRESSION ANALYSES ABSTRACT BETWEEN SILICA CONTENT AND TEAR STRENGTH

Sample	Correlation (r)	(R^2) Value	Regression equation ($y = mx + c$)
N1	–0.997	0.995	$y = -0.729x + 13.793$
N2	–0.909	0.826	$y = -0.722x + 13.131$

for these samples. The samples could not undergo strength testing due to their disintegration following the ageing process (figure 4). The samples underwent FTIR, DSC, TGA, and EDS analyses, and SEM pictures were acquired both before and after the ageing procedure. Table 5 presents the sample codes and ageing durations for the samples evaluated before and after ageing.

In the analysis of the test results, the sample codes in the graphs are prefixed with the letters B or A. The symbol 'B' signifies the term 'before,' denoting the test outcome of the sample before ageing. The letter 'A' represents the coded term 'after,' denoting the test outcome of the sample post-ageing.

Table 5

FABRIC SAMPLE CODES EXPOSED TO AGEING PROCESSES AND DURATIONS

Sample codes	Duration of exposure to ageing
N1-1	500 hours
N2-3	500 hours
N2-2	300 hours
N1-3-1	500 hours
N1-5-1	500 hours
N1-5-4	200 hours
N1-5-5	300 hours
N2-1	200 hours
N2-5-1	500 hours

FTIR test outcomes preceding and following ageing

The samples in this study were analysed using a PerkinElmer Frontier FT-IR instrument, which works with wavelengths from 700 cm^{-1} to 4000 cm^{-1}. The FT-IR technique was utilised on the fabric samples B-N1, B-N1-5-1, B-N2-5-1, A-N1, A-N1-5-1, and A-N2-5-1. The collected data were individually documented on the computer and transformed into graphs. Figure 5 shows the results of the FTIR tests for the nonwoven fabric samples B-N1, B-N1-5-1, B-N2-5-1, A-N1, A-N1-5-1, and A-N2-5-1. Upon examination of figure 5, it is noted that the broad band between the wavelengths of 3200 cm^{-1} and 3800 cm^{-1} corresponds to the OH functional groups.

The distinctive peaks of pure polypropylene are as follows: 2949.81 cm^{-1} and 2917.46 cm^{-1} for C-H stretching vibrations, 1455.73 cm^{-1} for $–CH_2$ bending vibrations, 1375.60 cm^{-1} for $–CH_3$ bending vibrations, and 1067.22 cm^{-1} for C-C stretching vibrations. The distinctive peaks of silica include 1061.94 cm^{-1} for Si-O-Si stretching vibrations, 971.02 cm^{-1} for Si-OH stretching vibrations, and 798.36 cm^{-1} for Si-O bending vibrations [12, 20].

Upon analysis of the peaks in the FTIR spectrum, the peak at 2914.44 cm^{-1} is attributed to C-H stretching vibrations, the peak at 1450.46 cm^{-1} is associated with $–CH_2$ bending vibrations, the peak at 1375.24 cm^{-1} corresponds to $–CH_3$ bending vibrations, and the peak at 974.05 cm^{-1} is linked to C-C stretching vibrations.

DSC

Subsequent to the DSC experiments, the relevant results were transformed into graphs depicting the fluctuation of heat flow in relation to time or temperature. Negative or positive peaks indicate exothermic or endothermic reactions, depending on the technology used in the research measuring devices. DSC graphs exhibit varying endothermic and exothermic peaks contingent upon the presence of silica in the fabrics and their ageing status.

The DSC test was conducted on samples A-N1-5, A-N2-5, B-N1-5, B-N2-5, A-N1, and B-N1 to examine the impact of age on their thermal structure. Figure 6 below displays the graph pertaining to these samples.

In the DSC tests performed on the samples, a notable alteration was detected between the pre-ageing and post-ageing samples. The peak values in the curves of the pre-ageing samples range from 10 to 15 mW, whereas the peak values in the curves of the post-ageing samples range from 15 to 20 mW. This circumstance suggests that the crystallisation temperatures in the post-ageing samples have diminished as a result of the thermal treatment they experienced.

As seen in figure 6 above and table 6 below, the pre-ageing peak values for all samples decreased to lower temperatures after ageing. This may be attributed to the temperature-dependent degradation

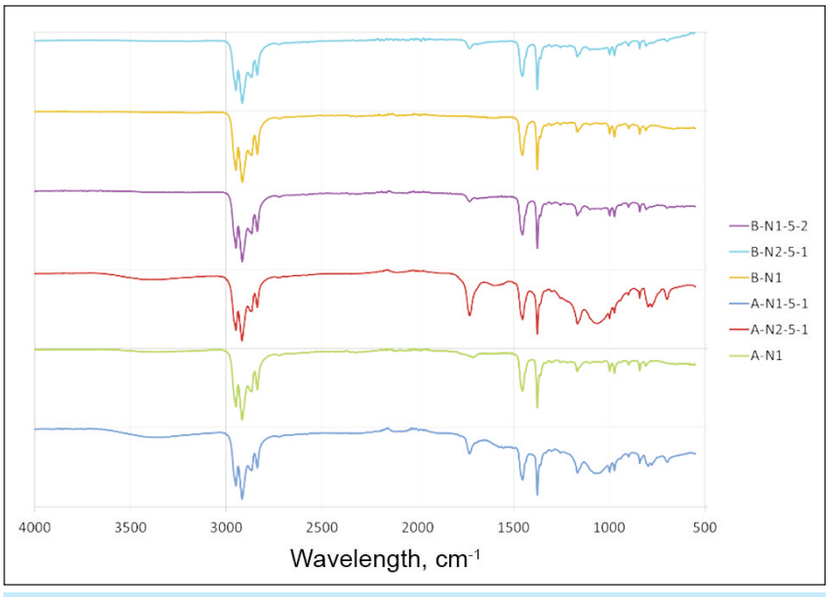


Fig. 5. FTIR test findings for non-woven fabric samples B-N1, B-N1-5-1, B-N2-5-1, A-N1, A-N1-5-1, A-N2-5-1

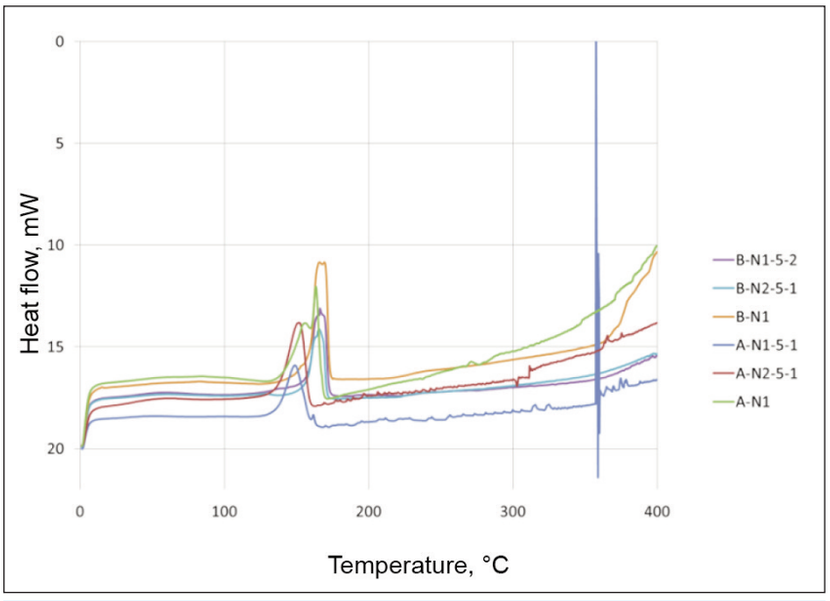


Fig. 6. Differential Scanning Calorimetry test results of fabric samples labelled A-N1-5, A-N2-5, B-N1-5, B-N2-5, A-N1, and B-N1

Table 6

DECOMPOSITION TEMPERATURES OF SAMPLES PRE- AND POST-AGEING

Sample codes	Temperatures (°C)
B-N1	168.5
B-N1-5	166.6
B-N2-5	166.5
A-N1	156.6
A-N2-5	153.0
A-N2-5	150.0

of the PP constituent fabric structure during the ageing process. As seen in table 6, the degradation temperatures were higher in samples without silica additives.

TGA

TGA analysis was performed to assess the thermal stability of fabric samples. Alternatively, it can be described as the temperature-dependent percentage mass reduction of the substance. The study was performed in a nitrogen environment (200 ml/min) at temperatures ranging from 30°C to 600°C, with a constant heating rate of 10°C/min. Sample weights were calibrated to 5–10 mg in accordance with the testing protocol.

Upon examination of figure 7, it is evident that there is no substantial difference in the early degradation temperatures of the samples. In all samples, weight loss occurs at approximately 150°C and persists until 450–500°C, except the A-N1 sample, where weight stabilises beyond this temperature range. The region between the 100% line and the 20% line represents the degradation zone of the PP polymer. The region between the 20% and 10% lines is where silica persists as a residue. This scenario aligns with the existing literature. The figure indicates that only the A-N1 sample persisted in weight loss over the 10% threshold. This circumstance suggests that the A-N1 sample included no silica as a result of the applied treatments.

The TGA data indicate that the degradation temperatures of the samples containing additional silica decreased. This scenario is inconsistent with the literature. This scenario is believed to have developed from the chemical substances employed in the printing process during the incorporation of silica [20]. The study reveals that degradation temperatures have slightly diminished with the ageing process. This condition aligns with the findings in the literature [20, 21].

SEM – EDS Images

EDS views of the N1-5 sample's surface at 100 µm and 200 µm scales are presented in figure 8. The luminous particles in the photographs signify that the silica powder has been effectively deposited on the surface and interspersed among the fibres.

Both the pre- and post-ageing EDS pictures of the N1-5 sample, with a 20 µm pixel size, are displayed in figure 9, *a* and *b*. Analysis of figure 9 reveals that the N1-5 sample's pre-ageing silica powder content

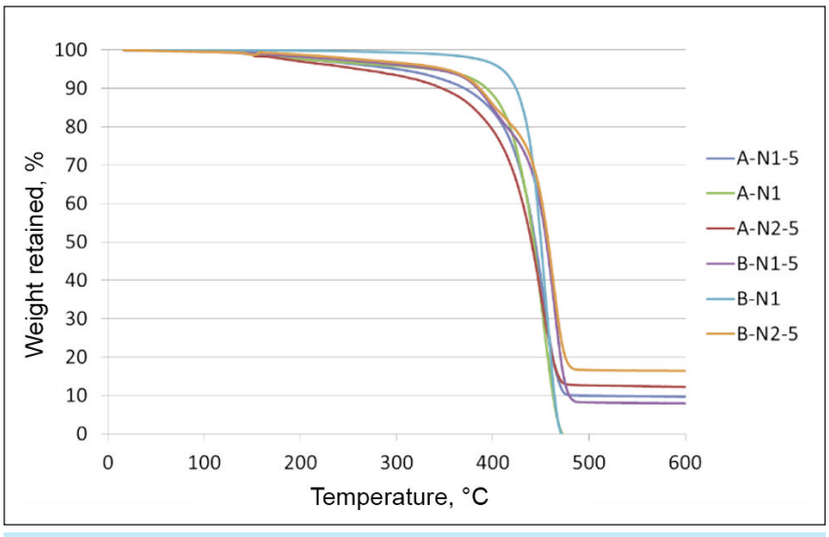
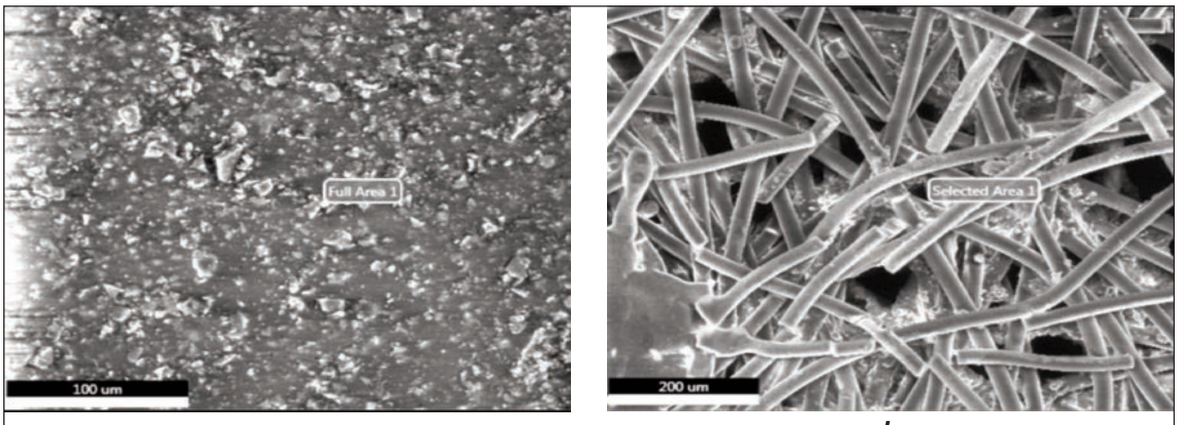
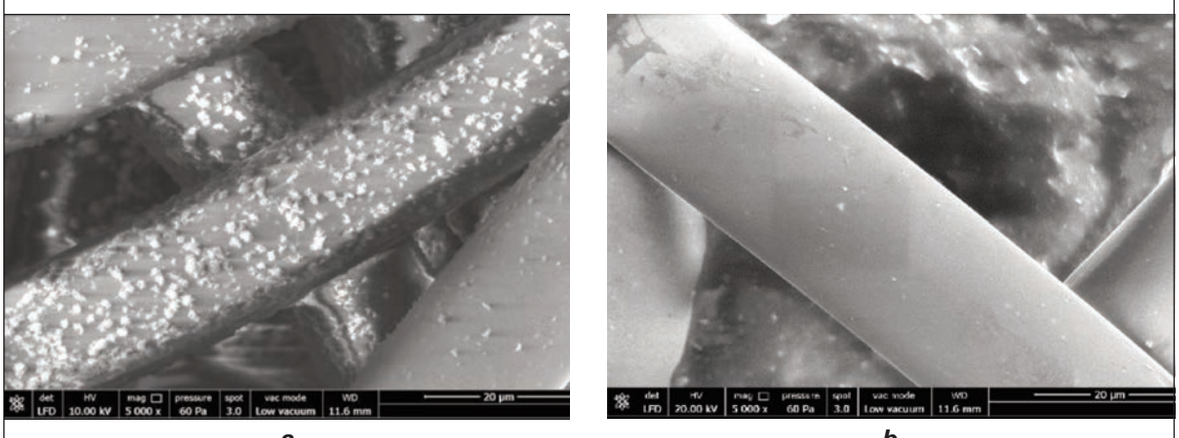


Fig. 7. The TGA test outcomes of fabric samples designated A-N1-5, A-N2-5, B-N1-5, B-N2-5, A-N1, and B-N1



a *b*

Fig. 8. Results of: *a* – EDS images of B-N1-5 at 100 µm; *b* – B-N1-5 at 200 µm samples



a *b*

Fig. 9. Results of: *a* – SEM pictures of B-N1-5 at 20 µm; *b* – A-N1-5 at 20 µm samples

has considerably dropped in comparison to its post-ageing silica powder content.

Once more, figures 10 and 11 display the N1-5 sample's EDS results both before and after ageing. The EDS point analysis of the B-N1-5 and A-N1-5 fabric samples shows the percentage of different elements found in the chemical compounds of the powders used as additives, as shown in the images from the EDS % elemental analysis results. The EDS examination revealed that the B-N1-5 and A-N1-5 samples included only carbon, oxygen, and silicon. The B-N1-5 fabric sample exhibited a carbon content of 61.04%, an oxygen content of 31.27%, and a silicon content of 7.69%. In contrast, the A-N1-5 fabric sample had a carbon content of 83.44%, an oxygen content of 14.72%, and a silicon content of 1.84%. This scenario indicates that external environmental factors, including sunlight, dew, and precipitation

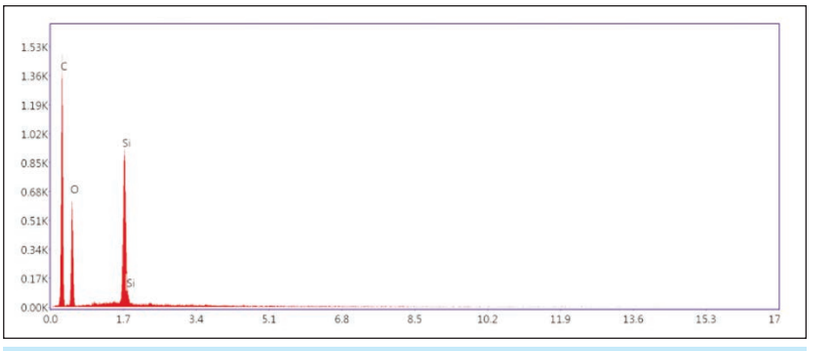


Fig. 10. EDS analysis results for sample B-N1-5

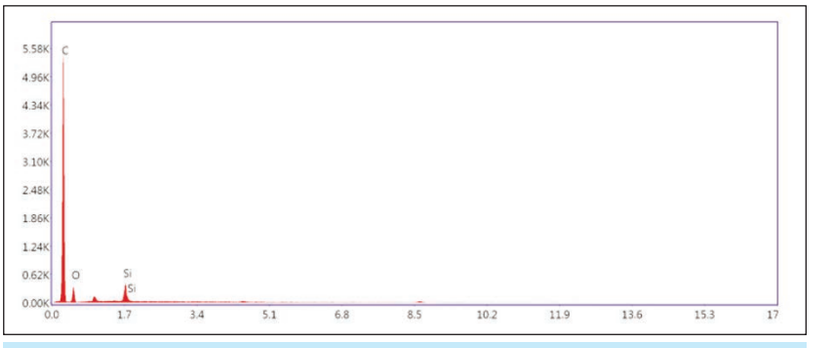


Fig. 11. EDS analysis of sample A-N1-5

during ageing, may have diminished the silica content in the fabric samples.

CONCLUSIONS

This work produced a novel agricultural textile by incorporating silicon dioxide (silica) into both UV-stabilized and non-UV-stabilized nonwoven polypropylene (PP) textiles. The objective was to augment the protective efficacy of agricultural coverings against external elements, including adverse weather and pests, while simultaneously enhancing their resilience to ageing and durability under field circumstances.

The experimental findings indicated that the application of silica at concentrations of 2%, 3%, and 5% significantly influenced the essential physical properties of the nonwoven polypropylene textiles. Air permeability experiments indicated that a rise in silica concentration progressively diminished air permeability values. These results have also been supported by regression analyses. Silica additives have dramatically reduced the air permeability of the composite material. The greatest effect has been seen when a small amount (2%) of the additive is added, as opposed to no additive at all. Although diminished airflow may first appear disadvantageous, it can be beneficial in agricultural contexts by facilitating enhanced control of microclimatic conditions beneath the fabric, aiding in moisture retention, and safeguarding crops from pests and inclement weather. Tensile and tear strength assessments indicated that the incorporation of silica resulted in a marginal reduction in the mechanical strength of the textiles. Nevertheless, this decrease remained within permissible boundaries (about 11% in tensile strength and up to 25% in tear strength at the maximum silica concentration). Similar results have been seen in the regression analyses.

This suggests that the coating procedure did not substantially undermine the integrity of the underlying nonwoven polypropylene fabric. The findings indicate that silica particles may engage with the fibre structure by infiltrating the fibre network, potentially diminishing inter-fibre friction, which marginally influences the fabric's resistance to mechanical stress. Notwithstanding this, the textiles retained adequate strength for functional agricultural application.

The UV ageing tests validated that the silica-treated textiles demonstrated enhanced durability under accelerated weathering circumstances. While high-intensity ageing cycles of 500 hours resulted in total disintegration, modified 200- and 300-hour testing offered realistic insights into the fabrics' performance under standard UV exposure. The FTIR study verified that the chemical structure of the polypropylene matrix mostly remained unaltered, exhibiting unambiguous indications of silica integration prior to ageing and evidence of deterioration or silica loss subsequent to ageing.

Thermal investigations (DSC and TGA) indicated that the incorporation of silica and UV ageing marginally affected the thermal stability and crystallisation characteristics of the textiles. A slight decrease in thermal breakdown temperatures was noted in silica-treated samples relative to untreated samples. This phenomenon can be ascribed to the interactions between silica particles and the polypropylene matrix, along with the chemical agents employed in the fixing process. Nevertheless, thermal stability persisted within an acceptable range for standard agricultural circumstances.

SEM and EDS investigations confirmed the presence and distribution of silica particles on the fabric surfaces. Prior to ageing, the silica particles were equally distributed throughout the fibres, significantly improving the fabric's barrier function. Post-ageing SEM and EDS data revealed a significant decrease in silica concentration, presumably because of the influence of UV radiation, moisture, and various environmental variables. This discovery underscores the necessity of enhancing the fixation process to augment silica retention over prolonged use in open-field environments.

The study illustrates that the direct incorporation of silica into nonwoven agricultural textiles presents distinct advantages.

Silica functions as a physical insecticide, compromising bugs' protective barriers and diminishing reliance on toxic chemical pesticides, hence promoting environmentally sustainable pest management. The enhanced textiles retain adequate strength and permeability to shield crops from inclement weather while fostering optimal growing conditions. The improved resistance to UV degradation suggests that silica treatment can prolong the operational lifespan of crop coverings in practical environments.

In summary, the novel method of treating nonwoven polypropylene textiles with silica particles effectively tackles the dual issues of pest management and weather resistance in agricultural contexts while adhering to sustainability objectives and minimising reliance on chemical pesticides. Future research may focus on improving how silica is attached to ensure it stays longer, looking at different sizes of silica particles, and testing how well these textiles work in various weather conditions during real field trials. These enhancements would further establish silica-treated agricultural textiles as a feasible alternative for contemporary, sustainable, and resilient agriculture.

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Applying a linguistic MCDM method to handle the machinery purchase problem in the textile industry

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ABSTRACT – REZUMAT

Applying a linguistic MCDM method to handle the machinery purchase problem in the textile industry

Machinery investment decisions are complex, multi-criteria problems that require balancing cost, performance, and quality factors under uncertainty. This research introduces a linguistic multi-criteria decision-making (MCDM) method regarding machinery investments, integrating both qualitative and quantitative information in a structured computational framework. To ensure objectivity in the evaluation process, the entropy weighting method is employed to determine the criteria importance based on data dispersion. The proposed model enables experts' linguistic judgments to be transformed into comparable numerical scales, allowing seamless integration with quantitative data in a single decision matrix. An empirical application to the laser cutting machine investment issue in the textile sector demonstrates the method's effectiveness in ranking alternatives and reducing subjectivity in decision-making. Results show that the model provides transparent, reproducible, and computationally efficient evaluations. The study contributes to the broader industrial engineering literature by extending linguistic MCDM applications to machinery investment decisions, offering managers a systematic and data-driven tool for complex capital allocation problems.

Keywords: *investment selection, linguistic MCDM, machinery selection, management, textile companies*

Aplicarea unei metode lingvistice de luare a deciziilor multicriteriale (MCDM) pentru gestionarea problemei achiziționării de utilaje în industria textilă

Deciziile privind investițiile în utilaje reprezintă probleme complexe, multicriteriale, care necesită găsirea unui echilibru între factorii de cost, performanță și calitate în condiții de incertitudine. Acest studiu prezintă o metodă lingvistică de luare a deciziilor multicriteriale (MCDM) aplicabilă investițiilor în utilaje, care integrează atât informații calitative, cât și cantitative într-un cadru computațional structurat. Pentru a asigura obiectivitatea procesului de evaluare, se utilizează metoda ponderării prin entropie pentru determinarea importanței criteriilor în funcție de dispersia datelor. Modelul propus permite transformarea deciziilor lingvistice ale experților în scale numerice comparabile, facilitând integrarea fără probleme cu datele cantitative într-o singură matrice decizională. O aplicație empirică care vizează problema investiției într-o mașină de tăiat cu laser în sectorul textil demonstrează eficacitatea metodei în ierarhizarea alternativelor și reducerea subiectivității în procesul decizional. Rezultatele arată că modelul oferă evaluări transparente, reproductibile și eficiente din punct de vedere computațional. Studiul contribuie la literatura de specialitate din domeniul ingineriei industriale prin extinderea aplicațiilor MCDM lingvistice la deciziile privind investițiile în utilaje, oferind managerilor un instrument sistematic și bazat pe date pentru gestionarea problemelor complexe de alocare a capitalului.

Cuvinte-cheie*: selectarea investițiilor, MCDM lingvistic, selectarea utilajelor, management, companii din industria textilă*

INTRODUCTION

Machinery investment decisions are crucial to sustaining the competitiveness and operational efficiency of manufacturing firms. These decisions are typically capital-intensive and influence key performance outcomes such as product quality, productivity, and flexibility. Selecting the most appropriate machinery alternative, therefore, represents a complicated MCDM problem that needs the simultaneous evaluation of both quantitative and qualitative factors. A suboptimal investment may lead to inefficiencies, unnecessary capital expenditure, and reduced long-term competitiveness.

The decision environment in machinery selection is inherently uncertain, as many evaluation criteria, such as usability, precision, or aesthetic design, are linguistic or qualitative in nature. Experts often express their assessments through linguistic terms rather than precise numerical values, which complicates aggregation and comparison. To address this, linguistic MCDM methods provide a robust computational mechanism for modelling human judgment and transforming qualitative evaluations into quantifiable forms. These methods enable decision makers to integrate both linguistic and numerical data consistently within a unified framework.

Previous research has successfully applied MCDM approaches such as AHP, TOPSIS, and VIKOR in areas including equipment selection, supplier evaluation, and personnel recruitment. For example,

Štirbanović et al. [1] used TOPSIS and VIKOR methods to deal with the flotation machine selection and compared the results. Thasni et al. [2] employed the fuzzy TOPSIS method for evaluation of cloud service providers. Chen and Hung [3] used a two-phase MCDM method for the personnel recruitment problem. Uddin et al. [4] used an integrated model by combining the analytic hierarchy process (AHP) with the technique for order of preference by similarity to ideal solution (TOPSIS) for enterprise resource planning (ERP) system selection in Bangladesh. While AHP was used for computing the criteria weights, TOPSIS was employed to determine the ranking order of alternatives.

As stated above, MCDM methods are widely used in almost all aspects of business decisions. However, MCDM studies addressing issues in the textile or clothing industry are quite limited. For example, Yayla et al. [5] used the Fuzzy TOPSIS method for supplier selection in the garment industry. Aydın et al. [6] evaluated the performance attributes of retailers using a supply chain operation reference model and the analytical hierarchy process in the clothing industry. Onden and Eldemir [7] used a combination of geographic information systems and fuzzy analytic hierarchy process (fuzzy AHP) to evaluate the textile manufacturing facility location alternatives.

Karabasevic et al. [8] employed SWARA and EDAS methods to evaluate websites in the textile industry. Bathrinath et al. [9] conducted a risk analysis in the textile industry using a hybrid MCDM method. Ulutaş and Karakuş [10] used an integrated MCDM method to select the location for a textile manufacturing facility.

Although the existing MCDM studies have made important contributions to decision-making problems in manufacturing and the textile industry, there are some limitations in the existing literature. Many studies use quantitative data. This may not be sufficient to understand the subjective nature of expert judgements. In addition, criteria weights are often calculated using subjective methods such as AHP [4, 9] or expert scoring. This may be biased and reduce reproducibility. Few studies provide an integrated computational framework that simultaneously combines linguistic evaluations and objective weighting mechanisms within a single decision matrix. There is a need for decision makers to combine linguistic information with data-driven weighting techniques to increase objectivity and transparency in decision-making problems.

Therefore, the main aim of this study is to develop and apply a computational linguistic MCDM framework for machinery investment selection in the textile industry, where decision-making involves both quantitative data and qualitative expert judgments under uncertainty. To achieve this aim, the study pursues the following specific objectives: (i) to integrate linguistic expert evaluations and quantitative performance indicators within a unified decision matrix; (ii) to determine criterion weights objectively using the entropy weighting method; (iii) to rank alternative machinery investment options using a distance-based evaluation mechanism; and (iv) to demonstrate the applicability of the proposed framework through a real-world case study involving advanced textile machinery.

This study makes three contributions. First, it introduces a data-driven and computationally efficient linguistic MCDM framework that integrates expert knowledge with quantitative measures. Second, it extends the use of entropy-based weighting in linguistic environments, ensuring greater objectivity in industrial decision-making. Third, it provides a replicable decision-support tool that can be adapted to other machinery selection and capital investment problems beyond the textile sector.

The following sections are as follows. The theoretical foundation and methodology of the suggested approach are explained in the 2nd and 3rd sections. An empirical application for laser cutting machine selection is outlined in the 4th section. The 5th section presents the conclusion and addresses implications, limitations, and suggestions for further study.

PRELIMINARIES

Definition 1. Linguistic term set $L = \{L_0^t, L_1^t, ..., L_{t-1}^t\}$ is the group which includes t kinds of linguistic variables. Each linguistic variable can be represented as a triangular fuzzy number [11].

Definition 2. Suppose that Θ is the linguistic transfer function. This function will transfer a linguistic variable into a crisp value n ($n \in [0,1]$) as follows [11].

$$\Theta(L_b^t) = n \tag{1}$$

where $n = \frac{b}{t-1}$.

Definition 3. Suppose that Θ^{-1} is the linguistic transfer inverse function. This function can transfer crisp value n ($n \in [0,1]$) into a linguistic variable as follows [11].

$$\Theta^{-1}(n) = L_{n*(t-1)}^t \tag{2}$$

Definition 4. Suppose that Θ and Θ^{-1} are the linguistic transfer function and the linguistic transfer inverse function, respectively. Let $G_1, G_2, \ldots, G_k$ be the linguistic opinions of k experts. The collective opinion of experts (G^{int}) will be integrated as follows [11].

$$G^{int} = \Theta^{-1}\left(\frac{\sum_{h=1}^{k}\Theta(G_h)}{k}\right) \tag{3}$$

PROPOSED METHOD

Machinery investment selection can be considered as an MCDM issue. It can be formulated by the following notation.

(1) Expert set $E = \{E_1, E_2, \ldots, E_k\}$. k means the number of experts.

(2) Investment target set $I = \{I_1, I_2, \ldots, I_m\}$. m means the number of investment targets.

(3) Criteria set $C = \{C_1, C_2, \ldots, C_b, C_{b+1}, \ldots, C_n\}$. n means the total number of criteria. Criteria C_1 to C_b are quantitative criteria. Criteria C_{b+1} to C_n are qualitative criteria.

(4) A decision matrix X can be described as follows.

$$X = \begin{array}{c} \\ I_1 \\ I_2 \\ \cdots \\ I_m \end{array} \begin{array}{c} \begin{array}{ccccccccc} C_1 & C_2 & \cdots & C_b & C_{b+1} & C_{b+2} & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,b} & \tilde{x}_{1,b+1} & \tilde{x}_{1,b+2} & \cdots & x_{1,n} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,b} & \tilde{x}_{2,b+1} & \tilde{x}_{2,b+2} & \cdots & x_{2,n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{m,1} & x_{m,2} & \cdots & x_{m,b} & \tilde{x}_{m,b+1} & \tilde{x}_{m,b+2} & \cdots & x_{m,n} \end{bmatrix} \end{array} \quad (4)$$

where x_{ij} is the rating of investment target i with respect to criterion j.

The proposed linguistic MCDM algorithm proceeds through the following computational stages (figure 1 for a schematic flowchart):

Step 1. Define investment targets. In the beginning, an investor must choose an investment field. In this investment field, some high-quality machinery investment targets can be chosen.

Step 2. Design criteria. A panel of experts collaboratively defines the most relevant cost and performance criteria for assessing alternatives.

Step 3. Collect experts' opinions and quantitative information for each machine investment target.

Afterwards, quantitative information of each machine investment target should be collected. Let x_{ij}^{qn} be the crisp performance of machinery investment target i with respect to quantitative criterion j.

Following this, experts will express their opinions about the performance of those machine investment targets with respect to qualitative criteria. Let $\tilde{x}_{ijk}$ be the linguistic opinion of expert k about the performance of machine investment target i with respect to qualitative criterion j. The aggregated opinion can be computed by the following formula [12, 13]:

$$\tilde{x}_{ij} = \triangle^{-1}\left(\frac{\sum_{k=1}^{K}\triangle(\tilde{x}_{ijk})}{K}\right) \quad (5)$$

Step 4. Transforming experts' opinions and quantitative information. To integrate the entire information reasonably, the performance of machine investment targets with respect to all criteria should be transformed.

(1) The transformed method for benefit qualitative criterion can be computed as

$$t_{ij} = \triangle^{-1}(\tilde{x}_{ij}) \quad (6)$$

(2) The transformed method for the benefit quantitative criterion can be computed as

$$t_{ij} = \frac{x_{ij}^{qn}}{\max_i\{x_{ij}^{qn}\}} \quad (7)$$

(3) The transformed method for the cost qualitative criterion can be computed as

$$t_{ij} = 1 - \triangle^{-1}(\tilde{x}_{ij}) \quad (8)$$

(4) The transformed method for the cost quantitative criterion can be computed as

$$t_{ij} = \frac{\min_i\{x_{ij}^{qn}\}}{x_{ij}^{qn}} \quad (9)$$

Step 5. Construct the normalised decision matrix as $D = [x_{ij}]_{m\times n}$, where $x_{ij} = \dfrac{t_{ij}}{\sum_{i=1}^{m} t_{ij}}$.

Step 6. Calculate the weight of each criterion.

The decision-making evaluation process is often biased by the subjective judgement of the evaluator if the weights are set based only on the subjective opinion of the decision maker or expert. Therefore, it is more objective to evaluate the importance of criteria by considering the distribution of data. 'Entropy' is a thermodynamic concept that describes the degree of confusion in a thermodynamic system. The entropy weight method is mainly used to calculate the entropy value and relative weight of each criterion by taking advantage of the distribution of data in the decision matrix. The greater the data dispersion of the criterion, the lower the entropy value and the higher the entropy weight, i.e. the higher the importance of the criterion [14].

Calculate the entropy value (E_j) of criterion (C_j) as follows:

$$E_j = -k\sum_{i=1}^{m} x_{ij} \ln x_{ij} \quad (10)$$

where $k = \dfrac{1}{\ln m}$ and $0 \le E_j \le 1$.

Calculate the dispersion (d_j) of criterion (C_j) and the weight (w_j) of criterion (C_j) as follows:

$$d_j = 1 - E_j \quad (11)$$

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad (12)$$

Step 7. Construct the weighted decision-making matrix V as follows:

$$V = [v_{ij}]_{m\times n} \quad (13)$$

where $v_{ij} = x_{ij} * wj$.

Step 8. Based on the weighted decision-making matrix, determine the positive ideal solution (A^+) and negative ideal solution (A^-) as follows [14, 15]:

$$A^+ = \{v_1^+, v_2^+, \ldots, v_n^+\} \quad (14)$$

$$A^- = \{v_1^-, v_2^-, \ldots, v_n^-\} \quad (15)$$

where $v_j^+ = \max\limits_j v_{ij}$, $v_j^- = \min\limits_j v_{ij}$.

Step 9. Calculate the distance (S_i^+) between investment target (I_i) and positive ideal solution (A^+), the distance (S_i^-) between investment target (I_i) and negative ideal solution (A^-) as follows:

$$S_i^+ = \left[\frac{1}{n}\sum_{j=1}^{n}(v_{ij} - v_j^+)^2\right]^{1/2} \quad (16)$$

$$S_i^- = \left[\frac{1}{n}\sum_{j=1}^{n}(v_{ij} - v_j^-)^2\right]^{1/2} \quad (17)$$

Step 10. Calculate the closeness coefficient (CC_i) of investment target (I_i) as follows:

$$CC_i = \frac{S_i^-}{S_i^- + S_i^+} \quad (18)$$

Step 11. According to the closeness coefficients, we can determine the ranking order of all investment targets. If $CC_i > CC_j$, then investment target I_i is better than target I_j.

To provide a clear overview of the procedure, the entire process of the proposed linguistic MCDM method is illustrated in figure 1. The flowchart summarises the sequential steps, starting from the

definition of investment targets and criteria, followed by the collection and transformation of quantitative and qualitative data, calculation of criteria weights, and the determination of closeness coefficients for ranking the alternatives. This visual representation helps readers quickly grasp the logical structure and steps of the methodology.

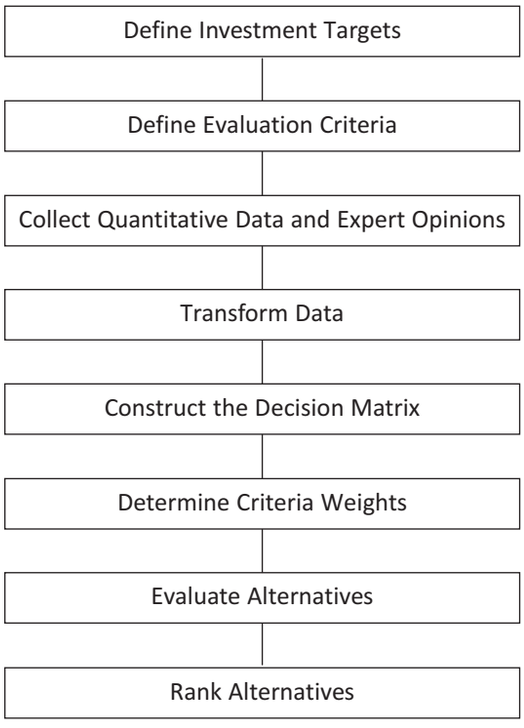


Fig. 1. Workflow diagram of the proposed linguistic MCDM method for machinery selection

EXAMPLE

Data analysis

The proposed linguistic MCDM framework was applied to a real-world laser cutting machine selection issue in the textile sector. The objective was to demonstrate how the model integrates qualitative expert judgments and quantitative data within a unified computational system. The steps are the execution process.

Step 1. Define the investment target. In the textile industry, many laser cutting machine types can be selected, such as alternative 1 (I_1), alternative 2 (I_2) and alternative 3 (I_3).

Step 2. Design criteria. Six criteria should be considered in selecting a suitable machine, such as cost (C_1), machinery appearance (C_2), engraving speed (C_3), cutting speed (C_4), resolution ratio (C_5) and resetting positioning accuracy (C_6). The criteria, cost (C_1), is a quantitative criterion, while the others are qualitative.

Step 3. Collect quantitative information of each machine investment target with respect to the criteria as seen in table 1. For the qualitative criterion, three experts use seven scale linguistic variables (very poor, poor, medium poor, fair, medium good, good and very good) to evaluate the performance of each machine investment target with respect to the criteria, as seen in table 2. We use formula 5 to integrate the opinions of experts.

Step 4. Transforming quantitative and qualitative performances of each machine investment target with respect to the criteria as given in table 3. Cost (C_1) is a cost quantitative criterion. Machinery appearance (C_2), engraving speed (C_3), cutting speed (C_4), resolution ratio (C_5) and resetting positioning accuracy (C_6) are benefit qualitative criteria.

Step 5. The normalised decision matrix can be shown in table 4.

Step 6. Calculate the weights of all criteria as seen in table 5.

Step 7. The weighted decision matrix can be shown as given in table 6.

Step 8. Determine the positive and negative ideal solutions as seen in table 7.

Step 9 and Step 10. Calculate the distances and closeness coefficients of all targets as seen in table 8.

Step 11. Based on the closeness coefficients, the ranking order of the three machine investment targets is $I_3 > I_1 > I_2$.

Table 1 presents the quantitative performance data of the three laser cutting machine alternatives with respect to the cost criterion (C1). Lower values correspond to lower investment costs, which are preferable since cost is a minimisation (cost-type) criterion. This variable provides a baseline for comparing the economic efficiency of each alternative in subsequent computational steps.

Table 2 reports the linguistic evaluations of three alternatives across five qualitative criteria (C2–C6), as assessed by three domain experts (E1–E3). Experts used a seven-point linguistic scale ranging from “very poor” to “very good”. These linguistic inputs serve as the foundation for the subsequent transformation process, where qualitative assessments are mapped into comparable crisp numerical values.

In table 3, the linguistic evaluations have been converted into numerical values using the linguistic transformation function, and the quantitative data have been normalised to a comparable scale. These

Table 1

QUANTITATIVE PERFORMANCE RATINGS			
Criterion	**Alternative 1 (I1)**	**Alternative 2 (I2)**	**Alternative 3 (I3)**
cost (C1)	7280	9380	4880

Table 2

LINGUISTIC PERFORMANCE RATINGS			
E1	**Alternative 1 (I1)**	**Alternative 2 (I2)**	**Alternative 3 (I3)**
C2	very good	medium good	good
C3	good	good	good
C4	good	good	good
C5	medium good	medium good	medium good
C6	good	good	good
E2	**Alternative 1 (I1)**	**Alternative 2 (I2)**	**Alternative 3 (I3)**
C2	good	poor	medium good
C3	good	good	fair
C4	good	medium good	medium good
C5	fair	good	fair
C6	good	good	medium good
E3	**Alternative 1 (I1)**	**Alternative 2 (I2)**	**Alternative 3 (I3)**
C2	good	fair	medium good
C3	medium good	medium good	medium good
C4	medium good	fair	fair
C5	medium good	good	good
C6	very good	very good	good

Table 3

TRANSFORMED DATA OF ALL TARGETS			
Criterion	**Alternative 1 (I1)**	**Alternative 2 (I2)**	**Alternative 3 (I3)**
C1	0.6703	0.5203	1.0000
C2	0.8889	0.4444	0.7222
C3	0.7778	0.7778	0.6667
C4	0.7778	0.6667	0.6667
C5	0.6111	0.7778	0.6667
C6	0.8889	0.8889	0.7778

Table 4

NORMALISED DATA OF ALL TARGETS			
Criterion	**Alternative 1 (I1)**	**Alternative 2 (I2)**	**Alternative 3 (I3)**
C1	0.3060	0.2375	0.4565
C2	0.4324	0.2162	0.3514
C3	0.3500	0.3500	0.3000
C4	0.3684	0.3158	0.3158
C5	0.2973	0.3784	0.3243
C6	0.3478	0.3478	0.3044

transformed values are used to construct the decision matrix.

Table 4 displays the normalised decision matrix, which ensures that all criteria are dimensionless and comparable.

Table 5 presents the criterion weights derived using the entropy method. The highest weight corresponds to machinery appearance (C2 = 0.4371), reflecting the criterion's high variability across alternatives and thus greater decision influence. Conversely, resetting positioning accuracy (C6 = 0.0226) shows minimal

Table 5

THE WEIGHTS OF ALL CRITERIA	
Criterion	**Weights**
C1	0.4246
C2	0.4371
C3	0.0298
C4	0.0319
C5	0.0588
C6	0.0226

Table 6

THE WEIGHTED DECISION MATRIX			
Criterion	**Alternative 1 (I1)**	**Alternative 2 (I2)**	**Alternative 3 (I3)**
C1	0.1299	0.1008	0.1938
C2	0.1867	0.0933	0.1517
C3	0.0104	0.0104	0.0089
C4	0.0118	0.0101	0.0101
C5	0.0175	0.0222	0.0191
C6	0.0079	0.0079	0.0069

differentiation, contributing less to the overall ranking. The entropy weighting technique objectively quantifies importance without relying on subjective input from experts.

Table 6 shows the weighted decision matrix. This matrix reflects the combined impact of each alternative's performance and the relative importance of each criterion.

Table 7 identifies the positive ($A+$) and negative ($A-$) ideal solutions for each criterion. These reference points are essential for measuring each alternative's Euclidean distance to the ideal condition, a core principle in the TOPSIS-based component of the proposed method.

Table 7

THE POSITIVE AND NEGATIVE IDEAL SOLUTIONS		
Criterion	**A^+**	**A^-**
C1	0.1938	0.1008
C2	0.1867	0.0933
C3	0.0104	0.0089
C4	0.0118	0.0101
C5	0.0222	0.0175
C6	0.0079	0.0069

Table 8 summarises the computed distances of each alternative to the positive and negative ideal solutions and their resulting closeness coefficients (CCi). The alternative with the highest CCi is considered the optimal choice. Here, Alternative 3 (CC3 = 0.7571) ranks highest, followed by Alternative 1 (CC1 = 0.6044), while Alternative 2 (CC2 = 0.0371) performs worst.

Comparison and explanations

The simple weighting method is one of the most employed multi-criteria decision-making approaches. Based on the data in table 6, the performance values calculated for the three alternatives using this method are 0.364 (alternative 1), 0.2447 (alternative 2), and 0.3905 (alternative 3). The ranking of the three alternatives aligns with the methodology proposed in this study. If the decision-maker were to employ subjective preferences, an optimistic decision-maker would base judgements on maximum values, yielding performance values of 0.1867 (alternative 1), 0.1008 (alternative 2), and 0.1938 (alternative 3). In contrast, a pessimistic decision-maker would base judgements on the minimum values, yielding performance scores of 0.0079 (alternative 1), 0.0079 (alternative 2), and 0.0069 (alternative 3). This demonstrates that the three scenarios produce unstable ranking outcomes due to decision-makers' subjective preferences. In fact, the simple weighted method merely calculates each alternative's performance value using a linear model for ranking. However, the ranking method proposed in this study simultaneously considers each alternative's distance from the positive ideal solution and its distance from the negative ideal solution across six criteria. Utilising these two distances to compute a closeness coefficient yields a value that enables more objective and stable alternative ranking. This study employs the entropy method to calculate criterion weights primarily based on the degree of data dispersion for each alternative across each criterion. In other words, when all alternatives exhibit identical data for a given criterion, it signifies that criterion holds no distinction among the alternatives and is therefore deemed insignificant. This approach enables a more objective calculation of criterion weights and mitigates bias arising from evaluators' subjective judgements. Typically, qualitative criteria often require input from evaluators. Consequently, when the number of evaluators is small, their opinions may be more concentrated, potentially leading to smaller assigned weights.

Table 8

THE DISTANCES AND CLOSENESS COEFFICIENTS OF ALL TARGETS			
Alternative	**Alternative 1 (I1)**	**Alternative 2 (I2)**	**Alternative 3 (I3)**
S_i^+	0.0261	0.0538	0.0144
S_i^-	0.0399	0.0021	0.0448
CC_i	0.6044	0.0371	0.7571

In the example presented in this paper, the three experts exhibited considerable divergence in their assessments of the three proposals under the criterion 'machinery appearance'. Conversely, their evaluations under the criterion 'resetting positioning accuracy' demonstrated greater consistency.
Consequently, when comparing the merits of the three alternatives, the criterion 'resetting positioning accuracy' exerted a relatively minor influence due to the proximity of the assessment values, resulting in a low weighting value. Conversely, the assessment opinions for the criterion 'machinery appearance' were more divergent, thus carrying greater influence and consequently a higher weighting value.
In summary, the main contributions of this paper comprise: (1) This study employs an entropy method to calculate criterion weights, enabling a more objective weighting process while mitigating bias arising from evaluators' subjective judgements. (2) The proposed ranking method simultaneously considers each alternative's distance from the positive ideal solution and its distance from the negative ideal solution across six criteria. By calculating closeness coefficients based on these dual distances, the resulting values enable more objective and stable alternative ranking.

CONCLUSIONS

This study presented a computational linguistic MCDM framework for machinery investment selection, addressing the challenges of combining qualitative and quantitative information in industrial decision environments. The proposed model integrates linguistic expert evaluations with quantitative performance data and employs the entropy weighting method to derive objective criterion weights. This hybrid structure ensures a transparent and reproducible evaluation process, reducing reliance on purely subjective expert judgments.
An empirical application to laser cutting machine selection in the textile industry verified the practicality of the proposed model. The results demonstrated that Alternative 3 achieved the highest performance score, primarily due to its low cost and strong qualitative evaluations in key criteria. These findings confirm the method's capacity to process hybrid data effectively and generate rational, data-driven investment decisions.
From a managerial perspective, the proposed framework provides a systematic decision support tool that can help managers make well-informed investment choices under uncertainty. It facilitates the integration of expert knowledge and measurable data within a unified computational system, enabling more consistent, evidence-based, and auditable decisions.
Despite these contributions, this study has several limitations. The application was limited to a single case study and involved a small group of experts, potentially limiting the generalizability of the findings. Future research should expand the empirical scope by applying the proposed framework to other industrial sectors.
Overall, this research contributes to the industrial engineering and computational decision-making literature by demonstrating how linguistic MCDM can be operationalised as a data-driven, objective, and replicable computational tool. The model not only extends the methodological frontier of MCDM applications but also provides industrial practitioners with a reliable and scalable framework for complex machinery and capital investment decisions.

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