Industria Textilă

ISSN 1222–5347

1/2026

Special Issue on Advanced textile technologies

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

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

Edited in 6 issues per year, indexed and abstracted in:
Science Citation Index Expanded (SCIE), Materials Science Citation Index®, Journal Citation Reports/Science Edition, World Textile Abstracts, Chemical Abstracts, VINITI, Scopus, Toga FIZ technik, EBSCO, ProQuest Central, Crossref
Edited with the Romanian Ministry of Research, Innovation and Digitalization support

EDITORIAL BOARD:

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Aknowledged in Romania, in the Engineering sciences domain, by the National Council of the Scientific Research from the Higher Education (CNCSIS), in group A
Journal edited in colaboration with **Editura AGIR**, 118 Calea Victoriei, sector 1, Bucharest, tel./fax: 021-316.89.92; 021-316.89.93; e-mail: editura@agir.ro, www.edituraagir.ro

The influence of knitting structures of men's socks on thermophysiological comfort in dynamic conditions

DOI: 10.35530/IT.077.01.2024177

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ABSTRACT – REZUMAT

The influence of knitting structures of men's socks on thermophysiological comfort in dynamic conditions

The influence of environmental conditions on the thermophysiological comfort of men's socks with different knitting structures was investigated using an objective evaluation of comfort in dynamic conditions. Men's socks made in three knitting structures – R22, R31 and R71 rib constructions with the same raw material composition were used: bamboo yarn, filament polyamide yarn and wrapped elastomeric yarn for the sock welt. The influence *of climate factors artificially generated in the climate chamber was analysed by measuring three physiological parameters: skin temperature, relative humidity on the skin's surface and temperature of the microclimate between socks and shoes. The results of the research indicate that the knitting structures of socks have a significant impact on their thermophysiological comfort. For an ambient temperature of 20°C and a relative humidity of 50% (autumn and spring conditions), preference is given to socks with R22 construction.*

Keywords: *socks, thermal properties, rib constructions, physiological properties, comfort*

Influența structurilor de tricot ale șosetelor pentru bărbaţi asupra confortului termofiziologic în condiții dinamice

Influența condițiilor de mediu asupra confortului termofiziologic al șosetelor pentru bărbaţi cu diferite structuri de tricot a fost investigată folosind o evaluare obiectivă a confortului în condiții dinamice. S-au folosit șosete pentru bărbaţi realizate în trei structuri de tricot – patent R22, R31 și R71 cu aceeași compoziție a materiei prime: fire din bambus, fire filametare din poliamidă și fire elastomerice înfășurate pentru partea superioară a șosetei. Influența factorilor climatici generați artificial în camera climatică a fost analizată prin măsurarea a trei parametri fiziologici: temperatura pielii, umiditatea relativă la suprafața pielii și temperatura microclimatului dintre șosete și încălțăminte. Rezultatele cercetării arată că structurile de tricot ale șosetelor au un impact asupra confortului termofiziologic al șosetelor. Pentru o temperatură ambientală de 20˚C și o umiditate relativă de 50% (condiții de toamnă și primăvară), se preferă șosetele cu structura R22.

Cuvinte-cheie*: șosete, proprietăți termice, tricot patent, proprietăți fiziologice, confort*

INTRODUCTION

The thermal comfort or comfort when wearing clothing made of different knitted fabrics is defined on the basis of objective analysis in the field of clothing physiology, structural and thermal properties of textile materials, microclimate, dry and wet heat flow, etc. The thermal comfort of clothing is a subjective evaluation by which a person expresses their satisfaction with their thermal environment. It is a psychological phenomenon related to the physical environment or physiological state, and it is difficult to determine exactly whether or not users are satisfied with thermal comfort (warmth, freshness, satisfaction, etc.).

Socks are one of the most popular knitted products, made by knitting staple or filament yarns of different raw material composition (cotton, wool, bamboo, polyamide, polyacrylic, etc.). Cotton socks, for example, are soft, absorb sweat and water vapour well, are easy to care for and are very durable (especially mercerised cotton). Wool socks provide excellent thermal insulation and have an excellent ability to absorb moisture and sweat. Socks made of bamboo fibres are quite thick and soft; they not only absorb moisture but also odours, so the feet stay fresh all day, and the person feels comfortable. They have antibacterial properties, a very soft texture and are ideal for sensitive skin. They are characterised by good air exchange; the disadvantages are the high cost of producing these fibres, and the products have a low level of strength and tear quickly [1–3].

The knit structure of the socks affects the thermophysiological properties of the product, which is directly reflected in the knitted fabric's ability to allow air and water vapour to pass through, wick sweat away from the feet, achieve thermal resistance and conductivity, etc. The raw material composition and the structure of the yarn, the density, thickness, bulk density or porosity of the knitted fabric are also important structural factors that determine the properties and comfort of socks [4, 5].

Numerous studies have shown the influence of materials and knitted construction on the comfort of socks [6–8]. In Ozdil's research [6], the thermal comfort properties of socks knitted from popular fibres in the field, such as wool, acrylic, cotton and PA, were investigated. Thermal resistance, thermal absorption, thermal conductivity, water vapour permeability and air permeability were analysed. The results show that the thermal conductivity values of woollen socks are lower than those of acrylic ones. The thermal resistance values of wool-acrylic socks are higher than 100% acrylic socks and give a feeling of warmth at first contact. Socks containing PA fibres provide high values of thermal conductivity and thermal absorption.

The effect of the fibre mix on the comfort of the socks is interesting [7]. Socks are knitted from traditional fibres such as cotton, bamboo and viscose and new types of regenerated fibres such as Modal, Promodal, Micromodal, Linen-Modal, and Lyocell. According to the air conductivity test, socks knitted from cotton had the lowest results, and Modal socks had the highest. According to the percentage of water vapour, the Micromodal sample had the lowest score, and the Modal sample had the highest score. In water resistance, the Modal sample had the worst result, and the bamboo had the highest value. The higher the thermal conductivity, the higher the heat transfer from the skin to the fabric. The viscose sample gave the highest values, and the Micromodal sample had the lowest values. The increase in thermal absorption of textile materials leads to a feeling of coldness at the first touch; the cotton sample gave the lowest, and the viscose the highest. Cotton proved to be the most suitable material for the production of socks, while Modal, Promodal and viscose are unsuitable, but at the same time suitable for the production of inner and outer parts of socks. In terms of moisture transfer, viscose, Promodal, bamboo and lyocell scored similarly and were not considered suitable sock materials. Micromodal and cotton are more suitable for use in socks.

Skin-to-fabric friction and other characteristics of some sock fabrics produced from cotton and regenerated cellulose fibres were investigated by surface friction, tear resistance, pilling and abrasion tests [8]. According to the results, cotton and its blend with Modal had better performance for burst strength, and cotton/Modal had better performance for pilling and abrasion resistance. Skin-to-fabric friction is lower for viscose among cellulose fibres, allowing for a smoother surface for leather garments. The breaking strength of the fabric is correlated not with the strength of the yarn, but with the breaking work. Cotton/Modal blend can be suggested for daily or functional socks.

This article describes investigations into the thermophysiological properties of socks with the same raw material composition and different knit structures under dynamic conditions – when walking in shoes. The results of heat exchange and sweat, as well as the temperature of the microclimate under the conditions of movement, make it possible to obtain information about which type of knit construction of socks is best suited for wearing under certain climatic conditions.

MATERIAL AND METHOD

Material and test methods

Short men's socks made of the same yarn type in three different rib constructions were used for the test. A bamboo fibre yarn (30.75 tex) with a nominal content of 77% was used as the base yarn. In addition, a filament yarn made of PA 6.6 (4.4/13 tex × 2) with a nominal content of 22% and finally, at the beginning of the sock, the cuff, an elastomer yarn (100 tex), which is wrapped with PA yarns (78 dtex) in two layers, with a nominal content of 1%.

The socks are made in three knitted structures (rib constructions), with the following labelling: R22, R31 and R71. A "Lonati Bravo 856" two-cylinder hosiery machine with a cylinder diameter of 95 mm and 168 needles was used to make the socks.

The measurements of the most important properties of the socks were carried out using suitable standards or tests:

- Thickness of the socks, according to the SRPS EN ISO 5084:2013 standard [9].
- The porosity (P) is calculated according to the equation: $P = (1 - m/\rho \times h) \times 100$; where m is the mass per unit area (g/cm^2), h is the thickness of the knitted fabric (mm), and ρ is the fibre density (g/cm^3) [10].
- Water vapour transmission of materials, according to the ASTM E96 [11].
- Air permeability, according to the SPRS EN ISO 9237:2010 [12].

The basic characteristics and the same thermophysiological performances of the socks are listed in table 1.

Test protocol

In the experiment, the influence of three identical models of socks in size number 11.5 (43–44) with different knitting structures and the same raw material composition was monitored on the thermal-physiological comfort when walking in shoes. All of the wear trial tests were performed under artificially designed ambient conditions in a computer-controlled climatic chamber. During the wear tests, the temperature of the skin, the relative humidity of the skin and the temperature of the microclimate (the space between socks and shoes) were measured at various points on the foot using the MSR 12 Modular Signal Recorder.

The test subjects (three male participants) took part in the study, always dressed in the same way and in the same wardrobe and wearing leather shoes, with the upper part and the inner sole of the shoe made of 100% natural leather. This testing was conducted as a preliminary or pilot study, aimed at identifying

Table 1

MORE IMPORTANT INDICATORS OF SOCKS FOR THE THERMOPHYSIOLOGY OF THE PRODUCT						
Rib construction	**Thickness (mm)**	**Horizontal density (1/cm)**	**Vertical density (1/cm)**	**Porosity (%)**	**Water vapour transmission (g/m²/24h)**	**Air permeability (m³/m²/min)**
R22 	1.886±0.04	12.83±0.4	10.66±0.2	85.50±1.1	4703.61±45.5	57.48±1.3
R31 	1.710±0.1	10.50±1.2	11.00±1.1	87.65±1.8	5246.34±58.3	65.40±1.5
R71 	1.877±0.08	10.00±1.0	11.50±1.1	89.61±1.7	6331.79±51.4	56.40±1.7

trends and assessing the feasibility of the testing protocol. While the data collected provides useful insights, we recognise that a larger and more diverse sample is necessary to obtain physiologically relevant and statistically valid results. Future testing will be expanded to include a greater number of participants in accordance with scientific and methodological standards.

Selection of participants

The selection of participants took place in such a way that the test person was observed while standing, so that disorders of the longitudinal arch of the foot, flat feet or high feet could be observed. Then the feet were examined from behind while the respondent stood on the toes; muscle contraction, the degree of heel inversion, the height of the arch of the foot and the degree of lateral symmetry were evaluated. Also, discolouration of parts of the feet, swelling, or deformities were observed. After the examination, respondents with very similar feet, without deformities, were selected to participate in the experiment.

Physiological parameters monitored for the study

The following physiological parameters (temperature and relative humidity of the skin, microclimate temperature) in the climatic chamber were monitored using the MSR Modular Signal Recorder from MSR Electronics GmbH.
Sensors for measuring the temperature (T61, T62, T63, T68, T69, T161) and relative humidity (RH1, RH2, RH4, RH5) are placed directly on the skin of the feet, while microclimate temperature sensors (T67, T162) are placed on the socks, under the shoes (figure 1).

Fig. 1. Positions of the sensors for measuring the temperature and relative humidity on the feet and the temperature of the microclimate on the socks

Thermo-physiological test protocol

The test subjects performed two treadmill exercises while wearing normal clothing and leather shoes under warm environmental conditions (ambient temperature 20°C, relative humidity 50%, and air velocity 0.5 m/s). The test subjects performed the activity in the following order:

- Acclimatisation under the same testing conditions: 30 minutes
- The first phase: Exercise I (subject walking on the treadmill in the test climate chamber at a speed of 2.5 km/h on the flat in the direction of the wind): 30 minutes
- Rest period: 20 minutes
- The second phase: Exercise II (subject walking on the treadmill in the test climate chamber at a speed of 3.5 km/h on the flat in the direction of the wind): 30 minutes
- Rest period: 5 minutes.

The test period after each phase will allow the test subject to complete a questionnaire on comfort.

RESULTS AND DISCUSSION

Some indicators of socks

Table 1 shows data on the most important indicators of socks, which are decisive for the thermophysiological state of the sock during use. Numerous values of the statistical parameter standard deviation are also shown in table 1 (mean ± standard deviation). The thickness of the sock varies depending on the knitting structures, given the same composition and type of yarn [13]. The socks in the R22 construction have a slightly greater thickness, which is connected to the method of production and the change of loops on the upper and lower cylinders. The thickness of the knitted fabric, as a rule, affects the thermophysiological properties of socks, because the thickness of the socks affects the porosity of the product, which in turn affects the permeability of water vapour and air. Relations are not always directly proportional, as can be seen from table 1, the type of knitting structure has a visible influence, in this case.
According to table 1, R71 rib knitted socks dominate when it comes to water vapour permeability, while R22 rib knitted socks have the highest thickness and lowest porosity. R31 rib knitted socks are characterised by the smallest thickness and the highest air permeability. All these properties determine the behaviour of socks on the feet when walking in shoes; they affect the exchange of heat and moisture, i.e., the comfort of socks and feet in dynamic conditions. It should be added that the socks worn on the feet with shoes are in a tensioned state with pressure from the shoes, while all the properties in table 1 were measured in a relaxed or resting state of the socks without any external pressure. For this reason, the results from table 1 must be taken conditionally when used to predict the behaviour of socks under dynamic conditions of movement in tension and compression.

Skin temperature of the feet while wearing socks

The results of the skin temperature of the feet wearing socks and shoes during the stay in the climate chamber, under dynamic conditions, are shown in figures 2 to 4. In each graph, there are 6 dependencies (curved lines) from 6 sensors that measure the temperature change on the skin of both feet during the 80 min stay in the air conditioning chamber. Certain regularities are noticeable in the curves in the graphs of figures 2 to 4 from the sensors that measure the temperature of the skin of the feet. Namely, at sensors T61 (upper part of the right foot, next to the toes), T62 (arch of the right foot), T68 (upper part of the left foot, next to the toes) and T69 (arch of the left foot), in all cases, a higher temperature was recorded in relation to the temperatures of sensors T63 (above the ankle of the right foot) and T161 (above the ankle of the left foot).
According to the curves from the graphs of these figures, all knitting structures give similar but not identical temperature curve flows from the sensors placed on the skin of the feet. All individual curves follow a certain order of appearance on the graphs, i.e. temperature sensors T62 and T69 have the highest positions on the graphs, i.e. register the highest temperature of the skin of the feet in socks and shoes. Next are the temperature sensors T61 and T68, whose curves are placed a little lower on the graphs, and finally, with the lowest position and thus the lowest temperature, come the curves from the temperature sensors T63 and T161, which are placed above the ankles of both feet and below the socks.
According to figure 2 (R22 construction), the curves of the temperature sensors T61, T62, T68 and T69 have a similar flow. Until about 2000 s, they show a constant increase in temperature, followed by a drop until about 3000 s, and then the temperature increases continuously until the end of the test. The other sensors, T63 and T161, have an initial mild increase in skin temperature in the graph with a partial decrease between 2000 and 2500 s (rest in the climate chamber). In the case of R31 construction, figure 3, a similar phenomenon occurs, the initial rise in temperature occurs up to about 2000 s, followed by a drop or stagnation (sensor T68) up to about 3000 s with a subsequent rise. In the R71 construction, the temperature curves in the graph of figure 4 appear differently. Namely, here only the temperature sensors T62 and T69 have a similar appearance to the other constructions, pronounced initial growth up to 2000 s and then a drop up to 3000 s with subsequent continuous growth. Sensors T61, T68 and T161, with an initial slight increase up to 2000 s, show a short drop and stagnation up to 3000 s, then there is a continuous rise until the end of the experiment. The T63 sensor (figure 4) completely deviates from the usual flow observed with other socks. Namely, here a continuous increase in the flow of the curve was observed until 3000 s, when a sharp drop in the flow of the curve followed until about 3300 s, with a subsequent increase until the end of the graph. These

differences in the appearance of the curves from individual temperature sensors are expected; however, it is a matter of different knitting structures of socks with expected different behaviour in practical use.

In general, the lowest temperature range of the feet's skin during the entire experiment was registered with the R71 rib knitted socks, while the R22 rib knitted socks had the highest temperature range of the feet's skin, regardless of the sensor.

The temperature curves of the T63 and T161 sensors, mostly for all socks, run almost parallel to the x-axis, with slight, rhythmic variations during testing in the climate chamber. As expected, on the part of the leg just above the ankle, which is covered only by the sock, the temperature of the skin is lower than the temperature of the other parts of the foot covered by shoes. This is connected to the fact that this part of the sensor is covered only by a sock and not by a shoe, so there is better ventilation, and there is also the influence of the movement of the surrounding air (0.5 m/s). Of course, in all this, the knitting structure of socks has a decisive influence.

Regardless of the knitting structures, if the influence of the activity in the climate chamber is observed, the highest temperature of the skin of the feet in socks and shoes was registered in all samples, during fast walking („walking II“, 3.5 km/h) in the last 20 minutes of the test when the curves temperatures have a constant rise, reaching a maximum in the last minutes of the test.

For R22 construction, the temperatures from the sensors T62 and T69 (arch of the right and left feet) have the highest numerical values during the activity “walking I”, 34°C and 35°C, which exceeds the limit of the comfort zone (average skin temperature from 31.4°C to 33°C). For other knitting structures, temperatures from the same sensors reach values of 33.5°C – 34.3°C, which are closer to the comfort zone. In this sense, from the aspect of thermal comfort, socks in the R71 construction turned out to be the best.

Relative humidity of the skin of the feet

Socks are expected to release water vapour or moisture quickly and dry quickly. Depending on the knitting structure, the fluid will be retained in the interstices of the fibres or absorbed by the fibres. Given that the selected samples of socks are of the same raw material composition, the differences will exist only due to the knitting structure that changes.

The results of testing the relative humidity of the skin of the feet, registered by sensors, when wearing the analysed socks, are shown in graphs in figures 5 to 7. Skin moisture was measured using 4 sensors, 2 on each foot, labelled as follows: RH1 (front of right foot next to toes), RH2 (arch of right foot), RH4 (front of left foot next to toes) and RH5 (arch of left foot).

The curves, which determine the change in the relative humidity of the skin over time in dynamic conditions, have a different flow from the beginning to the end of the test, during all 4800 s. The appearance of the curves from the graphs in these figures differs for different knitting structures of socks, as expected. On the other hand, the well-known higher swelling of

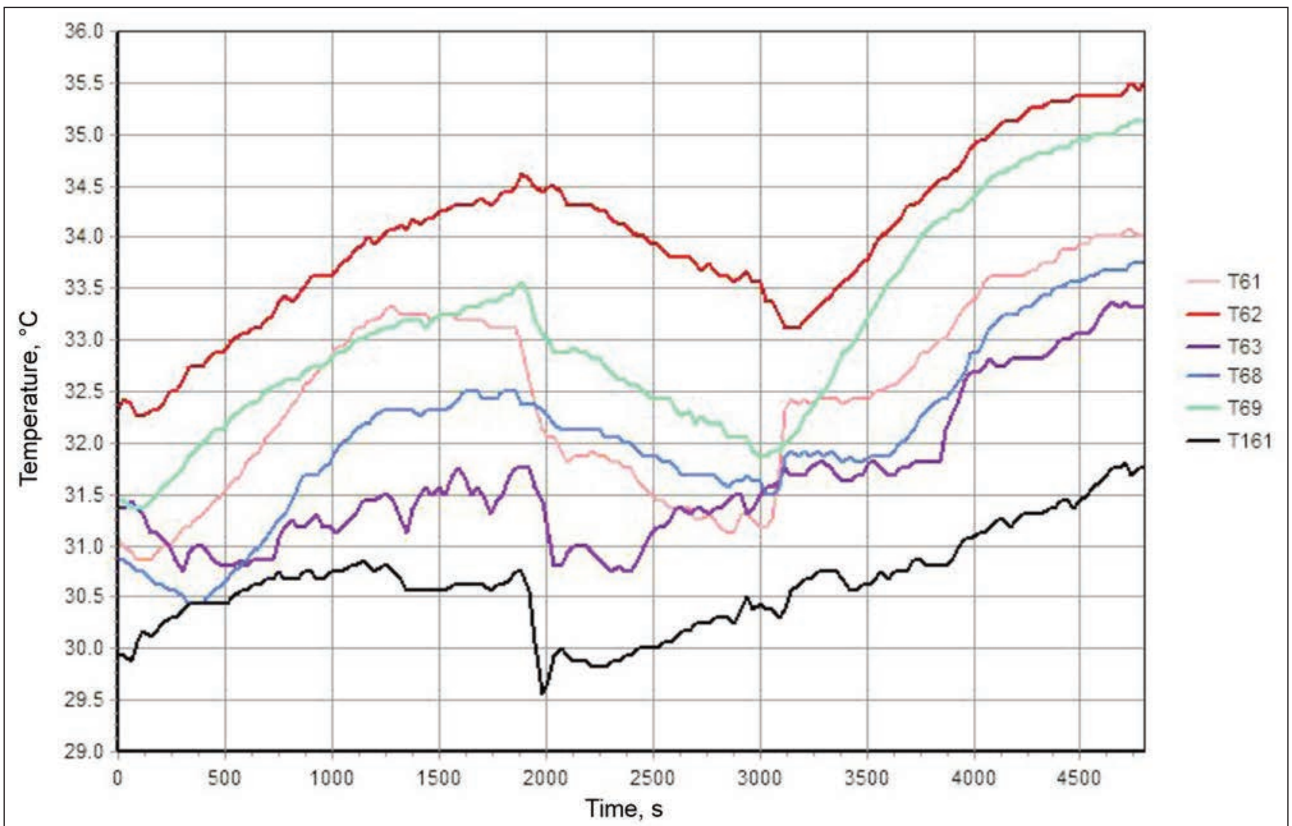

Fig. 2. Foot skin temperature when wearing R22 rib knitted socks during testing under dynamic conditions

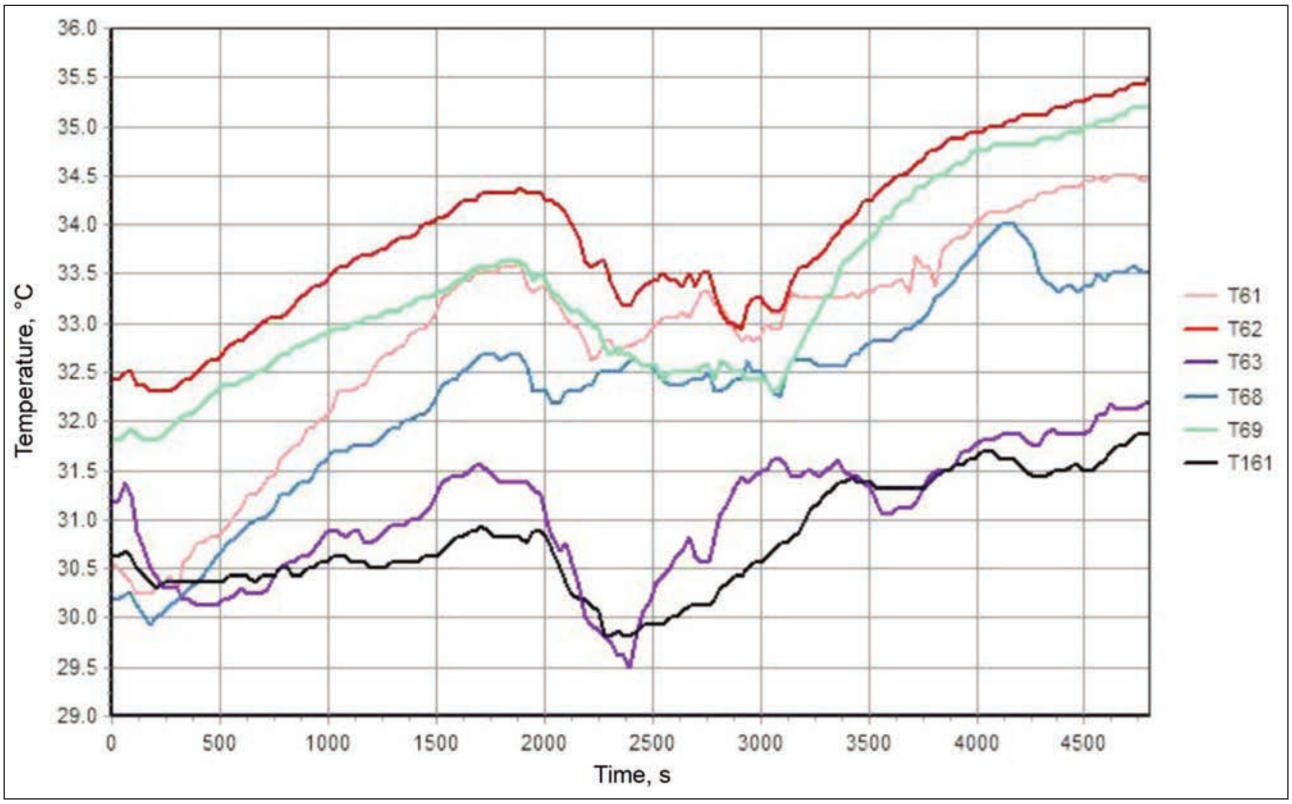

Fig. 3. Foot skin temperature when wearing R31 rib knitted socks during testing under dynamic conditions

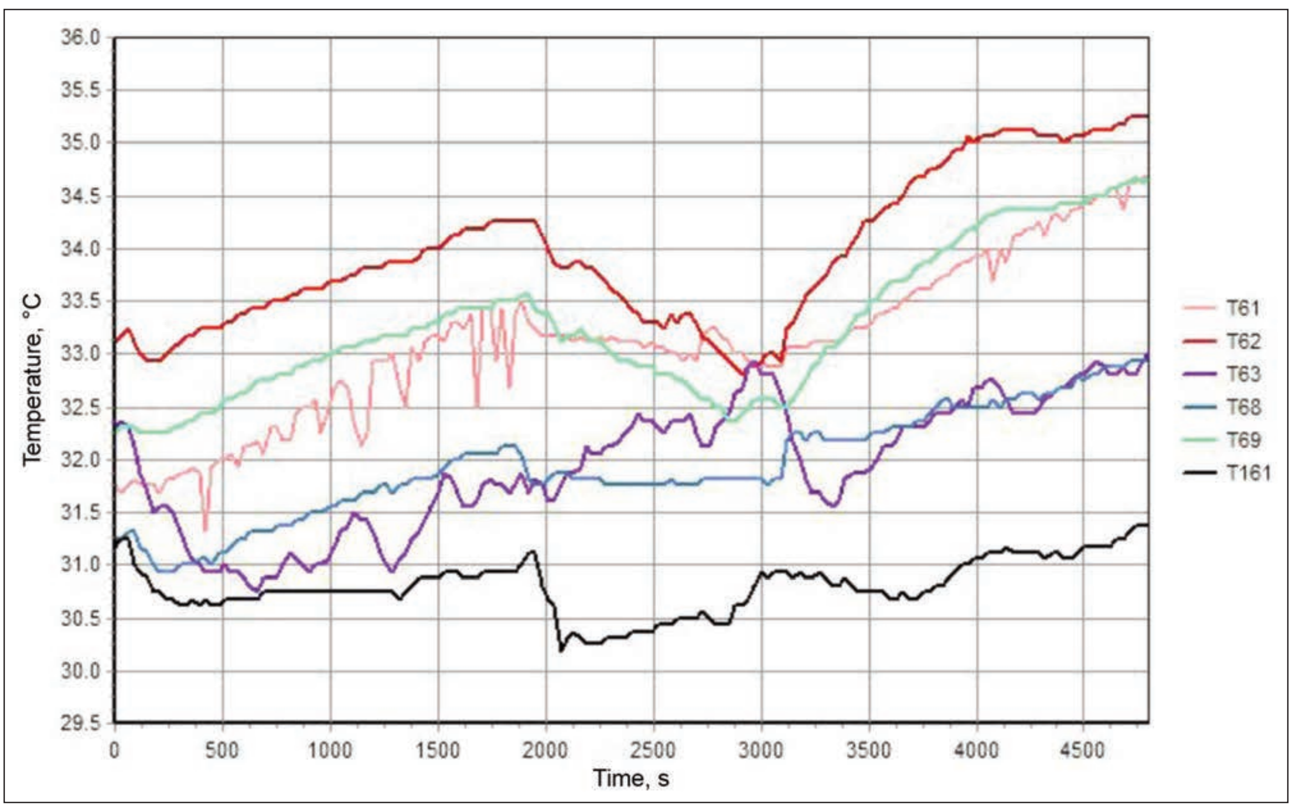

Fig. 4. Foot skin temperature when wearing R71 rib knitted socks during testing under dynamic conditions

bamboo fibres contributes to the retention of liquid in the fibres because the flow is slowed down, or even capillary closure may occur.

The initial higher relative humidity of the foot skin in socks and shoes during acclimatisation before the "walking I" phase in products with R71 construction confirms the fact that this rib construction does not allow a greater flow of moisture, i.e., heat (figure 7).

For socks in R22 and R71 constructions, figures 5 and 7, the humidity curves from sensors RH1 and

RH5 have a similar appearance; the changes are more intense in the part between 1900 and 3000 s, where a strong drop in the flow of the humidity curve was observed, during the phase “rest”. In the case of R31 rib knitted socks, for humidity from the same sensors and in the same range, a milder growth and stagnation of humidity change or only a slight decrease during rest in the middle of the experiment, was observed. The sensors RH2 and RH4, for all knitting structures, identically register skin humidity; the curves are very similar. When it comes to the humidity sensor RH5, located under the left foot (arch of the foot), in the R31 construction, it gives a relative humidity signal that is significantly different from the same signal in the other rib constructions. Namely, this is an error during the measurement; the RH5 sensor has broken, so this curve from the graph in figure 6 should not be taken into consideration. Also, the curve from the moisture sensor RH4 should be conditionally taken for socks with R22 construction, because the very high beginning of the curve (81% moisture) and the appearance of the curve are not realistic enough.

The lowest initial relative humidity was registered with socks in R22 construction (58% from sensor RH5), while the highest was recorded with socks in R71 construction (74% from sensor RH4). The same applies to the end of the experiment, i.e., at the final stage “walking II”.

If you compare the appearance of the curves on the graphs for temperature and humidity (figures 2 to 7), a coincidence is noticed, i.e. with most sensors, where the temperature is the highest, the humidity is the lowest and vice versa.

Physiological comfort is known to decrease if the value of average skin humidity is 30% or more. Values of over 60–70% humidity (sweat coverage) mean that the skin is already wet, so the feeling of comfort is unpleasant. Above this limit, the zone of intolerance begins with discomfort with impaired temperature regulation as a result of overheating. In the specific case, according to the results of the relative humidity of the skin on the foot, there is a partially impaired comfort when walking in bamboo socks, of different knitting structures, especially in the last phase of the experiment, “walking II”. The best product in this sense, in terms of physiological comfort during the entire experiment, was shown to be the R22 rib knitted socks.

In similar research with socks [14], the influence of textile, physiological and sensory parameters on the comfort of socks was analysed. Using sensors, foot temperature, fabric moisture and pain were measured. Significant correlations were found between physiological and sensory parameters, as well as between fabric friction and perceived comfort. Comfort depended on the fibre content of the socks and the humidity and temperature of the feet. The surface roughness and water content in the textile did not affect the comfort of the socks. Fabric friction and fibre content are relevant textile parameters for sock comfort. In subjective tests, socks with a high coefficient of friction were less comfortable than socks with a low coefficient of friction. Fibre content can affect

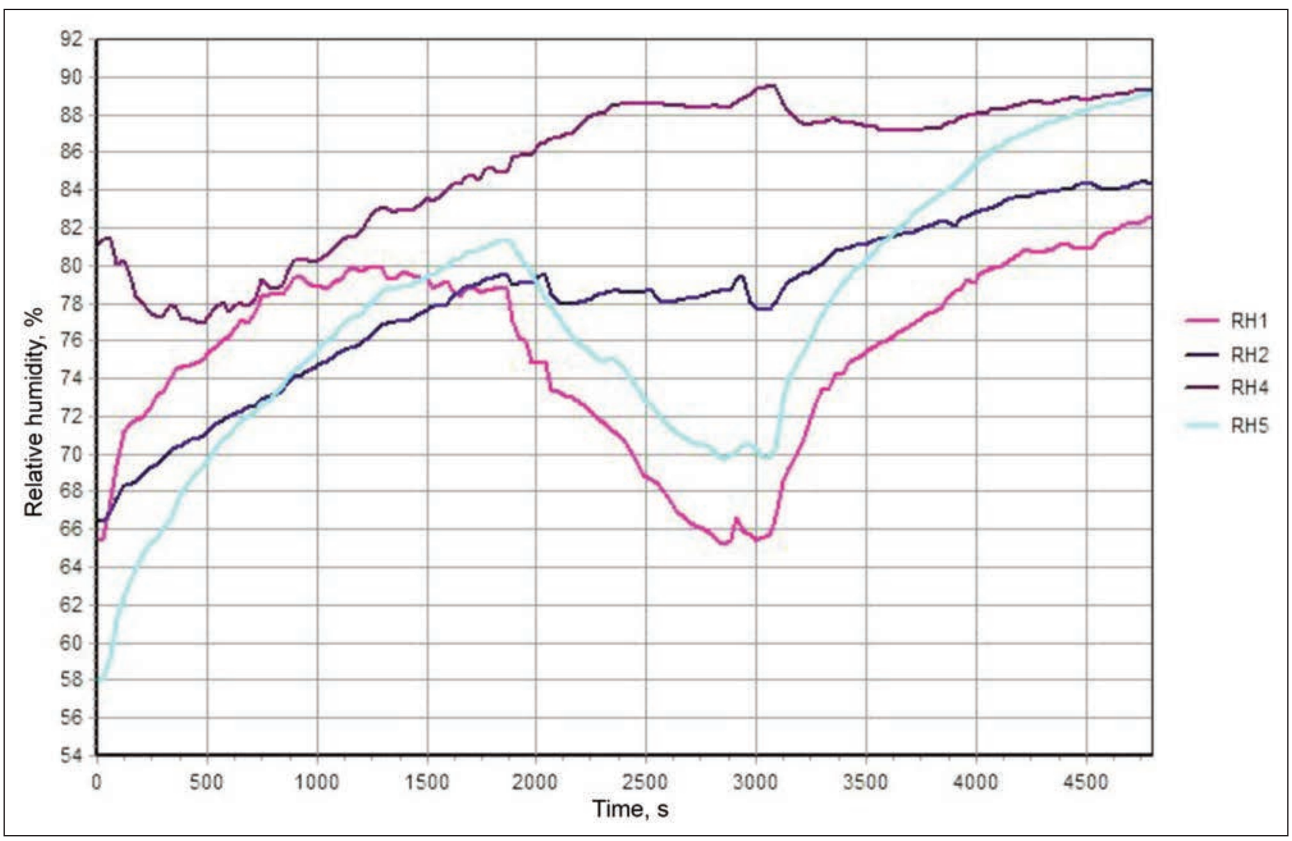

Fig. 5. Relative humidity of the foot skin when wearing R22 rib knitted socks during testing in dynamic conditions

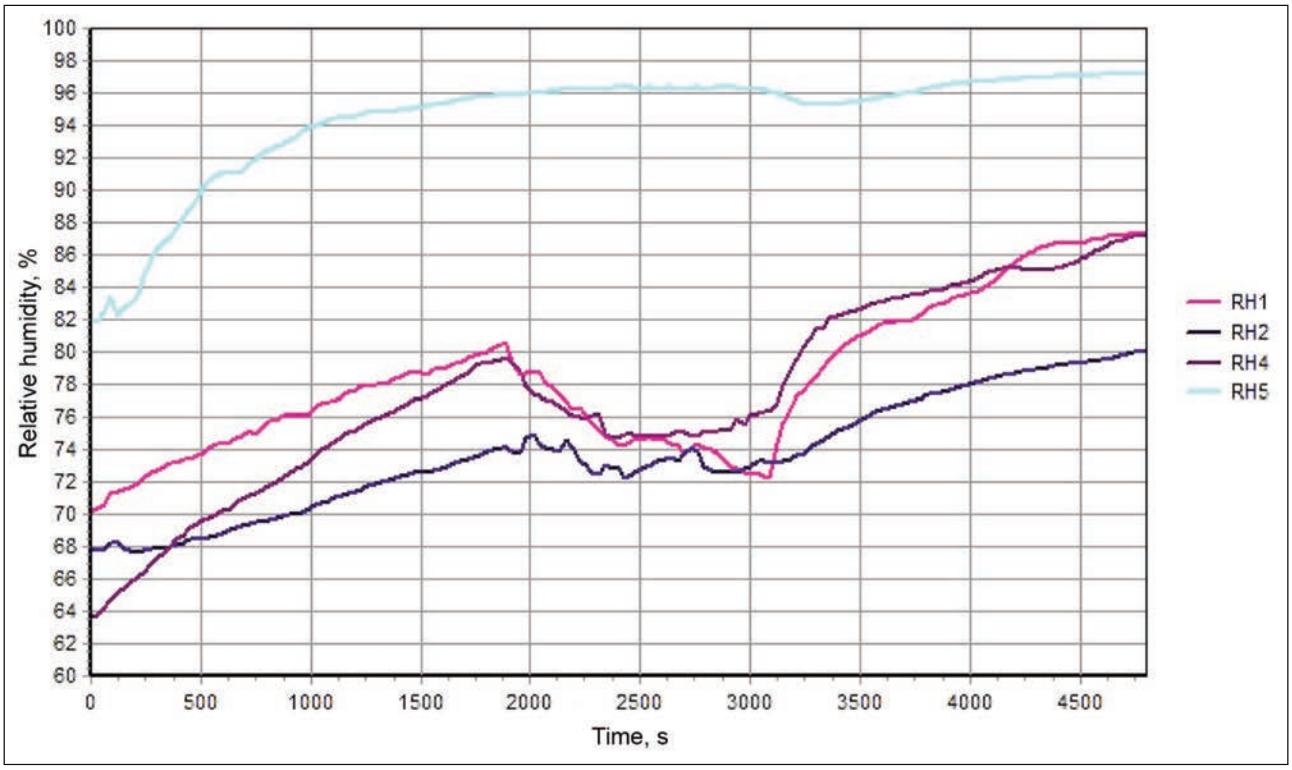

Fig. 6. Relative humidity of the foot skin when wearing R31 rib knitted socks during testing in dynamic conditions

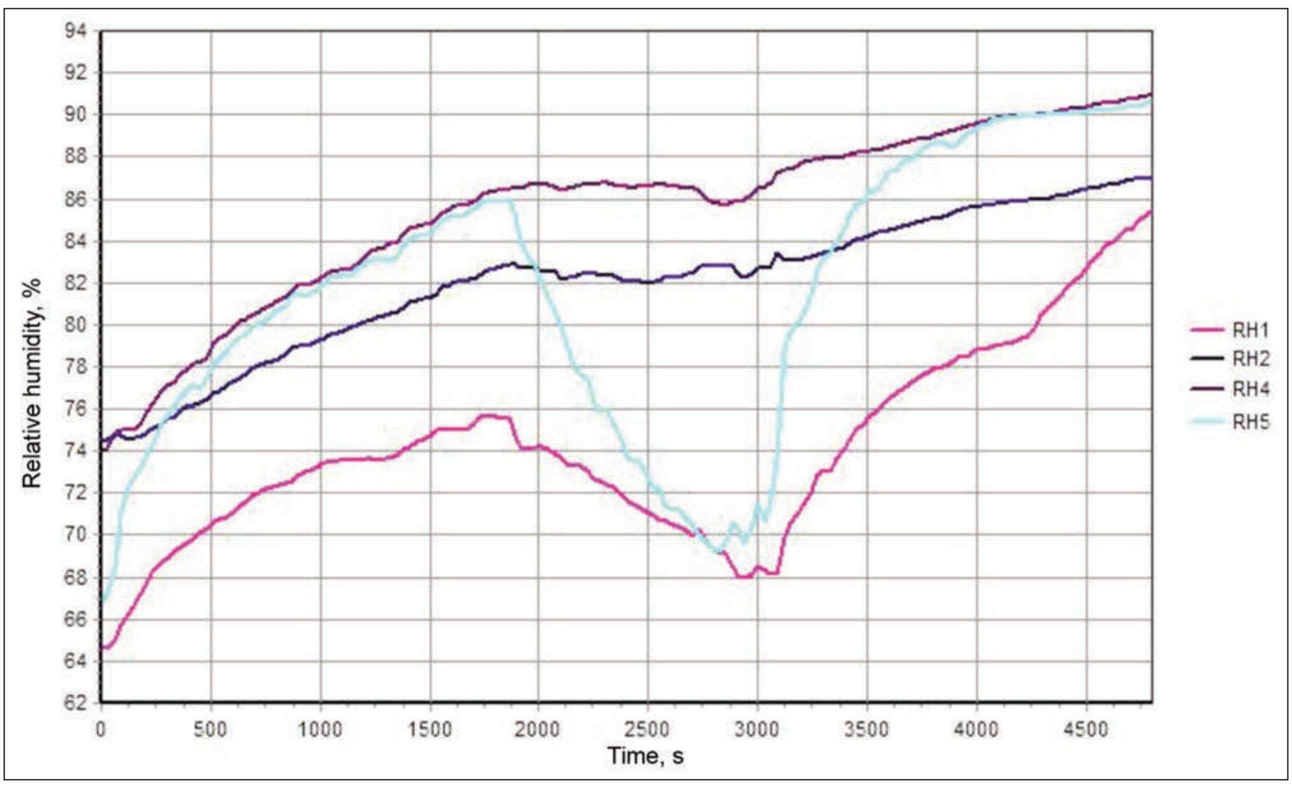

Fig. 7. Relative humidity of the foot skin when wearing R71 rib knitted socks during testing in dynamic conditionss

comfort; socks containing cotton are less comfortable than synthetic socks. However, many consumers still prefer clothing that contains cotton. Comfort is related to sensory parameters such as temperature and humidity. Fibres that can transport sweat from the sock are needed to avoid high foot temperature and humidity. The respondents were 11 men aged between 26 and 56 years. Participants wore the same shoes before each test. Before the start of the experiment, the subjects were conditioned for 15 minutes in the laboratory climate where the sports exercises took place. In order to measure physiological parameters, two sensors are integrated in each shoe, one in the area of the toes and one in the area of the ankle. The placement of these sensors is carefully chosen to avoid pressure points and friction. One sensor is fixed above the toes on the inside of the shoe.

Socks are the subject of research in the following paper, where a study was conducted that evaluated the effect of socks (made of different fibres) and the effect of not wearing socks on the perception of thermal comfort in relation to changes in the temperature of the skin of the feet and the microclimate of the shoes (temperature and humidity) during rest and exercise [15]. Ten women participated in the trials on different occasions. Four socks were evaluated (cotton, wool, polyester, Coolmax), and one test was without socks. The tests were conducted at 23°C and 50% relative humidity, and consisted of rest (10 min, sitting), treadmill running (40 min, 7.5 km/h) and recovery (15 min, sitting). Foot skin temperature and shoe microclimate were measured at seven places on the right foot. Foot skin hydration was measured at nine places. Not wearing socks resulted in a greater perception of foot wetness, stickiness and discomfort. As the tactile interactions caused by foot movement inside the shoe are strong determinants of foot wetness perception, socks are important in reducing the tactile cues generated. The results of this study show similar thermophysiological and perceptual responses when socks composed of different types of fibres are worn during rest and exercise. Also, similar thermophysiological responses were observed when wearing socks (regardless of fibre type) compared to not wearing socks. Surprisingly, however, exercising without socks resulted in greater perceived foot wetness, stickiness, and thermal discomfort.

In addition to socks, other clothing items are the subject of thermal and moisture comfort research [16]. In a climate chamber experiment, quantitative research guides underwear development. The thermal and wet comfort of pure cotton underwear is worse than that of blended or knitted underwear, which is consistent with previous results that the thermal and wet comfort of multi-fibre fabrics is better than that of same-fibre fabrics. Half an hour before the experiment, participants entered a room with artificial climate with constant temperature and humidity: ambient temperature (25±2)°, relative humidity (65±5)% and wind speed ≤0.1 m/s. The test personnel wore only an undershirt and underpants for the experiment. The temperature and humidity of the chest, back, hips and thighs of the human body change with the change of the exercise state, and the results of the heat and humidity comfort of each part are different, while the heat and humidity of the chest and back change greatly. In addition, the results of the subjective assessment of thermal and wet comfort are basically consistent with the objective assessment results. The simulated values are in good agreement with the experimentally measured values.

Furthermore, in order to evaluate the thermophysiological comfort of men's workwear, an analysis was performed based on the evaluation of the clothing system using test persons in a study simulating environmental conditions [17]. Analysis of the thermophysiological comfort of men's business clothing based on wear tests shows that environmental conditions, activity levels and thermal properties of the clothing system have a significant impact on the physiological parameters of the subjects and the subjective assessment of thermal comfort in a cold environment. At an ambient temperature of 10°C, when the study participants wore a four-layer clothing system, the mean skin temperature averaged about 32.5°C while sitting and about 31.6°C while walking. Subjective assessment showed that study participants felt thermally comfortable despite lower mean skin temperatures. Subjective assessment showed that study participants felt somewhat uncomfortable while sitting, but felt thermally comfortable or slightly cool while walking. The research shows that different environmental conditions, activity levels and thermal properties of the clothing system have a significant impact on the physiological parameters of the subjects and the subjective assessment of thermal comfort in a cold environment.

Microclimate temperature

Figures 8 to 10 show Temperature/Time graphs for the microclimate in the space between wearing socks and wearing tied shoes during dynamic walking conditions in the climate chamber. These graphs have two curves each, one curve comes from the T162 sensor (left foot) and the other from the T67 sensor (right foot).

For bamboo socks in all rib constructions, the curves from both sensors generally follow each other, after an initial rise to 1500–1900 s ("walking I" phase), the curve begins to fall with one sharp jump (R31 and R71 constructions, right foot) to about 3000 s (rest at the end of phase "walking I"), after which the curves continue to grow continuously until the end of testing in the climate chamber (phase "walking II"). This more intense jump after 2000 s was not registered with the microclimate sensor on the left foot. The existence of rapid cyclical or rhythmic shifts of the temperature curve from the sensor on the right leg between 2300 s and 3000 s in the R31 construction or between 2600 s and 3000 s in the R71 construction can be related to the subjective error that occurred during the resting time period after the "walking I" phase, it is probably a reflex movement of the toes, i.e. the front part of the foot (toes curling, bending the foot in the shoe, etc.), which was reflected in the result.

The graphs in figures 8 and 9 represent the temperature of the microclimate of socks in R22 and R31 constructions, for both feet with shoes in dynamic walking conditions. The temperature curves from the space between the sock and the shoe, for the left (sensor T162) and right (sensor T67) legs, follow each other, i.e., the differences are minimal. With socks in the R71 construction, the situation is a little different; the curves from these sensors do not follow each other. It is expected that there are real differences in the temperature of the microclimate of one foot and the other foot; it is unlikely that both feet give the same values of heat that accumulates in the space between shoes and socks. In addition to the knitting structures of the socks, this is also influenced by the pressure of the shoe, the strength of the laces, the shape of the foot, the fit of the shoe on the upper part of the foot, etc.

All these observations are related to the properties of the fibres from which the socks are made, as well as the structural, i.e., constructive characteristics of the knitted fabric from which the socks are made. As the composition and structural characteristics of the sock yarn are identical, the differences are attributed mainly to the differences in the knitting structures of the socks.

During the experiment in the climate chamber, the highest recorded values of skin temperature and microclimate are in the following sequence of rib constructions: R22>R31≥R71. For foot skin moisture results, the order of rib constructions is as follows: R71>R31>R71. Socks with R22 construction generally have the highest skin temperature during the experiment, which at first glance leads to the thought that the product with this knitting structure is the greatest insulator; however, it is not so, on the contrary, this knitting structure is the most heat permeable. Namely, if it is considered that socks with R22 construction leave the least amount of moisture on the skin of the feet, this means that they transmit the most heat and water vapour, so they do not allow a large condensation of moisture on the skin.

Therefore, if these socks with R22 construction were the greatest insulator, they should simultaneously have the greatest condensation of water vapour, that is, show the greatest moisture of the skin (which does not happen). It turns out that socks with R71 construction and/or R31 construction (a small difference between them) are the greatest insulators, in this case, because they cause the greatest moisture in the skin of both feet, that is, they are the least permeable to water vapour and heat, which causes condensation and sweating of the feet. Socks in R22 construction have the highest temperature of the skin of the feet; this heat is transferred to the sock and then to the space between the sock and the shoe, so as expected, they also have the highest microclimate temperature. This is not the case with R31 and R71 rib knitted socks because they are better insulators, heat condenses into moisture-sweat, and they have a slightly lower microclimate temperature.

Considering that moisture is more uncomfortable than heat, then bamboo/polyamide, 77/22%, R22 rib knitted socks give the best results for foot comfort while walking in shoes at 20°C and 50% relative humidity.

Many authors point out that the microclimate parameters of footwear, especially humidity, have a decisive influence on the feeling of the user in relation to thermal comfort. Research on shoe microclimate [15] evaluates the effect of sock fibre type and the effect of not wearing socks on the perception of foot thermal comfort in relation to shoe microclimate. Results have similar thermophysiological responses when wearing socks (regardless of fibre type) compared to no socks during rest and exercise.

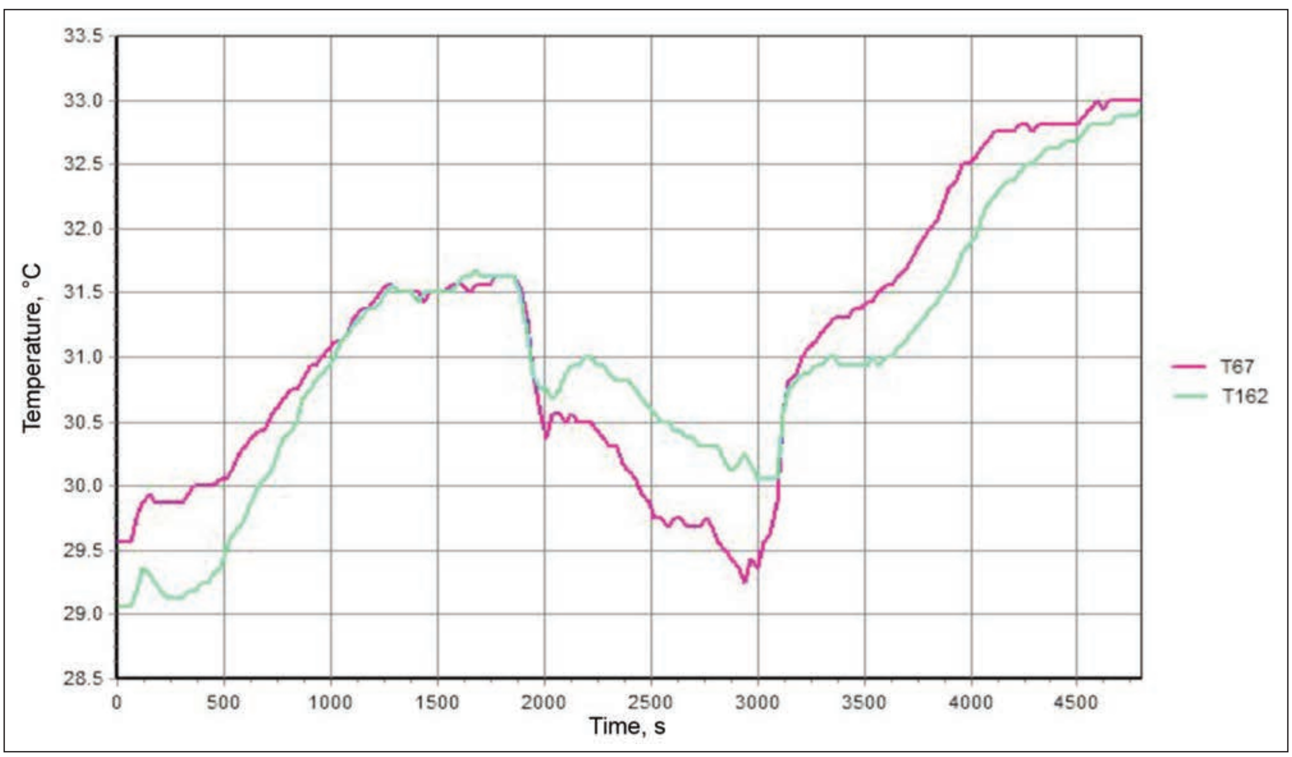

Fig. 8. Microclimate temperature in the space between R22 rib knitted socks and shoes during testing in dynamic conditions

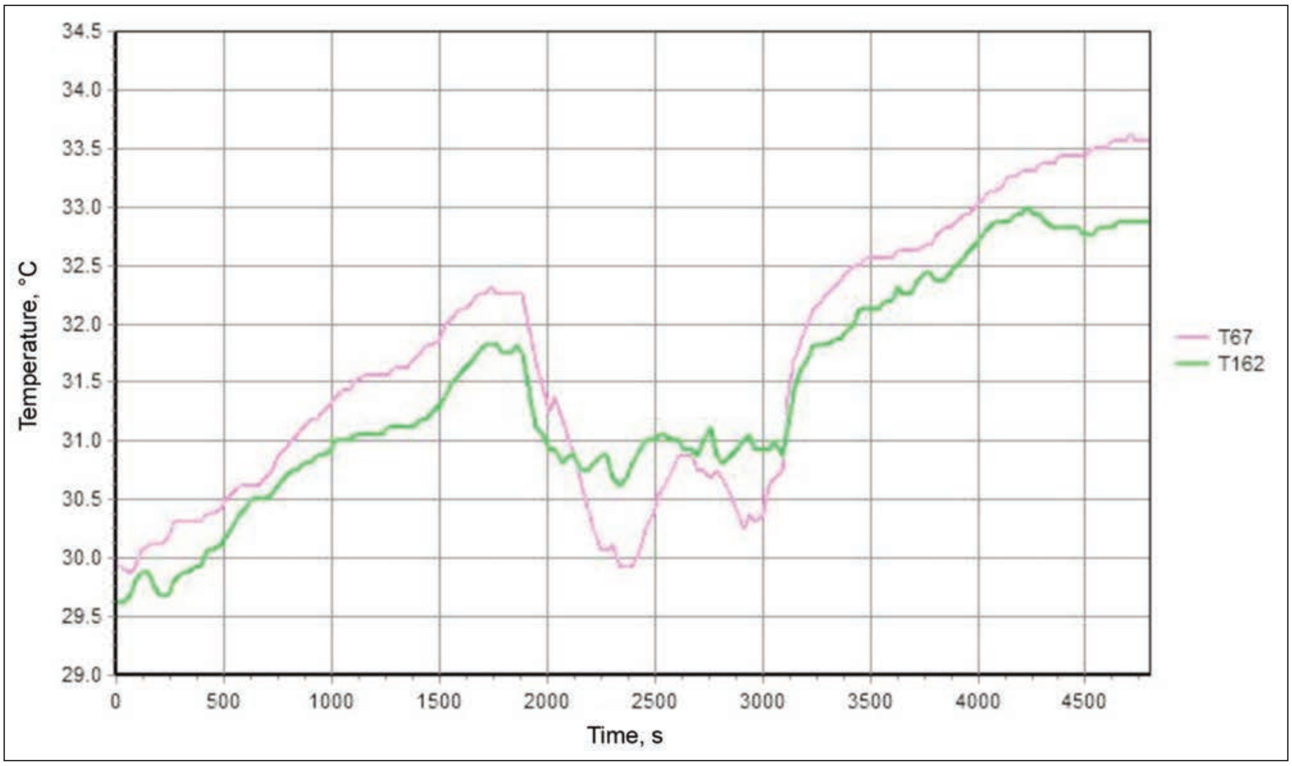

Fig. 9. Microclimate temperature in the space between the R31 rib knitted socks and shoes during testing in dynamic conditions

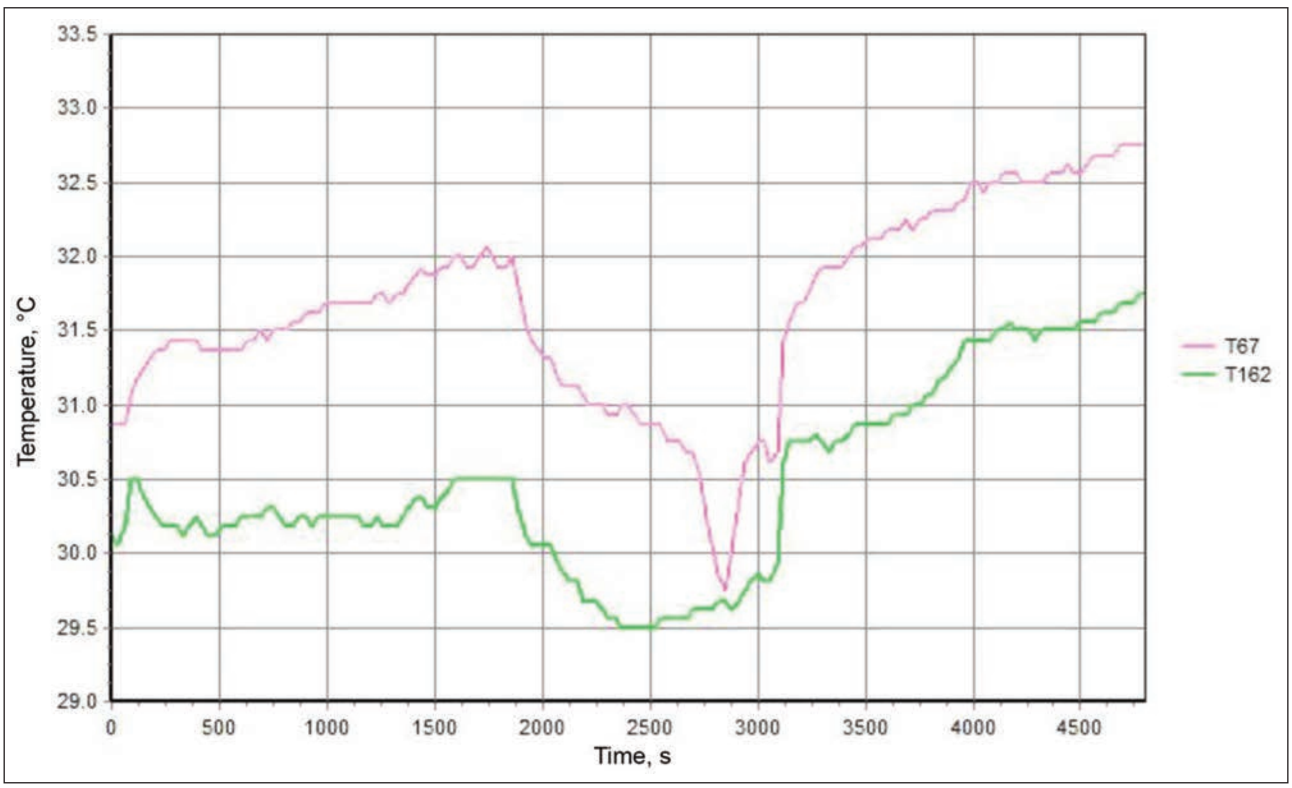

Fig. 10. Microclimate temperature in the space between the R71 rib knitted socks and shoes during testing in dynamic conditions

No differences were observed in foot temperature, shoe microclimate or foot skin hydration. Socks composed of different types of fibres were also shown to induce similar thermophysiological responses during rest and exercise, as no differences were observed in foot temperature, shoe microclimate, or foot skin hydration.

The following research deals with a validation study for the already published thermal simulation of the clothing system and the human environment through wear testing [18]. Three test persons and a clothing system were selected for this research. The temperature of the microclimate has a great influence on the temperature of the skin. Skin temperature has an almost similar pattern of variation on the microclimate temperature curve. For example, significant variations in microclimate temperature affect corresponding skin temperatures that show a similar pattern of temperature curves. Therefore, the occurrence of pumping in the air gaps between the clothes and the body causes not only a decrease in the temperature of the microclimate, but also the corresponding temperature of the skin. During the wear test, the subject has to perform various activities while walking on a treadmill, which causes forced convection on the moving parts of the body and also a pumping effect in the microclimate between the clothing and the body.

The indication of microclimatic conditions in footwear is also shown by the research of Irzmanska et al. [19], which points out that the accumulation of heat leads to an increase in the temperature of the skin of the feet and an increased humidity of the microclimate inside the footwear, to the point of saturation. These conditions cause an intense production of sweat, which again cannot evaporate and accumulates on the skin and inside the textile structure, which increases the user's discomfort. By analogy with the treadmill test, three characteristic phases of the development of the microclimate inside the footwear can be distinguished: the first phase – increased heat transfer to the skin and the beginning of intensive sweat production; the second stage – evaporation of produced moisture; and the third stage – local condensation of water vapour. Unfavourable microclimatic conditions inside rubber protective footwear disrupt thermoregulatory processes associated with blood flow in the lower extremities. This can subsequently disrupt the functioning of the entire human body. Therefore, it is crucial to control this microclimate. These changes in the internal microclimate seem to be influenced by the moisture sorption and desorption characteristics of the materials used in the interior of the footwear.

The respondents in this pilot study were always dressed in the same wardrobe; the models of socks on the feet changed, depending on the rib constructions. Three different respondents answered individually during the interview according to the international standard ISO10551 2019. Each of the respondents, during a test of subjective perception in laboratory conditions, wore one model of socks (a total of 3 models) and answered the questions 3 times (after a certain time spent in the air conditioning chamber). Detention in the climate chamber lasted a total of 110 min with acclimatisation. Results are recorded throughout the entire testing process.

The questions, before the air conditioning chamber, were: how was the previous night, how was the sleep, what was the last meal and the way to the institution where the measurement is performed, as well as the general feeling before the examination in the air conditioning chamber. During their stay in the climate chamber, the respondents were interviewed 3 times at certain intervals. Answers were given to questions about the subjective assessment of the thermal comfort of the feet in socks and shoes. The questions were about the feeling of heat, thermal comfort, desired thermal state, acceptability of the current thermal conditions, assessment of one's personal thermal tolerance of the environment and the degree of skin moisture.

For example, on the question "Feeling heat" in the feet, the subjective ratings were as follows:

- At the beginning of the research (after 28 min): for sock models R31 and R71, the answer is "Neutral" (in two respondents) and "A little warm" (in one respondent), while for the sock model marked R22, the answer is "Neutral" (for all respondents).
- In the middle of the research (after 48 min): for all models of socks, the answer is "Neutral" (for all respondents).
- At the end of the research (after 108 min): for the R31 sock model, the answer is "A little warm" (in two respondents) and "Warm" (in one respondent), while for the R71 and R22 sock models, the answer is "Warm" (for all respondents).

Or:

Answers to the question, "How moist is your skin?" on the foot:

- At the beginning of the research (after 28 min): for all models of socks, the answer is "Slightly moist" (the part under the foot and above the toes), by all respondents.
- In the middle of the research (after 48 min): for the sock model R31, the answer is "Dry" (the part under the foot and above the toes), for all respondents, for the sock model R71 and R22, the answer is "Slightly moist" (the part under the foot and above the toes) in two subjects, while the answer is "Dry" (the part under the foot and above the toes) in one subject.
- At the end of the research (after 108 min): for all models of socks, the answer is "Slightly moist" (the part under the foot and above the toes), by all respondents.

CONCLUSIONS

According to the results of testing the parameters that define comfort when wearing socks, obtained based on dynamic experiments, under simulated climatic conditions, the following conclusions can be drawn:

- Regardless of the knitting structures of the socks, the temperature of the skin of both feet in the socks is always the highest during walking ("walking I and II") and the lowest during the "resting" phase, i.e., at rest between two phases of walking.
- The lowest value of foot skin temperature in socks and shoes, during the entire experiment, was determined with socks in R71 and R31 constructions, while the highest temperature was registered with socks in R22 construction.
- The tested sock models are not completely suitable in terms of thermal comfort during the stay in the air

conditioning chamber during the "walking II" phase. Socks in the R71 construction are closer to the comfort zone than socks in other rib constructions.
- According to the results for foot skin moisture, there is a partially impaired physiological comfort when walking in socks, especially in the last phase of the experiment, "walking II". The best product in this sense was the R22 rib knitted socks.
- The microclimate temperature when wearing socks with basic bamboo yarn in R22 construction is slightly higher (on average 0.5–1 °C) in the whole range compared to the microclimate temperature of socks with other rib constructions.
- Socks in R22 construction, which have the highest thickness and lowest porosity in a relaxed state (at rest), are also better conductors of heat when walking in shoes. At the same time, socks in R32 and R71 constructions, which have the highest porosity, permeability of water vapor and air in a state of rest, show the property of lower heat conductivity in dynamic conditions (movement).
- In general, the combination of man-made and synthetic fibres in socks in the R22 construction, bamboo/polyamide composition, 77/22%, gives the best results for the comfort of the feet during walking in shoes, in specific conditions, 20 °C and 50% relative humidity.
- The objective measurement results in this pilot study, the subjective perception and prediction of the thermophysiological comfort of the test subjects in laboratory conditions, wearing the made sock models is also significant.

Considering the obtained results of the research on the influence of the construction of socks on the thermal-physiological comfort during practical use, the performed research represents a contribution in the area of comfort and convenience when walking.

ACKNOLEDGEMENTS

The author would like to thank the Faculty of Technology in Leskovac, Serbia, the Wool Institute in Leskovac, Serbia, and the University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia for their support.

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Design of weft-knitted spacer fabrics: impact of fabric structure parameters on thermal-wet comfort and cushioning performance

DOI: 10.35530/IT.077.01.2024161

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ABSTRACT – REZUMAT

Design of weft-knitted spacer fabrics: impact of fabric structure parameters on thermal-wet comfort and cushioning performance

Weft-knitted spacer fabrics are characterised by their lightweight nature, thermal insulation, air permeability, and elasticity. To explore their application potential in garment fabric development, this study proposes a novel weft-knitting process based on traditional spacer fabric knitting techniques, which incorporates functional yarns into the spacer layer. Based on this process, the influence of varying fabric structures, including the spacer layer structure, the number of spacer layers, and the type of reinforcing yarn, on the thermal-wet comfort and cushioning properties of weft-knitted spacer fabrics is analysed. A three-factor, three-level orthogonal experiment was designed to produce 9 fabric samples, which were tested for compressibility, air permeability, moisture permeability, and thermal insulation. Variance analysis of the test data reveals the relative significance of the three factors. Experimental results indicate that the structure of the spacer layer has the most significant impact on fabric performance, followed by the type of reinforcement yarn, while the number of spacer layers has a relatively minor effect. Furthermore, during the compression tests, the compression stress-strain curves were fitted and differentiated to analyse the cushioning performance of the spacer fabrics based on the trends observed in these curves. The experimental findings reveal that the compressibility of the fabric is inversely proportional to its cushioning properties.

Keywords: *spacer fabrics, spacer structure, knitting process, work of compression, thermal-moisture comfort*

Proiectarea tricoturilor din urzeală distanțiere: impactul parametrilor structurii tricotului asupra confortului higrotermic și asupra performanței de amortizare

Tricoturile din urzeală distanțiere se caracterizează prin greutate redusă, izolare termică, permeabilitate la aer și elasticitate. Pentru a explora potențialul lor de aplicare în dezvoltarea materialelor textile pentru îmbrăcăminte, acest studiu propune un proces inovator de tricotare din urzeală, bazat pe tehnici tradiționale de tricotare a tricoturilor distanțiere, care încorporează fire funcționale în stratul distanțier. Pe baza acestui proces, se analizează influența diferitelor structuri ale tricoturilor – inclusiv structura stratului distanțier, numărul de straturi distanțiere și tipul firului de întărire – asupra confortului higrotermic și proprietățile de amortizare ale tricoturilor din urzeală distanțiere. A fost conceput un experiment ortogonal cu trei factori și trei niveluri pentru a produce 9 eșantioane de tricoturi, care au fost testate pentru compresibilitate, permeabilitate la aer, permeabilitate la umiditate și izolare termică. Analiza varianței datelor de testare relevă semnificația relativă a celor trei factori. Rezultatele experimentale indică faptul că structura stratului distanțier are cel mai semnificativ impact asupra performanței tricotului, urmată de tipul firului de întărire, în timp ce numărul de straturi distanțiere are un efect relativ minor. În plus, în timpul testelor de compresiune, curbele de tensiune-deformație la compresiune au fost ajustate și diferențiate pentru a analiza performanța de amortizare a tricoturilor distanțiere pe baza tendințelor observate în aceste curbe. Rezultatele experimentale relevă faptul că compresibilitatea tricotului este invers proporțională cu proprietățile sale de amortizare.

Cuvinte-cheie*: tricoturi distanțiere, structură distanțier, proces de tricotare, activitate de compresie, confort higrotermic*

INTRODUCTION

Spacer fabric, a three-dimensional textile composed of two independent surface layers and a spacer layer, has attracted significant attention in functional textile research [1]. Scholars have made substantial efforts to explore the structural diversity of weft-knitted spacer fabrics, primarily focusing on two connection types: tuck connections and fabric-layer connections. For tuck-connected structures, Song et al. pioneered the development of such fabrics using glass fibres, demonstrating their ability to effectively utilise high-performance fibres for enhanced mechanical properties [2]. In the realm of fabric-connected designs, Unal and his team expanded beyond traditional loop-connected structures by proposing fabric-based connections, developing single-layer U-shaped and V-shaped weft-knitted spacer fabrics that laid the foundation for subsequent double-layer structures [3]. Abounaim later clarified the knitting principle of 2U-shaped (double-layer U-shaped) spacer fabrics [4], while Li optimised this technology by introducing a double ribbing structure at the spacer layer cross-linking, increasing fabric thickness and imparting cushioning performance to plain knitted fabrics [5]. Huang further advanced this field by developing 2V-shaped (double-layer V-shaped) spacer fabrics and confirming their superior buffering performance for local human body protection compared to 2U-shaped structures and shear thickening fluid-impregnated variants [6]. Atar et al. used finite element modelling to compare spacer fabrics with rectangular, trapezoidal, and triangular cross-sections [7]. They found triangular structures had the highest surface load-bearing capacity (rectangular the lowest) and lower transverse shear stiffness, showing cross-sectional geometry impacts mechanical performance.

The stable three-dimensional structure of these fabrics, attributed to the spacer layer, endows them with unique properties such as impact resistance and thermal insulation [8, 9]. Abbas et al. demonstrated that the number of stitches per repeat (SPR) significantly regulates energy absorption and negative Poisson's ratio (NPR) behaviours in 3D weft-knitted auxetic fabrics, with SPR=81 showing the highest energy absorption capacity [10]. On mechanical performance, Azita analysed the compression behaviour of tuck-connected spacer fabrics and revealed that a larger spacer yarn tilt angle enhances compression resistance [11], while Ryan identified spacer yarn diameter as a key factor influencing impact resistance [12]. Gong et al. and Umair et al. have respectively highlighted the potential of spacer fabrics in thermal-wet comfort for protective clothing and breathable insoles [13, 14], yet these studies often focus on single performance metrics in isolation.

In apparel applications, these structural innovations have enabled breakthroughs in comfort and functionality. For example, Annie et al. developed 3D weft-knitted spacer fabric bra cups, confirming comparable compression strength to traditional foam cups while enhancing breathability via porous structures, thus validating the feasibility of one-step forming technology [15]. Golnaz et al. investigated spacer fabrics for compression stockings, screening structures with pressure values equivalent to commercial products but superior wearing comfort [16]. Umair et al. further emphasised the importance of structural parameters (e.g., stitch density, layer thickness) in balancing cushioning and breathability for sports textiles, noting that gradient designs can optimise pressure distribution without compromising comfort [17]. Zhao et al. developed fully-fashioned weft-knitted spacer fabric helmets using UHMWPE fibres, achieving excellent mechanical properties, structural stability, and industrial production adaptability [18].

Fu et al. integrated intarsia techniques with spacer fabric structures to create sports knee pads, where segmented knitting and curved edge designs enhanced shock absorption while conforming to knee anatomy [19].

Currently, most studies on fabric performance have focused on impact resistance, while research on their thermal-wet comfort remains relatively limited. To address this, this article presents a novel weft-knitted spacer fabric with reinforcing yarns added to the spacer layer. Through a three-factor, three-level orthogonal experiment, the specific impact of the spacer layer (structure, number of layers, reinforcing yarn type) on thermal insulation, comfort, and cushioning properties was investigated. Using Merino wool yarn for the comfort-oriented surface layer and bulked or Kevlar yarn for the functional spacer layer, nine fabric samples were knitted and tested to clarify the structure-performance relationship, providing insights for garment fabric development.

MATERIALS AND METHODS

Material

The experiment involved the use of two strands of ultrafine merino wool, with a yarn count of 2/56NM. The knitting was performed on a STOLL computerised flat knitting machine, model CMS 530 HP, manufactured by the German company STOLL. The machine had a gauge setting of 7.2.

Fabrication of spacer fabrics

The new axial reinforced weft-knitted spacer fabric is based on a weft-knitted stitch structure, in which warp yarn and weft yarn are inserted during the knitting process to form the fabric [20]. The inserted warp and weft yarns mostly use thicker and harder high-performance fibre yarns. Inserting high-performance yarns into the three-dimensional spacer fabric can enhance the three-dimensional structure, and the inserted yarns can greatly improve the performance of the fabric [21]. The specific performance depends on the characteristics of the inserted yarns.

Based on the detailed introduction of the knitting process of traditional weft-knitted spacer fabrics by previous scholars [2–7], this paper designs a weaving process of inserting weft-directional reinforcing yarns into the spacer layer. Taking the 2V-shaped fabric as an example, the specific steps are shown in figure 1. The front needle bed performs plain stitch knitting. This step can be iterated to fine-tune the length of the upper surface layer (L1 in figure 1, *a*). The plain stitch is knitted separately by the front and back needle beds, collaborating with step a to construct the upper surface layer F1 of the fabric (figure 1, *b*). The front and back needle beds alternate between knitting one stitch on and skipping one stitch (figure 1, *c*). Reinforcing yarns are added to the front and back needle beds alternately. Tuck loops and floats are knitted alternately. After inserting three rows of floats, a row of tuck loops is knitted to form the reinforcing structure N1 (figure 1, *d*). The loops are knitted alternately on both the front and back needle beds. Steps (c), (d), and (e) collectively constitute the spacer layer K1 of the fabric (figure 1, *e*). The back needle bed executes plain stitch knitting, and this step can be repeated to adjust the length of the lower surface layer (L2 in figure 1, *f*). Step b is repeated, collaborating with step f to create the lower surface layer F2 of the fabric.

In this experiment, three types of weft-knitted spacer fabrics with different interval structures were designed, such as tuck connection, 2U-shaped fabric

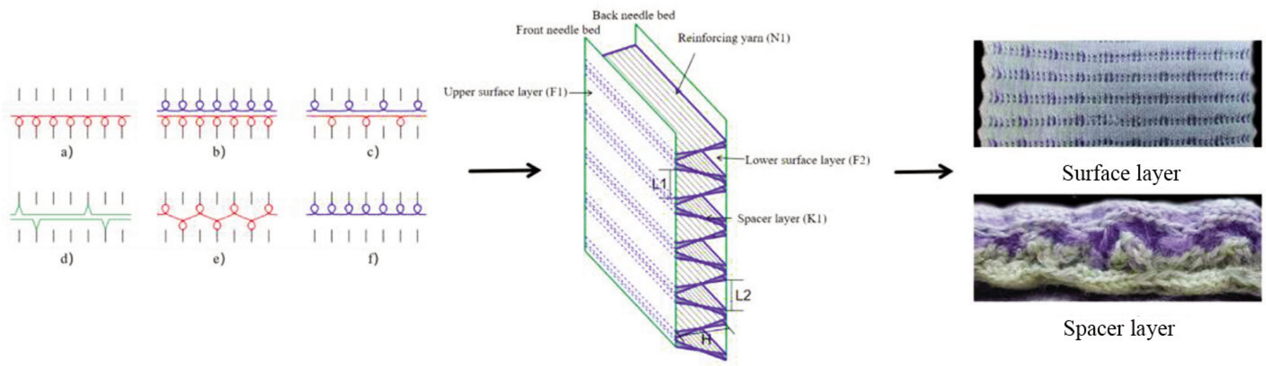


Fig. 1. Knitting flowchart of the new axial reinforced weft-knitted spacer fabric

connection, and 2V-shaped fabric connection. To investigate the effects of reinforcing yarns on the mechanical properties and thermal-wet comfort properties of spacer fabrics, two different types of reinforcing yarns were inserted into the spacer layer of the fabrics. Based on this, an orthogonal experiment with three factors and three levels was designed. 9 types of spacer fabric samples were knitted in total. The specification parameters and fabric structures of the samples are shown in table 1.

Compression tests

The compression testing was conducted in accordance with FZ/T 01054.1-1999 *General Principles for Fabric Style Test Methods* using a YG821L fabric style instrument. Samples were meticulously cut to dimensions of 65 mm × 50 mm and preconditioned before testing. Each sample was placed on a stable platform, and a rectangular compression plate (5 cm × 2 cm) was applied at a constant speed of 3 mm/min to record the compression stress-strain curves.

Thermal and moisture comfort tests

Air permeability tests

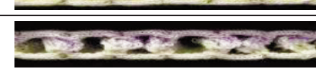
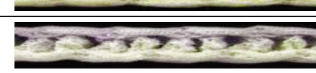
Air permeability testing was conducted in accordance with GB/T 5453-1997 *Textiles – Determination of fabric air permeability* using a YG461E-III automated air permeability tester (manufactured by Ningbo Textile Instrument Factory). Each fabric sample was tested over a standardised area of 25 cm^2. Under a test pressure of 100 Pa (as specified in the standard), the instrument measured the volume of air passing through the fabric per unit area and per unit time (mm/s).

Moisture permeability tests

Moisture permeability testing was conducted in accordance with GB/T 12704.2-2009 *Textiles – Test method for water-vapour transmission of fabrics – Part 2: Water method* using the YG601H-III computerised fabric moisture permeability tester. A total of 9 fabric types were evaluated under the evaporation method specified by the standard. Circular samples with a diameter of 70 mm were prepared and tested under controlled environmental conditions of 38±2°C

Table 1

SPACER FABRIC SAMPLES PARTICULARS

Type	Factor A	Factor B	Factor C	Cross-sectional view
L1	Tuck stitch	6	No reinforcing yarn added	
L2	Tuck stitch	8	Bulked yarn added	
L3	Tuck stitch	10	Kevlar yarn added	
U1	2U-shaped	6	Bulked yarn added	
U2	2U-shaped	8	Kevlar yarn added	
U3	2U-shaped	10	No reinforcing yarn added	
V1	2V-shaped	6	Kevlar yarn added	
V2	2V-shaped	8	No reinforcing yarn added	
V3	2V-shaped	10	Bulked yarn added	

Note: Factor A: the interlayer structure of spacer fabrics; Factor B: spacer layer count; Factor C: type of reinforcing yarn.

temperature and 50±2% relative humidity for a duration of 1 hour. The instrument measured the water vapour transmission rate (WVTR) through the fabric, with results reported in grams per square meter per hour (g/m^2·h).

Thermal insulation tests

Thermal insulation testing was conducted in accordance with GB/T 11048-1989 *Test Method for Thermal Insulation Property of Textiles* using a YG606D flat plate fabric insulation instrument. Test samples, each measuring 30 cm × 30 cm, were placed over the instrument's sample plate. The instrument directly recorded key parameters, including insulation rate, heat transfer coefficient, and clo value, which were then documented for analysis.

RESULTS AND DISCUSSION

Compression behaviour of spacer fabrics

By measuring the thickness difference that occurs when two different levels of pressure-light and pressure-heavy are successively applied to the same specimen, followed by the determination of the recovery observed after removing the load, we have calculated 4 key parameters, which are detailed below:

$$\text{Apparent thickness, } T_0 = R_{f1} - R_{o1} \text{ (mm)} \quad (1)$$

$$\text{Stable thickness, } T_S = R_{fh} - R_{oh} \text{ (mm)} \quad (2)$$

$$\text{Compression Rate, } C = \frac{T_0 - T_S}{T_0} \times 100\% \quad (3)$$

$$\text{Recovery thickness, } T_r = R_{fr} - R_{o1} \text{ (mm)} \quad (4)$$

$$\text{Compression Recovery, } RE = \frac{T_r - T_S}{T_0 - T_S} \times 100\% \quad (5)$$

In the equations provided: R_{f1} is the displacement of the pressure plate when the sample is under light pressure; R_{o1} is the initial displacement of the pressure plate under light pressure without a sample; R_{fh} is the displacement of the pressure plate when the sample is under heavy pressure; R_{oh} is the initial displacement of the pressure plate under heavy pressure without a sample; R_{fr} is the displacement obtained when the shape of the sample is restored under high pressure and lightly pressed again.

The pressure settings for automatic stop in the downward direction were 1 cN/cm^2 (light pressure) and 14.7 cN/cm^2 (heavy pressure). For this study, 9 samples were examined, and the mean values are presented in table 2. Using IBM SPSS, we performed an analysis of variance (ANOVA) on the collected data to assess the impact of various factors on fabric compressibility. The results obtained are summarised in table 3. Factor A has a significant impact on the compressibility of the fabric ($p<0.05$). Among the three factors considered, Factor A exhibited the strongest influence, followed by Factor C and then Factor B. However, the three factors have no significant impact on the compression recovery of the fabric.

The degree of fluffiness in a fabric is directly proportional to its compression rate. As evident from figure 2, *a*, the varying levels within factor A exert different degrees of influence on the fabric's compression rate, specifically: 2U-shape > 2V-shape > Tuck stitch. Similarly, within factor B, the order of influence is: 6 > 10 > 8. And within factor C, the impact is ranked as follows: None>Bulk>Kevlar.

Furthermore, the fabric's ability to retain its fullness and softness is enhanced with a higher compression recovery rate. In figure 2, *b*, the hierarchy of influence on fabric compression recovery within factor A shifts to: Tuck > 2V-shape > 2U-shape. Within factor B, the ranking changes to: 8 > 10 > 6. And within factor C, the order of impact becomes: Kevlar > Bulk > None.

In weft-knitted spacer fabrics, those with fabric-layer connections in the spacer layer are typically more fluffy compared to those with tuck-connections in the spacer layer. However, due to their hollow structure in the spacer layer, these fabrics exhibit significantly lower resilience compared to those with tuck connections. The number of spacer layers inversely correlates with both the compressibility and resilience of the fabric. As the number of spacer layers increases, the fabric becomes thicker and less susceptible to compression, yet its resilience improves. Additionally,

Table 2

PERFORMANCE RESULT OF WEFT-KNITTED SPACER FABRICS

No.	T_0 (mm)	T_S (mm)	C (%)	R_E (%)	Air permeability (mm/s)	WVT (g/m^2·h)	Heat retention rate (%)
L1	6.00	5.24	0.13	111.83	58.00	26.49	33.48
L2	6.00	5.64	0.06	162.04	20.02	24.01	37.83
L3	5.61	5.29	0.05	164.79	35.83	24.25	30.57
U1	11.09	8.04	0.27	103.89	545.67	26.52	63.44
U2	13.00	10.55	0.19	122.94	753.07	32.42	63.69
U3	14.39	10.61	0.26	106.28	582.70	32.51	66.74
V1	11.90	10.54	0.11	142.33	655.63	34.07	63.70
V2	15.86	12.60	0.21	101.11	570.03	35.55	69.19
V3	17.71	14.95	0.16	108.83	390.70	32.71	72.75

Note: T_0 – apparent thickness; T_S – stable thickness; C – compression rate; R_E – compression recovery; WVT – the moisture permeability.

Table 3

ANALYSIS OF VARIANCE FOR PERFORMANCE OF SPACER FABRICS										
Dependent variable	**C (%)**		**R_E (%)**		**Air permeability (mm/s)**		**WVT ($g/m^2 \cdot h$)**		**Heat retention rate (%)**	
	F	**P**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Factor A	24.808	0.039	2.769	0.265	318.173	0.003	24.437	0.039	263.187	0.004
Factor B	0.397	0.716	0.190	0.840	10.565	0.086	0.760	0.568	2.600	0.278
Factor C	6.170	0.139	2.690	0.271	20.870	0.046	4.193	0.193	5.576	0.152

Note: C – compression rate; R_E – compression recovery; WVT – the moisture permeability.

adding reinforcing yarn will reduce the fabric's compression rate to a certain extent.

To investigate the relationship between the compressibility and cushioning properties of fabrics, the Elongation (mm) – Force (cN) curves obtained from the tests were processed to generate Compression stress-Compression strain curve diagrams (figure 3). The calculated stress and strain parameters are as follows [22]:

$$\text{Compression strain} = \text{Elongation/Original height} \quad (6)$$

$$\text{Compression stress} = \text{Force}/10\ \text{cm}^2 \quad (7)$$

The compression process of the specimens can be categorised into two distinct stages: the compression phase and the rebound phase, depending on the variations observed in the respective curves. To further investigate the trend of compressive stress with respect to strain during the compression phase, non-linear curve fitting and differential analysis were applied to the stress-strain curves of 9 specimens. The findings obtained from this analysis are presented in figure 4.

Upon examination of the compression rate data tabulated in table 2, it becomes evident that a higher compression rate corresponds to a slower rate of change in compressive stress with respect to strain, resulting in a flatter curve. This observation suggests an inverse relationship between the compressibility

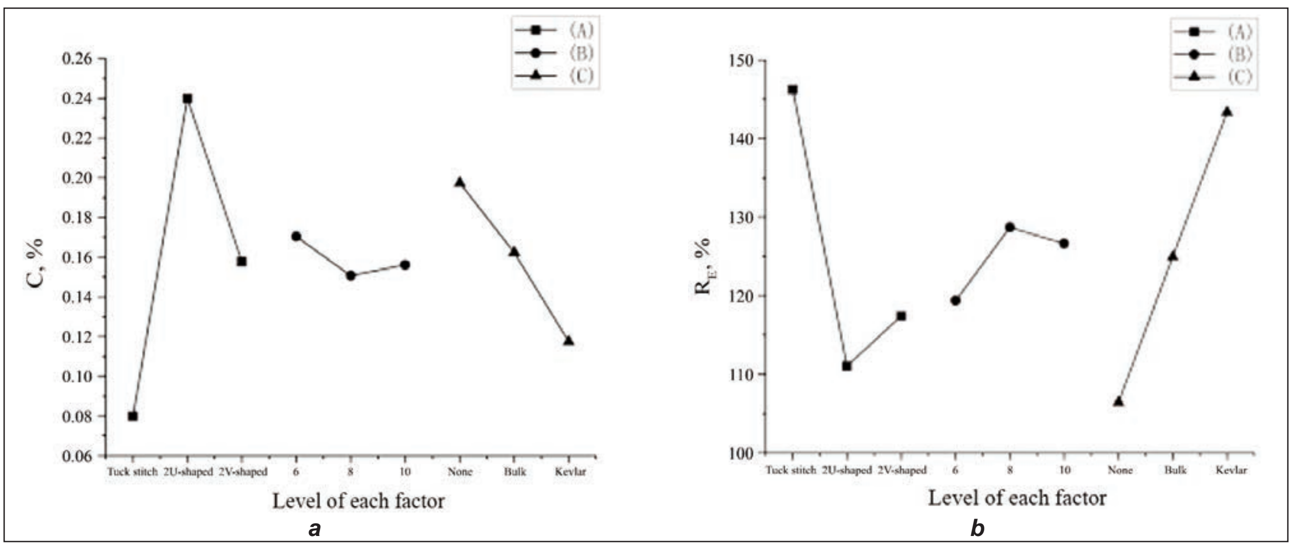


Fig. 2. Chart of compression behaviour for each factor level: *a* – Compression rate; *b* – Compression recovery

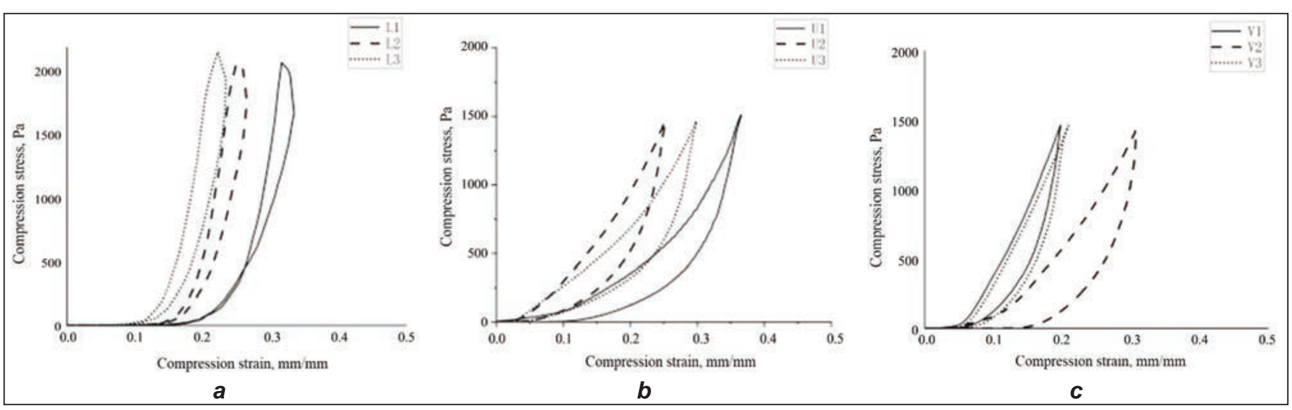


Fig. 3. The compression stress-strain curves of spacer fabric: *a* – Tuck stitch; *b* – 2U-shaped; *c* – 2V-shaped

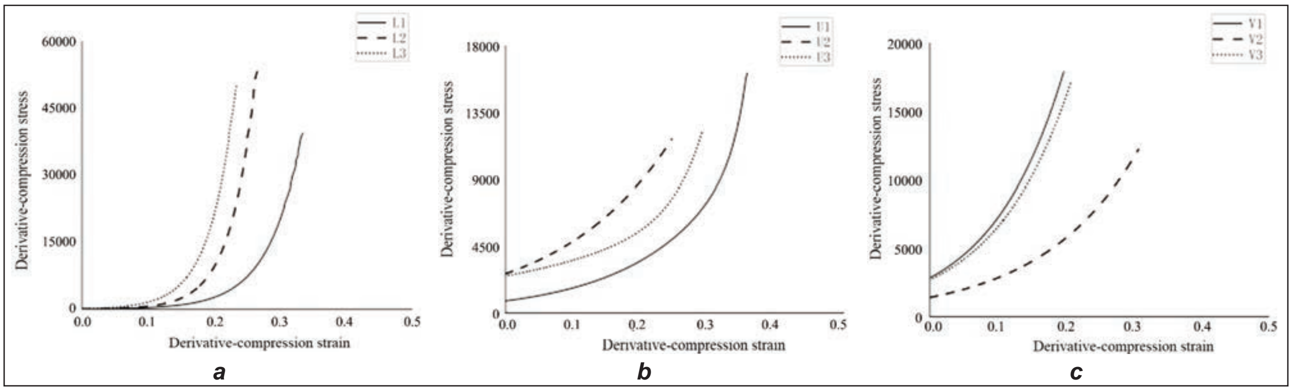


Fig. 4. Derivative of the compression stress-strain curves: *a* – Tuck stitch; *b* – 2U-shaped; *c* – 2V-shaped

and cushioning performance of the fabric. As the compressibility of the fabric increases, its fluffiness also enhances. However, during the compression process, the increment in compressive stress with increasing strain diminishes, indicating a decrease in the fabric's compressive resistance and cushioning capabilities.

Based on the analysis of figures 2 and 3, it can be concluded that the main factor causing the compression stress-strain variation of spacer fabrics is the type of reinforcing yarn, while the number of fabric layers has a relatively minor impact on the compression stress-strain behaviour.

Breathability of spacer fabrics

The results of the air permeability measurements for the 9 specimens are presented in table 2. Through analysis of variance, it was revealed that both Factor A and Factor C exert a significant influence on the air permeability of the fabric ($p<0.05$). Among the three factors, the significance was ranked as Factor A > Factor C > Factor B. To gain a more intuitive understanding of the impact of various factor levels on the air permeability of the spacer fabric, a chart of mean air permeability for each factor level was constructed. As shown in figure 5, *a*, adding bulk yarn to the spacer layer will reduce the air permeability of the fabric. This is because bulk yarn is fluffy, soft, warm, and elastic, and its higher volume allows the fabric to store more stationary air, reducing air flow. The Kevlar yarn, with higher strength and stiffness, enables the spacer layer of the fabric to be more upright, accommodating more flowing air and improving the air permeability of the fabric. Additionally, the structure of the spacer layer also affects the air permeability of the fabric. Compared to spacer fabrics connected by tuck stitches, spacer fabrics connected by fabrics have a certain height, larger air flow space, and better air permeability.

Moisture permeability of spacer fabrics

Based on the moisture permeability test results obtained from table 2. After analysis of variance (shown in table 3), it was found that Factor A has a significant impact on the moisture permeability of the fabric ($p<0.05$), and factors are ranked as follows: Factor A > Factor C > Factor B.

According to the chart of thermal-wet comfort at each factor level (figure 5, *b*), it can be seen that under different spacer layer structures and numbers of layers, the weft-knitted spacer fabric with fabric connections has better moisture permeability than the one with tuck stitch connections. When the number of layers in the spacer is larger, the moisture permeability is better. Therefore, the larger the gap in the spacer layer, the easier it is for water vapour to pass through, and the better the moisture permeability of the fabric. However, the addition of reinforcement yarn in the spacer fabric can cause its fibre diameter to expand after absorbing moisture, which affects the water molecule channels and results in poorer moisture permeability of the fabric.

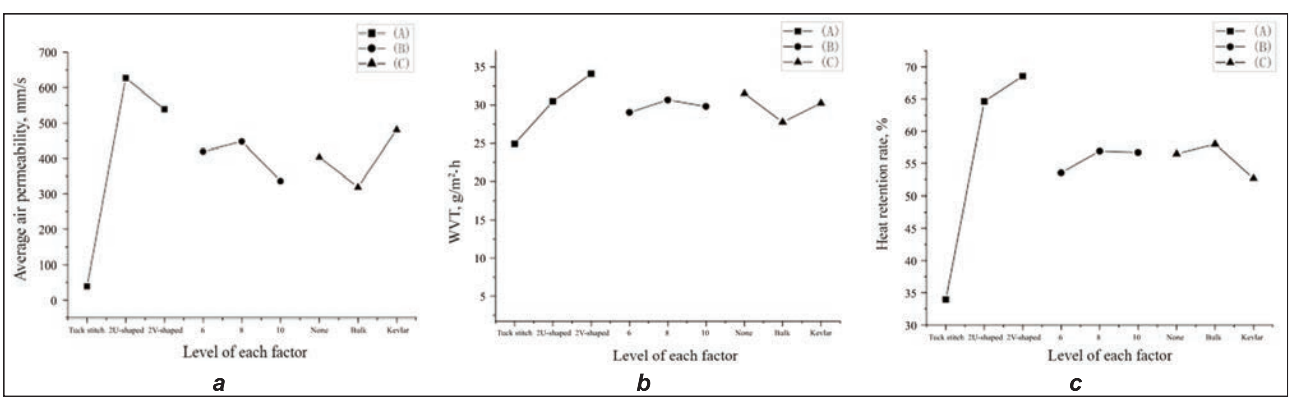


Fig. 5. Chart of thermal-wet comfort at each factor level: *a* – Air permeability; *b* – Moisture permeability; *c* – Heat retention rate

Thermal insulation properties of spacer fabrics

According to tables 2 and 3, it is evident that factor A exhibits a statistically significant impact on the thermal insulation characteristics of these fabrics ($p < 0.05$). Furthermore, the relative significance of the three influencing factors is ranked as follows: Factor A > Factor C > Factor B.

As depicted in figure 5, *c*, the weft-knitted spacer fabrics employing fabric connections possess a higher thickness compared to those utilising tuck stitch connections, thereby conferring a superior thermal insulation performance. Notably, the 2V-shaped configuration demonstrates enhanced stability and a higher heat retention rate than its 2U-shaped counterpart. Additionally, the bulk yarn, attributed to its fluffy texture and larger volume, effectively augments the amount of still air within the fabric, thereby enhancing its warmth retention capabilities.

CONCLUSIONS

This study systematically analysed the effects of spacer layer structure, reinforcing yarn type, and number of layers on the performance of weft-knitted spacer fabrics, with key findings as follows:

- The spacer layer structure exhibited the most significant influence on compressibility, air/moisture permeability, and thermal insulation ($p<0.01$), followed by the type of reinforcing yarn, while the number of spacer layers had a relatively minor impact. The double-layer V-shaped fabric-layer connection structure demonstrated superior cushioning performance compared to the double-layer U-shaped structure. Additionally, the insertion of reinforcing yarns further enhanced compression resistance. Compressibility was significantly negatively correlated with cushioning performance, meaning higher compression rates corresponded to poorer compression resistance and cushioning.
- Spacer fabrics with fabric-layer connections showed significantly better air permeability than those with tuck connections. Fabrics with larger spatial configurations in the spacer layer facilitated smoother water molecule migration, improving water vapour transmission rate and moisture permeability. The addition of bulked yarns significantly enhanced the thermal insulation properties of the fabrics. All tested samples had a thermal insulation rate exceeding 30%, meeting basic thermal insulation application requirements, with fabric-layer connection structures and bulked yarn-reinforced fabrics exhibiting superior heat retention performance.

ACKNOWLEDGEMENT

This study was supported by Beijing Fangyuan Oasis Technology Co., Ltd [(0239-E4-6000-19-0339) (19) FZ-020].

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Numerical investigation of crack orientation and location on the buckling stability of Aluminium stiffened plates: a study for marine and textile applications

DOI: 10.35530/IT.077.01.202590

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ABSTRACT – REZUMAT

Numerical investigation of crack orientation and location on the buckling stability of Aluminium stiffened plates: a study for marine and textile applications

This study numerically investigates the compressive buckling stability of Aluminium stiffened plates, which are critical components in marine structures and heavy machinery used in the textile industry, with a particular focus on the effects of crack orientation and eccentricity. Using linear finite element analysis (FEA), the plates were modelled with central and off-centre cracks under both clamped-free and simply supported-free boundary conditions. The analysis systematically varied the crack angle and its distance from the plate's centre to understand their influence on buckling modes and critical load coefficients. The results demonstrate a significant reduction in buckling stability due to the presence of cracks. This reduction is highly dependent on the crack's characteristics, as the most critical case for buckling occurs when the crack is oriented parallel to the stiffeners (at a 90° angle), significantly lowering the buckling load for both boundary conditions. Furthermore, the research findings of this article reveal that crack eccentricity plays a crucial role. For simply supported-free plates, the buckling load is most critically reduced when the crack is closer to the loaded edge (e_y=80mm), while for clamped-free plates, the opposite is true. Quantitatively, a crack can decrease the buckling coefficient by approximately 11% in clamped-free plates and 17% in simply supported-free plates in the most critical configurations. This research provides essential insights into the failure mechanisms of stiffened plates, emphasising the importance of considering crack parameters in structural design and maintenance to ensure the integrity of marine structures.

Keywords: *buckling stability, 1100 Aluminium alloy, stiffened plate, centre and off-centre cracks, FEM method, textile industry*

Investigarea numerică a orientării și localizării fisurilor asupra stabilității la flambaj a plăcilor rigidizate din aluminiu: studiu pentru aplicații marine și textile

Acest studiu investighează numeric stabilitatea la flambaj compresiv a plăcilor rigidizate din aluminiu, care sunt componente critice în structurile marine și în utilajul greu din industria textilă, cu un accent special pe efectele orientării și excentricității fisurilor. Folosind analiza liniară cu elemente finite (FEA), plăcile au fost modelate cu fisuri centrale și descentrate, atât în condiții de fixare liberă, cât și în condiții de susținere liberă. Analiza a variat sistematic unghiul fisurii și distanța acesteia față de centrul plăcii pentru a înțelege influența lor asupra modurilor de flambaj și a coeficienților de sarcină critici. Rezultatele demonstrează o reducere semnificativă a stabilității la flambaj datorită prezenței fisurilor. Această reducere depinde în mare măsură de caracteristicile fisurii, deoarece cazul cel mai critic pentru flambaj apare atunci când fisura este orientată paralel cu rigidizările (la un unghi de 90°), reducând semnificativ sarcina de flambaj pentru ambele condiții de margine. În plus, rezultatele cercetării din acest articol relevă faptul că excentricitatea fisurii joacă un rol crucial. Pentru plăcile cu sprihin liber, sarcina de flambaj este redusă în mod critic atunci când fisura este mai aproape de marginea încărcată (e_y=80 mm), în timp ce pentru plăcile cu fixare liberă, este valabil opusul. Din punct de vedere cantitativ, o fisură poate reduce coeficientul de flambaj cu aproximativ 11% în plăcile cu fixare liberă și cu 17% în plăcile cu susținere liberă în configurațiile cele mai critice. Această cercetare oferă perspective esențiale asupra mecanismelor de defectare a plăcilor rigidizate, subliniind importanța luării în considerare a parametrilor de fisuri în proiectarea și întreținerea structurale pentru a asigura integritatea structurilor marine și utilajului greu din industria textilă.

Cuvinte-cheie*: stabilitate la flambaj, aliaj de aluminiu 1100, placă rigidizată, fisuri centrate și descentrate, metoda FEM, industria textilă*

INTRODUCTION

Plates are the most important components of marine structures, bridges, and constructions, as well as heavy machinery, which are easily susceptible to buckling under compressive loading. If plate thickness is sufficiently small compared to other plate sizes, buckling under compression, shear, or tension can occur. Therefore, it is important to increase the plate's load-bearing capacity. One of the most useful ways is to reinforce the plates by using stiffeners. Stiffeners are transverse or longitudinal beams that are attached to the main plates to increase their strength. Cracks can be easily produced due to imperfections in manufacturing, such as imperfections in welding, corrosive environments, or fatigue loading. The presence of cracks can decrease plate stability. When plates contain defects such as cracks, investigation of the buckling phenomenon becomes more necessary, and it can be intensified due to the existence of cracks. Therefore, the effect of cracks on buckling stability is inevitable, and it is important to study the buckling behaviour of these plates to improve their bearing capacity for the safety assessment of the structures.

While a number of studies have investigated the buckling of cracked plates, a significant gap remains in the literature regarding the specific influence of off-centre cracks on the stability of stiffened plates. Existing research, such as that by Roberto Brighenti [1], has primarily focused on the buckling of unstiffened, cracked thin plates under various loads. Using the stress field of a deep beam, he suggested a rough theoretical method for calculating the critical load of tensioned plates. He demonstrated that the primary effect of cracks is the decrease of buckling compressive stress multipliers and that the presence of a crack in a compressed plate is advantageous (independent of the orientation of the break) since it raises the compressive buckling load in comparison to the uncracked case. It has been observed that the tension critical load multipliers tend to be greater than the corresponding compressive ones. Brighenti [2] also studied the fracture and buckling behaviour of broken tin plates under shear pressure in 2010. They demonstrated that, in real-world applications, only very low values of the critical stress-intensity factor can cause fracture failure rather than buckling in fractured plates under shear loading. Using finite element analysis, Alinia et al. [3] examined the impact of central cracks on the remaining strength and stiffness degradation of shear panels. They discovered that the buckling behaviour in shear panels may vary depending on the length and angle of cracks.

Seifi and Kabiri looked at how lateral pressure affected the buckling of plates having a central crack [4]. In contrast to the case with simply lateral support, they investigated how lateral compressive load decreases the critical buckling load while lateral tensile load raises it, and how lateral load usually doesn't alter the first mode.

Heo et al. [5] investigated the buckling of plates with edge and centre cracks using peridynamics. To ascertain the critical buckling loads, they employed the finite element program ANSYS. When peridynamic data were compared to experimental and numerical results, there was good agreement among the different approaches. Using both theoretical and practical approaches, Guz and Dyshel [6] examined the buckling of panels with centre and off-centre cracks under strain. The tensile and compressive buckling of plates that are weakened by core cracks was examined by Sih and Lee [7]. They demonstrated how the existence of core cracks affects the bearing capacity of plates. The buckling phenomenon in composite plates, including core cracks under compression, tension, and shear loading, was investigated by Nasirmanesh and Mohammadi [8]. They employed the conventional XFEM and FEM techniques. They demonstrated the greater accuracy of the XFEM technique. Using phase field theory and the finite element approach, Minh et al. [9] examined the stability of functionally graded materials under compressive loads.

The ultimate strength of steel plates with edge and central cracks under uniaxial compressive and tensile stresses was investigated by Paik et al. [10]. A numerical investigation on the failure mode and buckling stability of clamped or simply supported plates with small to big size cracks was conducted by Memarzadeh et al. [11, 12]. They discovered that the buckling of plates is more affected by significant cracks. Using a computational approach, Khedmati et al. [13] investigated the buckling of simply supported plates with tiny off-centre cracks.

A cracked thin steel panel subjected to successive tensile to compressive stress was shown to exhibit buckling and collapse behaviours by Sujiatanti et al. [14], both experimentally and statistically. They discovered that buckling behaviour can be impacted by the existence and extent of cracks. Rad and Panahandeh-Shahraki [15] investigated the buckling of functionally graded plates under strain. Using a single-domain Ritz technique, Milazzo et al. [16] investigated the buckling and post-buckling of broken plates. Usinga sell-solid mixed finite element approach, Tanaka et al. [17] examined the buckling and collapse of cracked panels under a series of tensile to compressive pressures. Their findings demonstrate that the buckling and collapse behaviour of cracked panels is significantly impacted by the crack opening and closure.

Seifi and Khodayari [18] also studied the buckling of a cracked thin plate under full and partial compression edge loading experimentally and numerically. They showed that the buckling load decreases by increasing the angle of the crack and the load. Also, perpendicular cracks to the loading cause a greater reduction in buckling load. Taheri and Memarzadeh [19] numerically and experimentally studied the compressive buckling stability of plates with centre and off-centre cracks. They found that the effect of crack eccentricity largely depends on the plate's support type, and the plates with two opposite free edges and larger cracks cause lower buckling stability. Sadek and Tawfik [20] numerically analysed the buckling behaviour of a steel-stiffened plate with a central crack. They found that a transverse crack is more stable than a longitudinal crack. Gullizi et al. [21] studied the buckling behaviour of cracked stiffened panels by the extended Ritze formulation. They compared their results with finite element simulations to show the accuracy of their approach.

The buckling of cracked plates, particularly that kind of plates with central cracks, has been the subject of numerous studies, which is remarkable. Researchers and designers continue to be concerned about the buckling behaviour of stiffened plates with off-centre cracks because there aren't enough studies in this field. Furthermore, no research has yet been done on the buckling stability of off-centre fractured stiffened plates with varying crack angles. However, these findings do not fully address the complex interaction between crack location, stiffeners, and buckling behaviour in a practical engineering context. This research study fills this critical gap by systematically analysing how off-centre cracks and their angular orientation affect the critical buckling load of Aluminium stiffened plates, a key structural component in marine applications and heavy machinery in the textile industry. By examining these parameters simultaneously, the study provides a more comprehensive and directly applicable dataset for the design and maintenance of real-world structures. This research's unique focus on stiffened plates with eccentric cracks, a scenario frequently encountered in practice, establishes the clear necessity and novelty of this work.

This study presents a novel and comprehensive numerical investigation into the buckling behaviour of Aluminium stiffened plates containing small cracks. Unlike prior research, this research study simultaneously analyses the influence of multiple crack parameters, including angle, off-centre location, and their interaction with different boundary conditions (clamped-free and simply supported-free) on buckling stability. This study provides new, quantitative data on the critical buckling load reduction caused by these cracks. By exploring this complex interplay, the findings of this study offer valuable insights into the specific failure mechanisms and provide a more realistic assessment of structural integrity, which is essential for the design and maintenance of marine structures and heavy machinery in the textile industry. This integrated approach significantly advances the understanding of how localised damage affects the global stability of stiffened plates.

According to fracture mechanics analysis of cracked plates, the stresses around the crack tip (figure 1) can be obtained as below [22]:

$$\sigma_{xx} = \sigma\sqrt{\frac{a}{2r}}\cos\frac{\theta}{2}\left[1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] \quad (1)$$

$$\sigma_{yy} = \sigma\sqrt{\frac{a}{2r}}\cos\frac{\theta}{2}\left[1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] \quad (2)$$

$$\sigma_{xy} = \sigma\sqrt{\frac{a}{2r}}\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \quad (3)$$

Corresponding to the above equations, the values of stresses approach infinity in the vicinity of the crack tip, as r approaches zero.

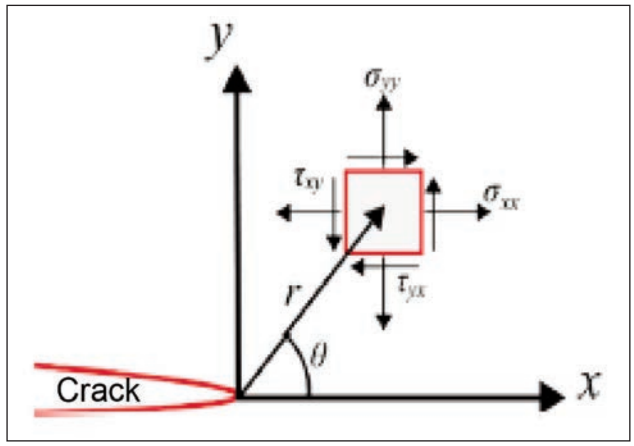

Fig. 1. Stresses around the crack tip [22]

Numerical approach

In the present study, plates were modelled and meshed in Abacus software using the finite element method. Eigenvalues and buckling coefficients were obtained by this method to show the influence of changing parameters, such as the location and direction of cracks, on the plate's buckling stability.

Determination of buckling coefficient

For a plate under uniform compressive loading, the analytical solution for the critical loads N_{cr} can be defined as follows:

$$k = \frac{N_{cr}\, w^2}{\pi^2 E t^3} 12(1 - \nu^2) \quad (4)$$

where k is the buckling coefficient, w is the width of the plate, and t is the thickness of the plate, E and ν are the modulus of elasticity and Poisson's ratio.

MATERIAL PROPERTIES

Nowadays, the utilisation of Aluminium and its alloys is being increased due to the benefits which they provide for marine and aerospace structures. The flexibility, high strength-to-weight ratio, high melting point, and corrosion resistance of Aluminium alloys have caught designers and engineers' attention. In the following table 1 mechanical properties of 1100 Aluminium are shown.

In this article, a sheet of 1100 Aluminium alloy with a length of 240 mm, a width of 240 mm and a thickness

Table 1

MECHANICAL PROPERTIES OF 1100 ALUMINUM

σ_y (MPa)	σ_u (MPa)	E (GPa)	ν
120	170	63.9	0.33

Table 2

DIMENSIONS OF T SECTIONS

l (mm)	h_w (mm)	t_w (mm)	b_f (mm)	t_f (mm)
240	25	1.5	20	1.5

of 1.5 mm has been studied in different cases. Also, dimensions of stiffeners (stiffeners with T section) are shown in table 2.

MODELLING

Numerical modelling has been done by finite element method with Abaqus software. Plates including cracks with the length of $2a = 60$ mm in different angles (0°, 30°, 60°, and 90°) with three different eccentricities (0, 40, 80) are investigated for both simply (SFSF) supported plates (two opposite edges are simply supported and the other edges are free) and clamped (CFCF) supported plates (two opposite edges are clamped and the other edges are free). Overall, 24 cases are modelled and demonstrated. The plates are meshed with an element S4R containing 6889 (83* 83) elements. Figure 2 shows different boundary conditions.

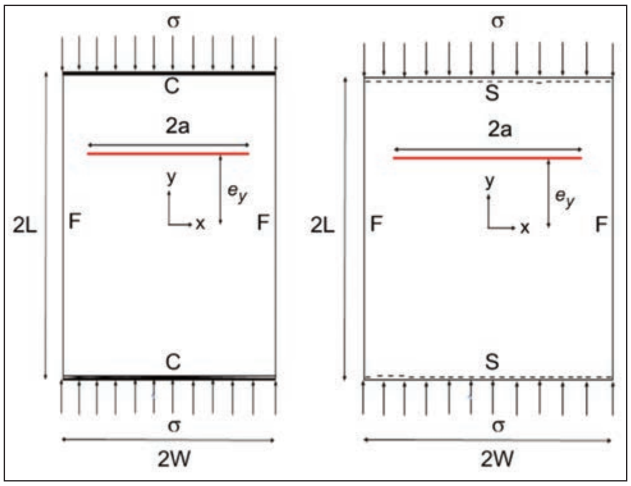

Fig. 2. Different boundary conditions

NUMERICAL SOLUTION

Buckling of simply supported stiffened plate (SFSF) and clamped stiffened plate (CFCF) with different angles of centre and off-centre cracks

For numerical analyses, a plate with a length and width of 240 mm has been modelled. The right and the left sides of the plate are free, and the top and the bottom of the plate are simply supported. After modelling and meshing, the critical buckling load (N_{cr}) which is the smallest value of eigenvalues (mode 1), has been obtained. The buckling coefficient (k) is evaluated from equation 4. The following tables 3–8 describe the results.

RESULTS AND DISCUSSION

In this section, the buckling behaviour of cracked stiffened plates with different boundary conditions will be investigated.

Result validation

To validate the numerical approach, a plate of identical size and material properties to that experimentally investigated by Taheri and Memarzadeh [19] was

Table 3

NUMERICAL RESULTS OF THE FIRST BUCKLING MODE WHEN THE STIFFENED PLATE IS SIMPLY SUPPORTED

Crack inclination	Crack eccentricity	Buckling load	Buckling coefficient
0°	0	13169	15.896
	40	13523	16.323
	80	13526	16.326
30°	0	13206	15.940
	40	13357	16.122
	80	13227	15.966
60°	0	13060	15.764
	40	13274	16.022
	80	13518	16.317
90°	0	12913	15.587
	40	12404	14.972
	80	12369	14.930

Table 4

NUMERICAL RESULTS OF THE SECOND BUCKLING MODE WHEN THE STIFFENED PLATE IS SIMPLY SUPPORTED

Crack inclination	Crack eccentricity	Buckling load	Buckling coefficient
0°	0	14707	17.752
	40	14989	18.092
	80	15195	18.341
30°	0	14806	17.872
	40	14985	18.088
	80	15195	18.258
60°	0	14905	17.991
	40	14998	18.103
	80	15192	18.337
90°	0	14990	18.094
	40	14979	18.080
	80	14889	17.972

Table 5

NUMERICAL RESULTS OF THE THIRD BUCKLING MODE WHEN THE STIFFENED PLATE IS SIMPLY SUPPORTED

Crack inclination	Crack eccentricity	Buckling load	Buckling coefficient
0°	0	17482	21.102
	40	17568	21.206
	80	17468	21.085
30°	0	17469	21.086
	40	17563	21.199
	80	17406	21.010
60°	0	16740	20.206
	40	17232	20.800
	80	17464	21.080
90°	0	16035	19.355
	40	16903	20.403
	80	17179	20.736

Table 6

NUMERICAL RESULTS OF THE FIRST BUCKLING MODE WHEN THE STIFFENED PLATE IS CLAMPED			
Crack inclination	**Crack eccentricity**	**Buckling load**	**Buckling coefficient**
0°	0	16313	19.689
	40	16382	19.764
	80	16421	19.819
30°	0	16360	19.745
	40	16379	19.768
	80	16386	19.776
60°	0	15808	19.079
	40	16187	19.535
	80	16390	19.781
90°	0	15161	18.498
	40	15582	18.806
	80	16364	19.750

Table 7

NUMERICAL RESULTS OF THE SECOND BUCKLING MODE WHEN THE STIFFENED PLATE IS CLAMPED			
Crack inclination	**Crack eccentricity**	**Buckling load**	**Buckling coefficient**
0°	0	16566	19.994
	40	16990	20.501
	80	17219	20.782
30°	0	16567	19.994
	40	16816	20.295
	80	16844	20.329
60°	0	16647	20.091
	40	16503	19.918
	80	16651	20.053
90°	0	16656	20.102
	40	16571	20.000
	80	16599	20.033

selected. Their original study focused on the buckling stability of this plate under a specific clamped-free-clamped-free (CFCF) boundary condition. The results of this study, obtained using Abaqus software, demonstrate strong agreement with these published experimental findings, as detailed in table 9. This

Table 8

NUMERICAL RESULTS OF THE THIRD BUCKLING MODE WHEN THE STIFFENED PLATE IS CLAMPED			
Crack inclination	**Crack eccentricity**	**Buckling load**	**Buckling coefficient**
0°	0	16926	20.428
	40	17233	20.793
	80	17623	21.269
30°	0	17099	20.637
	40	17539	21.168
	80	17972	21.693
60°	0	17493	21.115
	40	17731	21.402
	80	17907	21.720
90°	0	17743	21.417
	40	17744	21.418
	80	17721	21.390

correlation provides confidence in the accuracy of the current computational model.
Crack relative length is the following:

$$\frac{2a}{w} = 0.25 \tag{5}$$

where w is the plate width and $2a$ is the crack length. For both experimental and numerical investigations, the same material, size, and boundary conditions have been considered.

Stiffened plate with SFSF edges

Figure 3 shows the first buckling coefficient modes of the stiffened plate when the crack is located at different eccentricities in SFSF plates. As shown in the stiffened plate with SFSF edges, the lowest buckling coefficient occurs at $\theta = 90°$ and $e_y = 80$ mm. Therefore, the most critical case happens when the crack is parallel with the stiffeners. In other words, as the crack becomes vertical with respect to the loading edge (and also closer to the loading edge), the buckling load decreases. Figures 4 and 5 show the second and the third buckling modes, respectively. Also, figure 6 shows buckling mode shapes for stiffened plates with centric cracks at different angles.
A crack oriented at $\theta = 90°$ is perpendicular to the applied compressive load and parallel to the stiffeners.

Table 9

COMPARISON OF EXPERIMENTAL DATA WITH NUMERICAL DATA						
BC: CFCF						
Crack inclination	**Eccentricity (mm)**	**Experimental result**		**Numerical result**		
		Buckling load (N)	**Buckling coefficient**	**Buckling load (N)**	**Buckling coefficient**	**Difference (%)**
(No crack)	-	3248	3.916	3242.4	3.913	0.18
0°	0	2664	3.211	2995.2	3.615	12.42
0°	40	2907	3.504	3144	3.794	8.15
0°	80	2961	3.570	3162.3	3.816	6.7

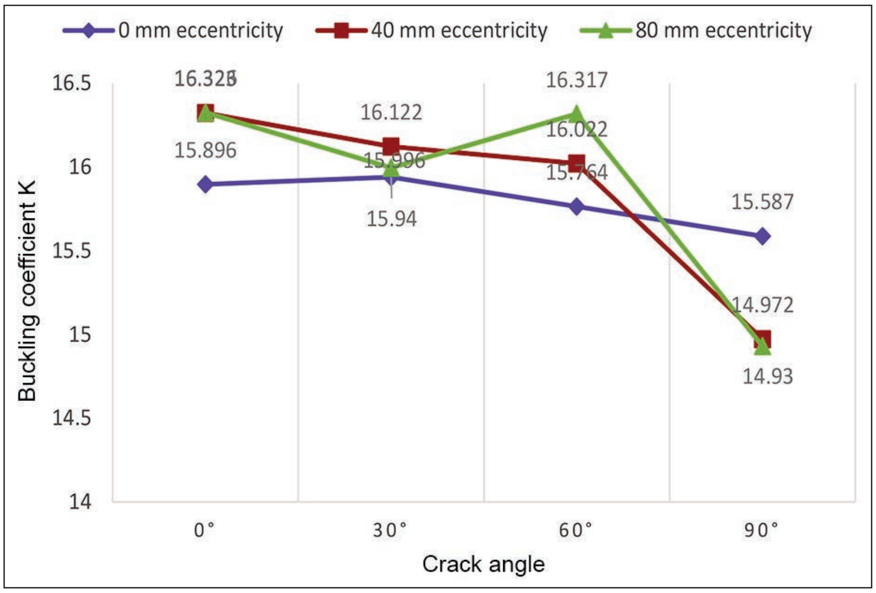

Fig. 3. First buckling mode of SFSF stiffened plate concerning crack angle at different eccentricities

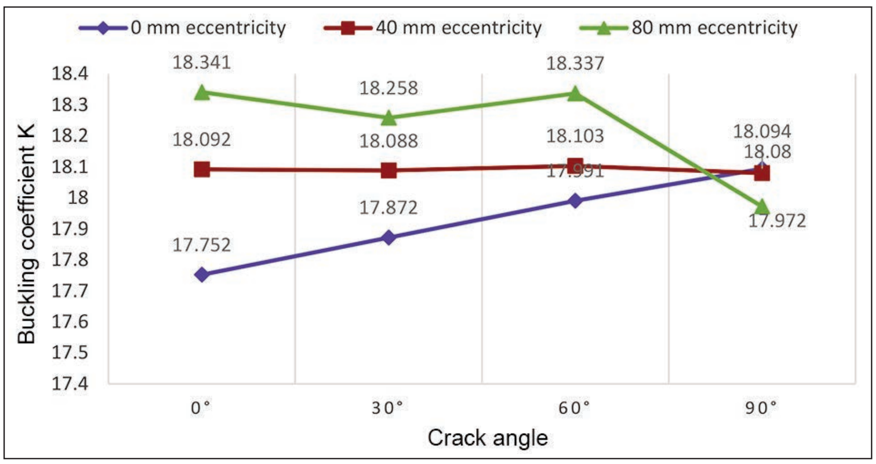

Fig. 4. Second buckling mode of SFSF stiffened plate for crack angle at different eccentricities

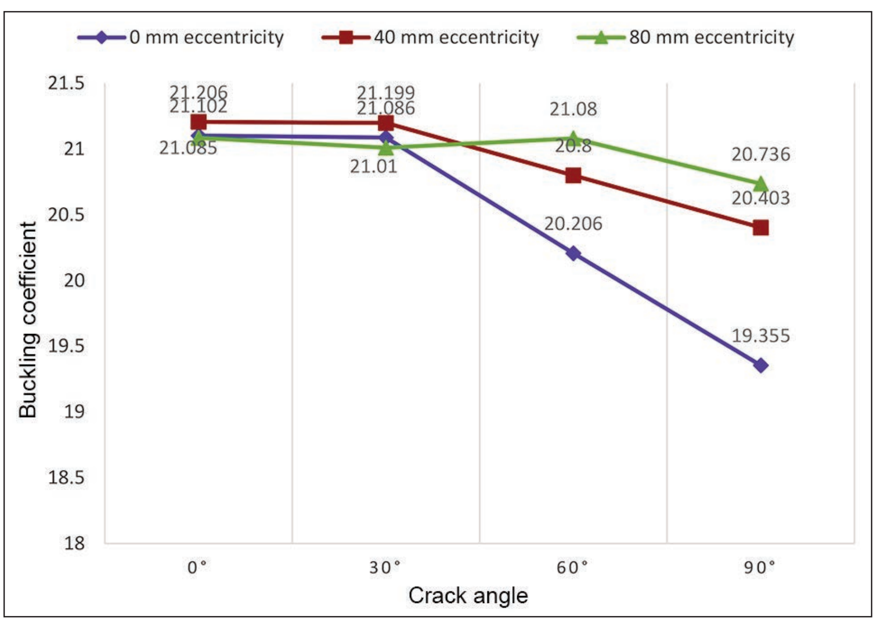

Fig. 5. Third buckling mode of SFSF stiffened plate for crack angle at different eccentricities

In this configuration, the crack acts as a stress concentrator along the primary load-bearing direction. The presence of the stiffeners, which are designed to support the plate against buckling, is compromised by a crack running alongside them. This essentially bypasses the stiffeners' reinforcing function, allowing the plate to buckle more easily. The crack effectively reduces the plate's effective width and its ability to resist in-plane compressive forces, leading to a substantial drop in the buckling coefficient. The eccentricity of e_y = 80 mm places the crack very close to the loading edge of the plate. Buckling often initiates near the unsupported or less constrained edges of a structure. By positioning the crack near the loading edge, the crack's weakening effect is amplified at the point where the compressive stress is highest, and the plate's resistance is weakest. This combination of a perpendicular crack and a location near the point of highest stress concentration creates a highly vulnerable area, causing the plate to lose stability and buckle at a much lower critical load.

Stiffened plate with CFCF edges

Figure 7 shows the first buckling coefficient modes of the stiffened plate when the crack is located at different eccentricities in CFCF plates. As shown in a stiffened plate with CFCF boundary conditions, the most critical buckling load happens in $\theta = 90°$ and e_y = 0. Also, it can be seen that in e_y = 80, the buckling load doesn't change with increasing the angle of the crack. Generally, it can be concluded that the most critical case occurs in $\theta = 90°$ and e_y = 0, and the least critical case occurs at e_y = 80 mm. Figures 8 and 9 show the second and third modes of buckling coefficients in stiffened plates with CFCF edges, respectively. In addition, the buckling mode

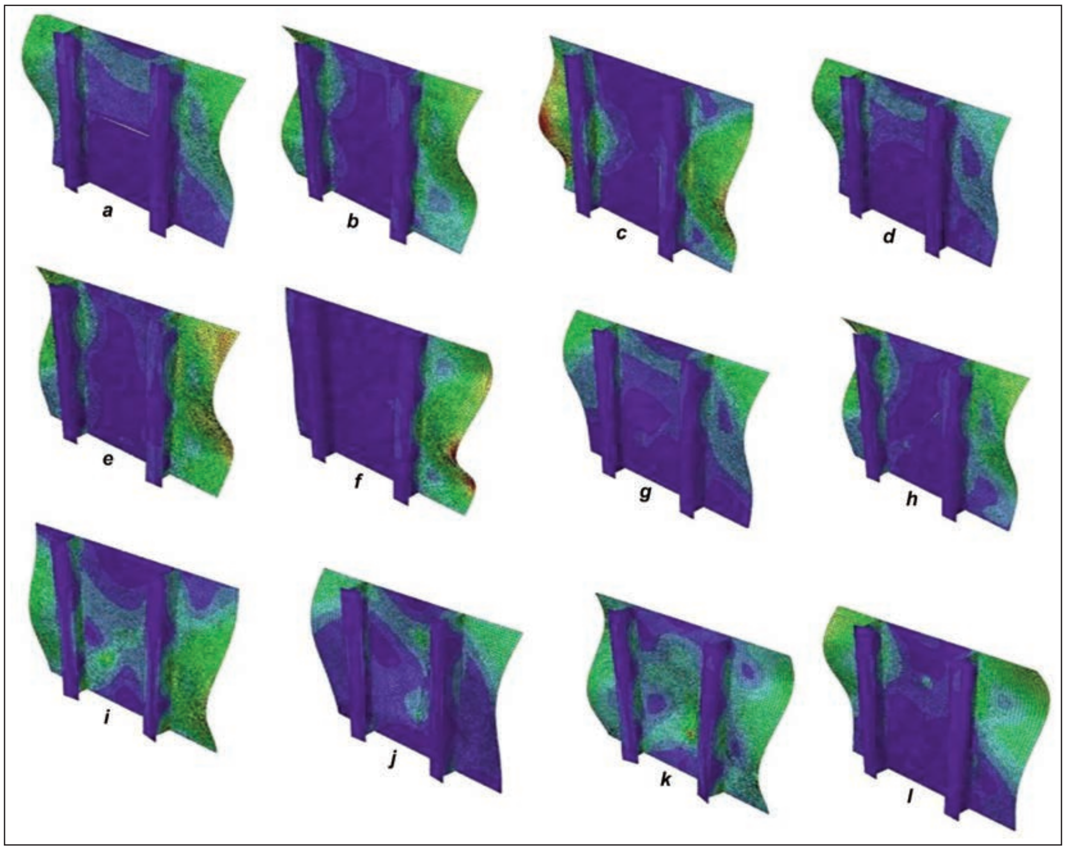

Fig. 6. Buckling mode shapes of SFSF stiffened plate with centric cracks at different angles: *a* – first buckling mode shape of a stiffened plate with a centric crack at θ = 0°; *b* – second buckling mode shape of a stiffened plate with a centric crack at θ = 0°; *c* – third buckling mode shape of a stiffened plate with a centric crack at θ = 0°; *d* – first buckling mode shape of a stiffened plate with a centric crack at θ = 30°; *e* – second buckling mode shape of a stiffened plate with a centric crack at θ = 30°; *f* – third buckling mode shape of a stiffened plate with a centric crack at θ = 30°; *g* – first buckling mode shape of a stiffened plate with a centric crack at θ = 60°; *h* – second buckling mode shape of a stiffened plate with a centric crack at θ = 60°; *i* – third buckling mode shape of a stiffened plate with a centric crack at θ = 60°; *j* – first buckling mode shape of a stiffened plate with a centric crack at θ = 90°; *k* – second buckling mode shape of a stiffened plate with a centric crack at θ = 90°; *l* – third buckling mode shape of a stiffened plate with a centric crack at θ = 90°

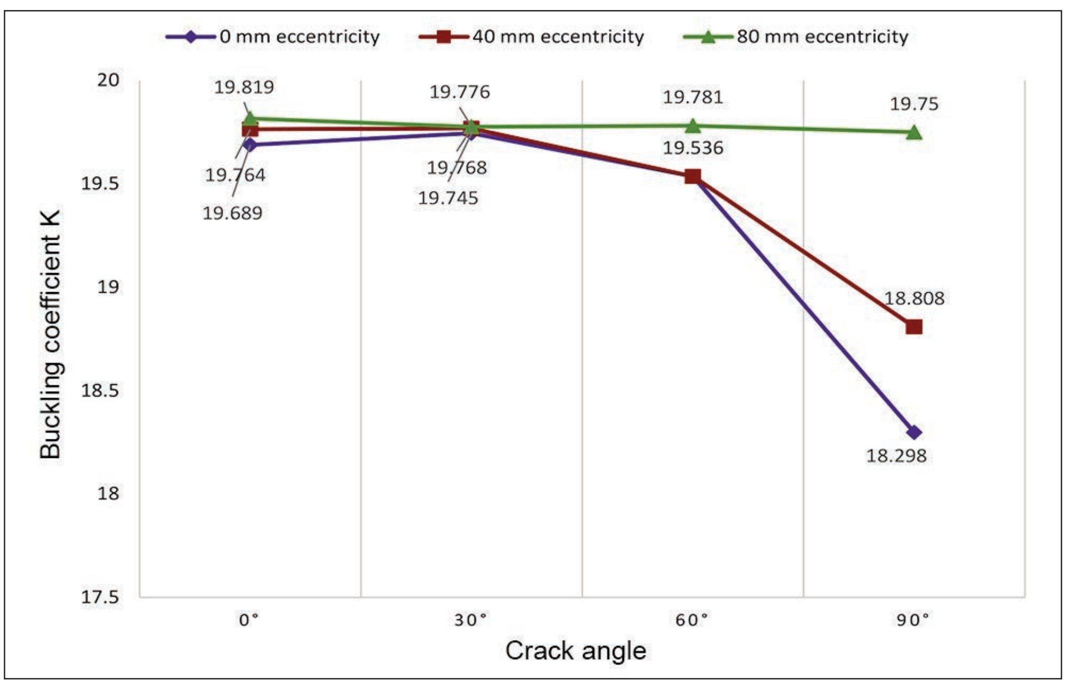

Fig. 7. First buckling mode of CFCF stiffened plate for crack angle at different eccentricities

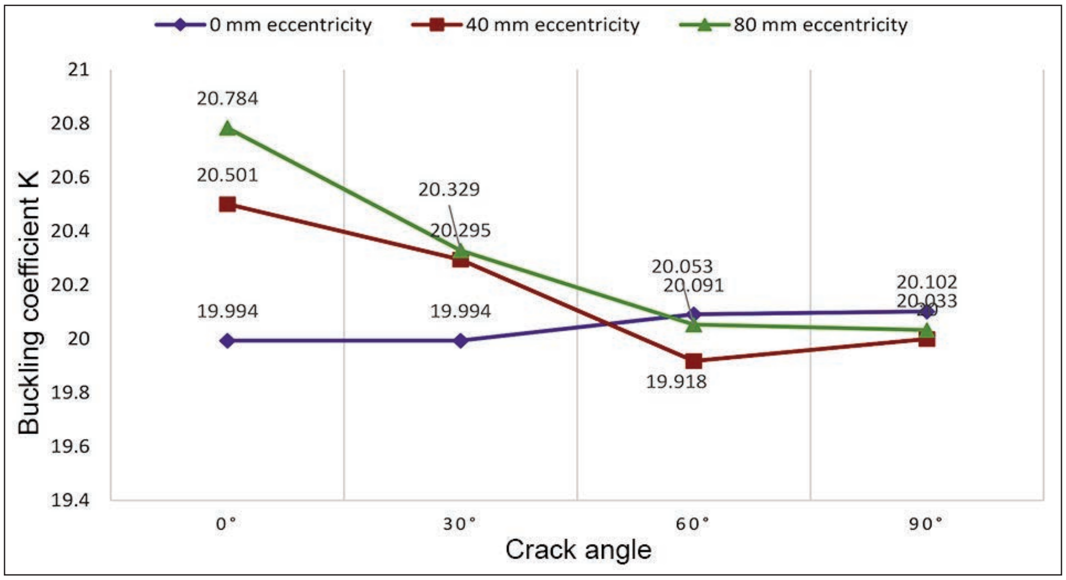

Fig. 8. Second buckling mode of CFCF stiffened plate concerning crack angle at different eccentricities

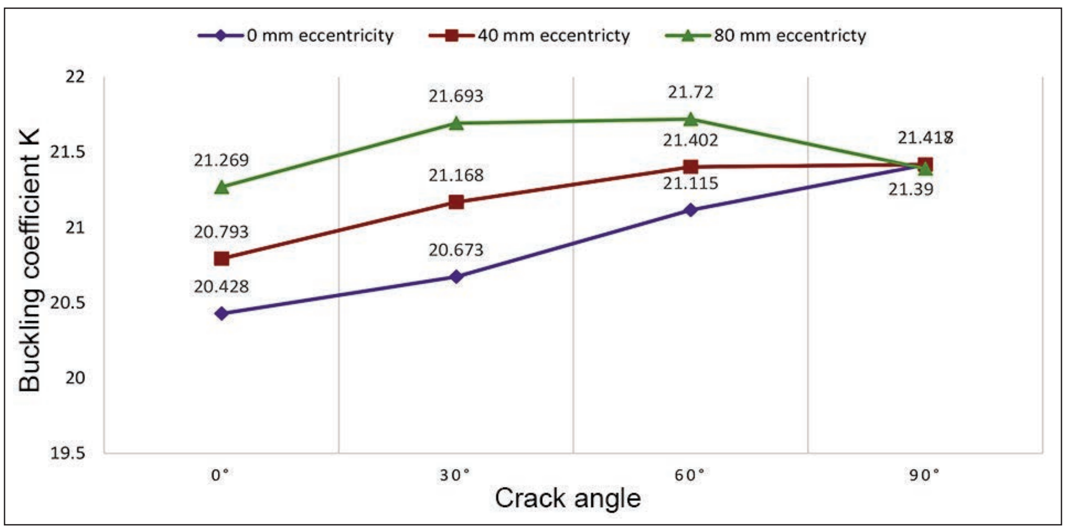

Fig. 9. Third buckling mode of CFCF stiffened plate for crack angle at different eccentricities

shapes of stiffened plates with centric cracks at different angles are shown in figure 10.

CONCLUSION

In this research study, the buckling behaviour of stiffened cracked plates made of Aluminium 1100 alloy under compressive loading was studied numerically by using Abaqus software. The following observation could be made on the findings of this work:

- The goal of the research was to achieve buckling loads and buckling coefficients of stiffened cracked plates in different cases. The effects of changing parameters such as the crack angle and its eccentricity, as well as the boundary conditions, were investigated.
- When the plates are reinforced by vertical or horizontal beams, their buckling stability increases; therefore, the effect of small cracks decreases and can be ignored. In the existence of a crack, as the crack angle increases from 0° to 90°, the buckling load decreases to the extent that in $\theta = 90°$ the most critical case occurs for both CFCF stiffened plates and SFSF stiffened plates.
- It was observed that as the crack becomes parallel with stiffeners, the buckling coefficient decreases. In stiffened cracked plates with SFSF boundary conditions, when the crack gets closer to the loading edge (e_y = 80 mm), the most critical case happens, whereas in CFCF stiffened cracked plates in e_y = 80 mm, the least critical case occurs.
- The presence of a crack significantly compromises the structural integrity of stiffened plates, as evidenced by a substantial reduction in their critical buckling load. In the most critical scenario, where the crack's orientation and location are least favourable buckling strength is reduced by approximately 11% for Clamped-Free-Clamped-Free (CFCF) stiffened plates and a more severe 17% for Simply Supported-Free-Simply Supported-Free (SFSF) plates.

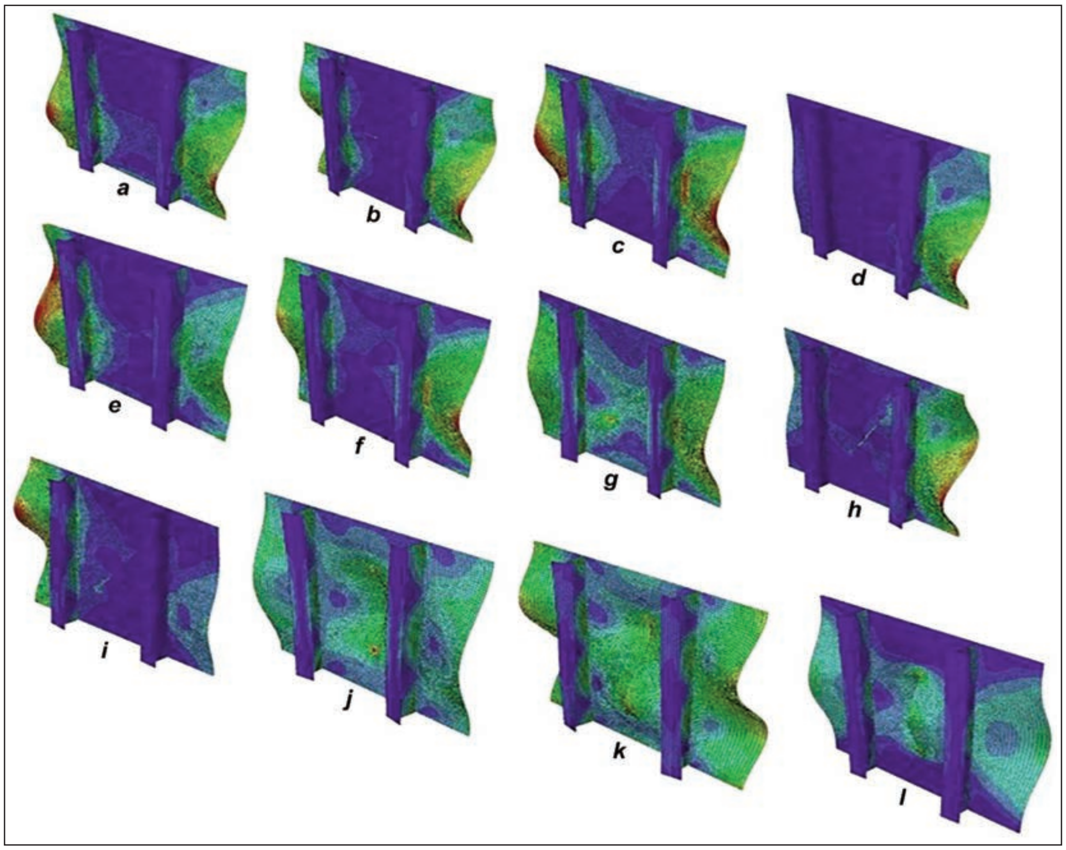

Fig. 10. Buckling mode shapes of CFCF stiffened plate with a centric crack at different angles: *a* – first buckling mode shape of a stiffened plate with a centric crack at θ = 0°; *b* – second buckling mode shape of a stiffened plate with a centric crack at θ = 0°; *c* – third buckling mode shape of a stiffened plate with a centric crack at θ = 0°; *d* – first buckling mode shape of a stiffened plate with a centric crack at θ = 30°; *e* – second buckling mode shape of a stiffened plate with a centric crack at θ = 30°; *f* – third buckling mode shape of a stiffened plate with a centric crack at θ = 30°; *g* – first buckling mode shape of a stiffened plate with a centric crack at θ = 60°; *h* – second buckling mode shape of a stiffened plate with a centric crack at θ = 60°; *i* – third buckling mode shape of a stiffened plate with a centric crack at θ = 60°; *j* – first buckling mode shape of a stiffened plate with a centric crack at θ = 90°; *k* – second buckling mode shape of a stiffened plate with a centric crack at θ = 90°; *l* – third buckling mode shape of a stiffened plate with a centric crack at θ = 90°

- This quantifies the vulnerability introduced by even a small crack and highlights that the plate's boundary conditions play a crucial role in determining the extent of the stability loss. The greater reduction in SFSF plates suggests they are more susceptible to this specific type of localised damage.
- The results are directly applicable to the design and maintenance of marine vessels and offshore platforms. The data on how crack orientation and location reduce buckling stability helps naval architects and engineers make more informed decisions when designing Aluminium stiffened plates for ship hulls, bulkheads, and other structural components.
- The research on stiffened plates can be applied to structural integrity assessments of heavy machinery and large flat processing components used in the textile industry.
- This study is limited to numerical analysis, lacking experimental validation for its findings. Future research should involve physical experiments to confirm the buckling behaviour of cracked stiffened plates under various loads. Additionally, extending the analysis to include fatigue crack growth and the effects of corrosive environments would provide a more comprehensive understanding for marine and textile applications.

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Digital gold mine: how data assets unlock green innovation potential in the textile industry

DOI: 10.35530/IT.077.01.202550

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ABSTRACT – REZUMAT

Digital gold mine: how data assets unlock green innovation potential in the textile industry

The textile industry faces increasing dual pressures of digital transformation and environmental compliance due to its traditionally resource-intensive and pollution-heavy operations. Simultaneously, textile manufacturers struggle with accessing sufficient capital for green technology investments despite urgent sustainability imperatives. This study examines how data asset capitalisation drives green innovation through alleviating financing constraints. Analysing Chinese textile listed firms (2013–2023), we find that data-rich companies achieve significantly greater environmental innovation performance. Our text-based measure of data assets reveals they function as quality signals to capital markets, reducing information asymmetry and easing resource constraints for green investments. This effect is amplified by analyst coverage and becomes more pronounced under environmental uncertainty and regulatory pressure. The temporal analysis shows an inverted U-shaped pattern with peak influence occurring two years after data asset development, suggesting an incubation period for capability building. Using geographic distance to data trading centres as an instrumental variable confirms the causal relationship. The findings highlight a critical pathway through which digital transformation catalyses sustainable development in the textile industry, bridging information economics and environmental innovation literature. Our research provides practical implications for textile manufacturers seeking to leverage digital capabilities for environmental competitiveness and for policymakers designing incentives at the intersection of digital and green development.

Keywords: *data asset capitalisation, green innovation, financing constraints, information asymmetry, environmental policy, textile industry*

Mina de aur digitală: modalitatea prin care activele de date deblochează potențialul de inovare ecologică în industria textilă

Industria textilă se confruntă cu presiuni duble din ce în ce mai mari din partea transformării digitale și a conformității cu normele de mediu, datorită operațiunilor sale tradiționale, care consumă multe resurse și poluează intens. În același timp, producătorii din domeniul textil se luptă să acceseze capital suficient pentru investiții în tehnologii ecologice, în ciuda imperativelor urgente de sustenabilitate. Acest studiu examinează modul în care capitalizarea activelor de date stimulează inovarea ecologică prin atenuarea constrângerilor financiare. Analizând firmele textile chineze cotate la bursă (2013–2023), constatăm că firmele bogate în date obțin performanțe semnificativ mai bune în materie de inovare ecologică. Măsurarea bazată pe text a activelor de date relevă faptul că acestea funcționează ca semnale de calitate pentru piețele de capital, reducând asimetria informațională și atenuând constrângerile de resurse pentru investițiile ecologice. Acest efect este amplificat de acoperirea analiștilor și devine mai pronunțat în condiții de incertitudine ecologică și presiune reglementară. Analiza temporală arată un model inversat în formă de U, cu o influență maximă care apare la doi ani după dezvoltarea activelor de date, sugerând o perioadă de incubație pentru consolidarea capacităților. Utilizarea distanței geografice față de centrele de tranzacționare a datelor ca variabilă instrumentală confirmă relația cauzală. Concluziile evidențiază o cale critică prin care transformarea digitală catalizează dezvoltarea durabilă în industria textilă, făcând legătura între economia informației și literatura de specialitate privind inovarea în domeniul mediului. Cercetarea noastră oferă implicații practice pentru producătorii din industria textilă care doresc să valorifice capacitățile digitale pentru a-și spori competitivitatea în materie de mediu, precum și pentru factorii de decizie care elaborează stimulente la intersecția dintre dezvoltarea digitală și cea ecologică.

Cuvinte-cheie*: capitalizarea activelor de date, inovare ecologică, constrângeri financiare, asimetrie informațională, politică de mediu, industria textilă*

INTRODUCTION

In the dual transition toward digital economy and sustainability, textile firms increasingly face the imperative to transform both their data management practices and environmental performance [1, 2]. The textile industry, as one of China's traditional manufacturing pillars, faces particularly acute challenges due to its resource-intensive processes and significant environmental footprint. While digital transformation and sustainable development have traditionally been studied as separate domains [3, 4], their potential synergies remain largely unexplored, especially in traditionally pollution-intensive sectors like textile manufacturing.

Data assets, digitised information resources that can be leveraged for organisational value creation, have emerged as critical strategic resources in the information age [5]. For textile manufacturers, these data assets encompass production parameters, supply chain information, energy consumption metrics, and customer preference data that can drive process optimisation and product innovation. Simultaneously, green innovation has become essential for textile firms responding to mounting environmental challenges and stringent industry-specific regulatory pressures [6]. The textile sector faces particularly rigorous environmental scrutiny due to issues such as high water consumption, chemical usage, and waste generation. However, the mechanisms linking these two strategic priorities remain underexamined despite their growing importance to contemporary textile industry strategy.

Green innovation in textile manufacturing, characterised by the development of environmentally beneficial technologies and processes such as waterless dyeing, recycled fibre processing, and energy-efficient weaving, typically requires substantial upfront investments with uncertain and distant returns [7, 8]. This distinctive innovation profile creates significant financing hurdles, particularly in emerging economies where capital market frictions are pronounced. Financing constraints have been consistently identified as a critical barrier to green innovation adoption in the textile sector [9, 10], with firms often struggling to secure adequate capital for environmentally oriented projects due to information asymmetries between firms and capital providers regarding the value and potential of such innovations.

Recent literature suggests that corporate digitisation initiatives may improve firms' ability to access external financing through enhanced information disclosure and reduced information asymmetry [11, 12]. Building on this insight, we theorise that data asset capitalisation, the process of transforming raw data into structured, analyzable resources with recognised economic value, may facilitate green innovation in textile firms by alleviating financing constraints. This potential mechanism is particularly relevant in the Chinese textile industry context, where capital market frictions are significant and government-driven environmental policies are creating urgent imperatives for green transformation across the textile value chain [13, 14].

Despite the theoretical importance of understanding how digital resources might enable sustainable innovation in the textile industry, several research gaps persist. First, empirical evidence on the direct relationship between data assets and green innovation outcomes remains scarce, particularly in traditional manufacturing sectors like textiles. Second, the transmission mechanisms through which data assets might influence green innovation have received limited attention, particularly from the perspective of financing accessibility in capital-intensive industries. Third, contingency factors that may moderate these relationships have not been systematically examined in the context of pollution-intensive sectors undergoing digital transformation.

To address these gaps, we investigate three interrelated research questions: (1) Does data asset capitalisation enhance textile firms' green innovation performance? (2) Do financing constraints serve as a transmitting mechanism in this relationship? (3) How do analyst coverage, environmental uncertainty, and policy pressure condition these relationships in the textile industry? By addressing these questions, we integrate insights from resource-based theory, information asymmetry theory, and contingency theory to develop a comprehensive understanding of the data-sustainability nexus in textile manufacturing.

We examine these questions using a sample of Chinese textile listed firms from 2013 to 2023, employing an innovative text analysis methodology to measure data asset capitalisation through semantic analysis of corporate disclosures. Our empirical strategy includes baseline regressions, instrumental variable analysis, and cross-sectional comparisons to establish robust causal inferences about the relationships.

This study offers several contributions to the literature. First, we establish an empirical link between data asset capitalisation and green innovation in the textile industry, bridging previously separate research streams on digital transformation and corporate sustainability in traditional manufacturing. Second, we uncover financing constraints as a key mechanism through which data assets facilitate green innovation in textile firms, extending existing work on the financing of environmental technologies. Third, we demonstrate the contextual nature of these relationships by identifying important boundary conditions specific to the textile sector. Finally, from a practical perspective, our findings provide actionable insights for textile manufacturers seeking to leverage their digital transformation initiatives to support sustainability goals, as well as for policymakers designing incentives at the intersection of digital and green development in traditionally pollution-intensive industries.

RESEARCH DESIGN

Variable measurement

Our study examines the relationship between data asset capitalisation and green innovation. Green innovation, our dependent variable, is primarily measured through Green Patent Intensity (GPI) – the ratio of granted green invention patents to total patents granted. For robustness checks, we employ Green R&D Investment (GRI), calculated as green R&D expenditure relative to total R&D expenditure. The focal explanatory variable, Data Asset Capitalisation (DA), is measured using text analysis methodology. We develop a comprehensive lexicon based on data asset regulations, using "information". "network". "digital". and "data" as seed words. Through Word2Vec neural network modelling and deep learning techniques, we construct a corpus of semantically similar terms and quantify their frequency in corporate annual reports to assess companies' data asset capitalisation levels.

We examine financing constraints (FC) as a transmission mechanism between data asset capitalisation and green innovation, with higher FC values indicating more severe financing limitations. Analyst coverage (AC), measured as the natural logarithm of analysts following a firm, captures external information intermediation and transparency levels. Our framework further incorporates environmental uncertainty (EU, measured via five-year rolling coefficient of variation in quarterly industry sales) and environmental policy pressure (EP, measured through environmental terminology frequency in municipal government work reports) to examine contextual contingencies.

Data sources and model setup

Our sample comprises Chinese textile listed firms from 2013 to 2023. Data sources include the Wind database, CSMAR database, corporate annual reports, the China National Intellectual Property Administration patent database, and municipal government work reports. We specify the following baseline regression model:

$$GPI_{i,t} = \alpha + \beta_1 DA_{i,t} + \gamma Controls_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (1)$$

where $GPI_{i,t}$ represents green innovation intensity, $DA_{i,t}$ denotes data asset capitalisation degree, and $Controls_{i,t}$ encompasses a vector of control variables detailed in table 1.

Table 1

CONTROL VARIABLES DEFINITIONS AND CALCULATIONS	
Variable	**Definition and calculation method**
Size	Natural logarithm of total assets
ROA	Net profit/Total assets
Growth	Revenue growth rate
RD	R&D expenditure/Revenue
CFO	Net operating cash flow/Total assets

RESULTS

Baseline model results

Our empirical analysis begins with examining the relationship between data asset capitalisation and green innovation. Table 2 presents the baseline regression results with two model specifications. In column (1), without control variables, data asset capitalisation (DA) exhibits a positive and statistically significant coefficient ($\beta = 0.092$, $p < 0.05$), suggesting that firms with higher levels of data asset capitalisation tend to demonstrate greater green innovation intensity. This relationship persists in column (2) after introducing our comprehensive set of control variables, where the coefficient remains positive and significant ($\beta = 0.081$, $p < 0.05$), albeit slightly attenuated. This attenuation suggests that firm characteristics partially explain the relationship, yet the independent effect of data asset capitalisation remains robust.

Table 2

BASELINE RESULTS		
Variables	**(1)**	**(2)**
	GPI	**GPI**
DA	0.092**	0.081**
	(2.54)	(2.24)
Size	-	0.043***
	-	(3.12)
ROA	-	0.067*
	-	(1.86)
Growth	-	0.025
	-	(1.34)
RD	-	0.139***
	-	(3.56)
CFO	-	0.052*
	-	(1.77)
Constant	0.208***	0.187***
	(4.65)	(4.29)
Industry FE	Yes	Yes
Year FE	Yes	Yes
Observations	4327	4327
R-squared	0.159	0.217

Note: T-statistics in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Robustness tests

To verify the stability of our findings, we conducted several robustness tests as reported in table 3. When employing green R&D investment ratio (GRI) as an alternative dependent variable in column (1), we observe a positive coefficient ($\beta = 0.074$) that remains statistically significant, albeit at a lower confidence level ($p < 0.1$). This suggests that data asset capitalisation influences not only patent-based outcomes but also firms' strategic allocation of research resources toward environmental sustainability. Column (2) implements firm fixed effects to control for time-invariant unobservable firm characteristics, and the effect persists ($\beta = 0.072$, $p < 0.1$), though with slightly reduced magnitude and significance. This finding indicates that while stable firm-specific factors contribute to the relationship, they do not fully account for the observed association between data asset capitalisation and green innovation.

Column (3) reveals particularly interesting temporal dynamics in the relationship between data asset capitalisation and green innovation. The impact of data asset capitalisation intensifies over time, with coefficients increasing from 0.081 ($p < 0.05$) for contemporaneous effects to 0.093 ($p < 0.05$) for one-year lags and reaching a peak of 0.107 ($p < 0.05$) for two-year lags, before declining to 0.076 ($p < 0.1$) for three-year lags. This inverted U-shaped pattern indicates that data assets require an incubation period to fully manifest their benefits for green innovation. Initially, firms may need time to develop capabilities for leveraging data assets effectively, reaching peak efficiency around the two-year mark, after which the marginal returns begin to diminish. This finding aligns with organisational learning perspectives that suggest firms experience a period of capability development before realising maximum returns on digital investments.

Table 3

ROBUSTNESS TESTS

Variables	(1)	(2)	(3)
	GRI	GPI	Temporal dynamics
DA	0.074^{*}	0.072^{*}	0.081^{**}
	(1.89)	(1.95)	(2.24)
DA (t-1)	-	-	0.093^{**}
	-	-	(2.27)
DA (t-2)	-	-	0.107^{**}
	-	-	(2.41)
DA (t-3)	-	-	0.076^{*}
	-	-	(1.84)
Controls	Yes	Yes	Yes
Industry FE	Yes	No	Yes
Year FE	Yes	Yes	Yes
Firm FE	No	Yes	No
Observations	4327	4327	3269
R-squared	0.198	0.247	0.237

Table 4 addresses potential endogeneity concerns through an instrumental variable approach. Using geographic distance to the nearest major data trading centre (DIST) as an instrument, we find that proximity to digital clusters significantly influences data asset development (first-stage coefficient = –0.193, $p < 0.01$). The instrument demonstrates adequate strength with a first-stage F-statistic of 17.83, exceeding the conventional threshold of 10. In the second stage, the instrumented data asset capitalisation variable maintains a significant positive effect on green innovation ($\beta = 0.093$, $p < 0.05$), providing greater confidence in the causal nature of the relationship. This instrumental variable analysis suggests that our findings are unlikely to be driven by reverse causality or omitted variables, lending credibility to our proposed directional influence from data asset capitalisation to green innovation.

Mechanism analysis

To deepen our understanding of how data asset capitalisation promotes green innovation, we explored potential pathways through which this relationship operates, as presented in table 5. Column (1) reveals that data asset capitalisation is associated with reduced financing constraints ($\beta = -0.128$, $p < 0.05$),

Table 4

INSTRUMENTAL VARIABLE ANALYSIS

Variables	First Stage	Second Stage
	DA	GPI
DIST	-0.193^{***}	-
	(-4.22)	-
DA (Instrumented)	-	0.093^{**}
	-	(2.07)
Controls	Yes	Yes
Industry FE	Yes	Yes
Year FE	Yes	Yes
Observations	4327	4327
R-squared	0.236	0.209
First-stage F-statistic	17.83	-

suggesting that firms with greater data assets encounter fewer obstacles in accessing capital. This finding aligns with the view that data assets serve as informational signals that reduce information asymmetry between firms and capital providers. In column (2), when both data asset capitalisation and financing constraints are included in the green innovation model, the direct effect of data asset capitalisation diminishes in magnitude and significance ($\beta = 0.063$, $p < 0.1$), while financing constraints exhibit a strong negative effect on green innovation ($\beta = -0.141$, $p < 0.01$). This pattern suggests that financing accessibility represents a critical pathway through which data asset capitalisation facilitates green innovation. Financial resources unlocked through reduced capital constraints appear to enable firms to undertake environmentally beneficial projects that might otherwise remain unfunded due to their typically longer payback periods and higher uncertainty.

Column (3) examines how analyst coverage (AC) moderates the relationship between data asset capitalisation and green innovation. The results show that

Table 5

MECHANISM ANALYSIS

Variables	(1)	(2)	(3)
	FC	GPI	GPI
DA	-0.128^{**}	0.063^{*}	0.061^{*}
	(–2.56)	(1.74)	(1.68)
FC	-	-0.141^{***}	-
	-	(–2.89)	-
AC	-	-	0.089^{**}
	-	-	(2.27)
AC × DA	-	-	0.096^{**}
	-	-	(2.31)
Controls	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	4327	4327	4327
R-squared	0.251	0.253	0.264

Table 6

CROSS-SECTION ANALYSIS				
Variables	**Low EU**	**High EU**	**Low EP**	**High EP**
DA	0.053	0.104^{**}	0.058^{*}	0.112^{**}
(1.64)	(2.28)	(1.69)	(2.35)	
Controls	Yes	Yes	Yes	Yes
Industry & Year FE	Yes	Yes	Yes	Yes
R-squared	0.201	0.237	0.198	0.228
Difference Test	$p=0.042^{**}$		$p=0.049^{**}$	

analyst coverage itself has a positive and significant effect on green innovation, indicating that firms followed by more analysts tend to engage in greater green innovation activities. More importantly, the interaction term between data asset capitalisation and analyst coverage displays a significant positive coefficient, suggesting that the positive effect of data asset capitalisation on green innovation is amplified when firms receive greater analyst attention. This finding supports the notion that external information intermediaries enhance the market recognition and valuation of firms' data assets, thereby strengthening the relationship between data assets and green innovation outcomes. For firms operating with high visibility in capital markets, data assets appear to yield greater green innovation benefits, possibly because analyst scrutiny helps validate the quality and potential of these digital resources, facilitating their effective deployment toward environmentally beneficial innovations.

Cross-section analysis

Table 6 presents our cross-sectional analysis exploring how environmental conditions moderate the relationship between data asset capitalisation and green innovation. The results reveal meaningful heterogeneity across different levels of environmental uncertainty (EU) and environmental policy pressure (EP). In low environmental uncertainty contexts, the coefficient for data asset capitalisation ($\beta = 0.053$) is positive but not statistically significant, whereas in high uncertainty environments, the effect becomes substantially stronger and statistically significant ($\beta = 0.104$, $p < 0.05$). The difference between these coefficients is statistically significant ($p = 0.042$), suggesting that the benefits of data asset capitalisation for green innovation are amplified under conditions of greater environmental volatility. This finding aligns with the perspective that data assets provide particularly valuable decision support in turbulent business environments, where real-time insights and predictive capabilities become critical advantages for navigating uncertainty.

Similarly, the influence of data asset capitalisation appears contingent on environmental policy pressure. In regions with low policy pressure, data asset capitalisation shows a modest association with green innovation ($\beta = 0.058$, $p < 0.1$), but this effect nearly doubles in magnitude in high-pressure regions ($\beta = 0.112$, $p < 0.05$), with the difference being statistically significant ($p = 0.049$). This suggests that data asset capitalisation becomes especially valuable for green innovation when firms face stronger environmental regulatory requirements. When policy mandates create imperatives for environmental performance, firms with sophisticated data capabilities appear better positioned to respond effectively through accelerated green innovation activities. This interaction between internal data capabilities and external policy pressures highlights the contextual nature of digital resources' value for sustainability initiatives.

CONCLUSION

This study advances our understanding of how digital transformation, specifically through data asset capitalisation, contributes to Chinese textile listed companies' environmental sustainability efforts by facilitating green innovation. Our findings reveal that data asset capitalisation has both direct effects on green innovation and indirect effects through alleviating financing constraints in the textile industry, with these relationships being contingent upon environmental uncertainty and policy pressures. The temporal dynamics observed suggest that textile manufacturers experience an incubation period of approximately two years before fully realising the environmental benefits of their data assets, indicating the need for sustained investment in digital capabilities.

These findings illuminate a critical pathway through which traditional manufacturing industries can navigate the dual challenges of digital transformation and environmental compliance. For textile manufacturers, the results suggest that investing in comprehensive data systems capturing production efficiency, resource consumption, and waste management metrics serves dual purposes: signalling technological sophistication to capital providers while building the analytical foundation for environmental improvements. The two-year incubation period we identify underscores the importance of patience and persistence in digital capability building, particularly given the textile industry's traditionally conservative approach to technology adoption. Policymakers can leverage these insights by designing incentive structures that recognise data asset development as a precursor to environmental innovation, while investors should view data asset capitalisation as an early indicator of firms' capacity for sustainable transformation in pollution-intensive sectors.

LIMITATIONS AND FUTURE RESEARCH

Several limitations constrain our findings' generalizability and suggest avenues for future research. Our single-country focus on Chinese textile listed firms limits applicability to other institutional contexts, while our text-based measurement of data assets may not capture tacit knowledge or informal data practices that contribute to green innovation capabilities. Despite employing instrumental variables, unobserved heterogeneity affecting both data asset development and environmental innovation outcomes cannot be eliminated. Future research should explore cross-country comparative studies examining institutional moderators, firm-level case studies investigating organizational processes beyond financing constraints, differential effects of various data asset types (production process, supply chain, consumer behaviour data) on green innovation dimensions, and longitudinal studies tracking digital maturity stages to deepen understanding of temporal dynamics in data-driven environmental transformation.

ACKNOWLEDGMENTS

This research was funded by Guangzhou Xinhua University within the framework of the University-level Scientific Research Project with project no. 2025KYYBSK10, supported by the Characteristic Innovation Project of General Higher Education Institutions in Guangdong Province with project no. 2023WTSCX154, and also backed by the 2016 Guangdong Province Key Discipline Construction Project in Public Administration (2020STSZD01) as well as the Guangdong Province Key Discipline Research Capacity Enhancement Project (2021ZDJS141, 2022ZDJS151).

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Minimum wage and green productivity in the textile industry: policy linkages and regional heterogeneity

DOI: 10.35530/IT.077.01.202567

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ABSTRACT – REZUMAT

Minimum wage and green productivity in the textile industry: policy linkages and regional heterogeneity

Enhancing green total factor productivity (GTFP) is essential for achieving high-quality development in the textile industry, necessitating both theoretical insights and effective policy measures. The purpose of this study is to examine how minimum wage policies affect environmental and economic efficiency in China's textile sector, providing empirical evidence to inform policy decisions that balance worker welfare with sustainable industrial development. This research examines the influence of the minimum wage on GTFP within the textile sector, utilising manually assembled minimum wage data along with panel data from 276 Chinese cities spanning the years 2004 to 2023. A fixed-effects model was employed to investigate the relationship between the minimum wage and GTFP. The results indicate that an increase in the minimum wage exerts a detrimental effect on GTFP in the textile industry. Further mechanism tests reveal that the minimum wage impacts GTFP growth in the textile sector through two primary channels: technological innovation and factor substitution. Heterogeneity analysis shows that the negative impact of the minimum wage on GTFP varies across different regions, city sizes, and administrative levels, with a more pronounced effect observed in the western regions, smaller cities, and cities with lower administrative status. These findings offer significant implications for improving GTFP in the textile industry and fostering high-quality economic development in China.

Keywords: *minimum wage, textile industry, green total factor productivity, technological innovation, high-quality economic development*

Salariul minim și productivitatea ecologică în industria textilă: măsuri politice și eterogenitate regională

Creșterea productivității totale a factorilor ecologici (GTFP) este esențială pentru realizarea unei dezvoltări de înaltă calitate în industria textilă, necesitând atât cunoștințe teoretice, cât și măsuri politice eficiente. Scopul acestui studiu este de a examina modul în care politicile privind salariul minim afectează eficiența economică și de mediu în sectorul textil din China, furnizând dovezi empirice pentru a informa deciziile politice care echilibrează bunăstarea lucrătorilor cu dezvoltarea industrială durabilă. Această cercetare examinează influența salariului minim asupra GTFP în sectorul textil, utilizând date privind salariul minim colectate manual, împreună cu date panel din 276 de orașe din China, acoperind perioada 2004–2023. A fost utilizat un model cu efecte fixe pentru a investiga relația dintre salariul minim și GTFP. Rezultatele indică faptul că o creștere a salariului minim are un efect negativ asupra GTFP în industria textilă. Teste suplimentare ale mecanismului relevă faptul că salariul minim influențează creșterea GTFP în sectorul textil prin două canale principale: inovarea tehnologică și substituția factorilor. Analiza eterogenității arată că impactul negativ al salariului minim asupra GTFP variază în funcție de regiuni, dimensiunea orașelor și nivelurile administrative, cu un efect mai pronunțat observat în regiunile vestice, orașele mai mici și orașele cu statut administrativ inferior. Aceste constatări au implicații semnificative pentru îmbunătățirea GTFP în industria textilă și pentru promovarea unei dezvoltări economice de înaltă calitate în China.

Cuvinte-cheie: *salariul minim, industria textilă, productivitatea totală a factorilor ecologici, inovație tehnologică, dezvoltare economică de înaltă calitate*

INTRODUCTION

In the context of global economic integration and increasing emphasis on sustainable development, labour policies have become critical factors influencing industrial competitiveness and environmental performance worldwide. As countries seek to balance social equity with economic efficiency, minimum wage policies have emerged as important policy instruments that affect not only worker welfare but also industrial productivity and environmental sustainability across different sectors globally.

Since the implementation of the Minimum Wage Regulations in 2004, China's minimum wage standards have seen increasing adjustment magnitudes and enforcement rigour, with regional minimum wages rising at an average annual rate of 10% in recent years. This trend aligns with global patterns, as many developing and developed countries have similarly adjusted their minimum wage policies to address income inequality and improve living standards, while grappling with the potential impacts on industrial competitiveness in an increasingly globalised market. As a factor endowment, the rising cost of labour induces changes in relative factor prices, thereby generating factor substitution effects. Against this backdrop, profit-maximising firms are compelled to adjust their input decisions by substituting capital or technology for labour. This, in turn, affects technological progress and efficiency within firms, ultimately influencing green total factor productivity [1].

The concept of green total factor productivity has gained international prominence as countries worldwide strive to achieve sustainable development goals while maintaining economic growth. The challenge of "green transformation" is particularly acute in traditional manufacturing industries, where the tension between environmental protection and economic competitiveness is most pronounced. Green total factor productivity is an inexhaustible driver of economic development and a key component of China's supply-side structural reforms. From an industry perspective, identifying factors influencing GTFP is of significant importance for expanding industry scale and improving development levels. GTFP in an industry is constrained by the institutional environment, with studies demonstrating that fiscal policies, investment attraction policies, and industrial policies all impact industry GTFP. The minimum wage is a government-mandated, enforceable institution that safeguards workers' remuneration. It stipulates the minimum wage that firms must provide to workers who are employed lawfully [2].

Research on the minimum wage has primarily focused on employment, wage, and export effects. Recently, scholars have begun examining its impact on GTFP. Studies have found that increases in the minimum wage may influence GTFP through two main pathways. First, rising labour costs may force firms to innovate technologically, thereby enhancing GTFP [3, 4]. Second, increases in the minimum wage may improve GTFP by promoting the exit of low-productivity firms and restricting the entry of firms with low production potential [5].

Another body of related literature examines the measurement methods and influencing factors of GTFP. Current methods for measuring GTFP mainly include the SBM model, the ML index, and the SBM directional distance function combined with the Luenberger productivity indicator [6]. Numerous scholars have investigated the impact of environmental regulations, foreign direct investment, and innovation on GTFP. However, no consensus has been reached on the effects of environmental regulations and foreign direct investment [7]. In contrast, innovation, as a significant driver of GTFP, affects it through technological progress and efficiency. Technology imports from abroad and firm-level R&D both enhance GTFP, while domestic technology purchases may, to some extent, inhibit GTFP growth [8].

The textile industry represents a particularly important case study in the global context, as it is one of the most internationally integrated manufacturing sectors and faces increasing pressure from both labour standards and environmental regulations worldwide. International trade patterns in textiles are significantly influenced by labour costs, making minimum wage policies a crucial determinant of global competitiveness. The impact of minimum wage increases varies across industries, with the textile industry being one of the most affected [9]. As a traditional labour-intensive sector, the textile industry has long relied on its capacity to absorb large numbers of workers with low entry barriers [10, 11]. Understanding how minimum wage policies affect green productivity in this sector has implications beyond China's borders, as it can inform policy decisions in other developing countries seeking to upgrade their textile industries while improving labour standards and environmental performance. Existing literature has predominantly focused on the manufacturing sector, with limited attention paid to the textile industry and the pathways through which minimum wage standards exert their influence.

This study employs a sample of Chinese cities to conduct an empirical examination of how minimum wage standards affect green total factor productivity (GTFP) in the textile industry, the underlying mechanisms involved, and whether significant differences exist across regions, city sizes, and administrative levels. This research contributes to the broader international discourse on sustainable industrial development and provides insights relevant to policymakers worldwide who are navigating the complex relationship between social policies and environmental outcomes. This research is crucial for achieving high-quality economic development in China.

While prior studies have yielded substantial findings, few scholars have explored the impact of minimum wage standards on GTFP in the textile industry. This study makes the following contributions: First, it links minimum wage standards to GTFP in the textile industry by matching city-level minimum wage data with panel data from Chinese cities to empirically analyse the impact of minimum wage standards on textile industry GTFP. Second, it theoretically examines how minimum wage standards influence GTFP in the textile industry and the channels through which this impact is transmitted. Third, it investigates the heterogeneous effects of minimum wage standards on GTFP across regions, city sizes, and administrative levels, discussing the urban disparities in China's economic growth quality and their sources.

The following articles are arranged as follows: the second part introduces the theoretical analysis and research hypothesis, the third part is the research design of this paper, the fourth part is the empirical test and result analysis of this paper, the fifth part is the heterogeneity analysis, and the sixth part is the research conclusions and policy implications of this paper.

THEORETICAL ANALYSIS AND RESEARCH HYPOTHESES

According to the literature, growth in green total factor productivity (GTFP) primarily relies on technological progress and efficiency improvements. First, minimum wage standards can influence firm innovation through cost and selection effects, potentially promoting GTFP growth in the textile industry. However, these standards may also inhibit industry innovation through crowding-out and employment effects, thereby impeding GTFP growth in China's textile sector [12]. Second, increases in minimum wage standards can lead to factor substitution, where capital replaces labour. This shift is often driven by heavy industries that sacrifice the environment, resulting in a negative impact on industry GTFP [13].

Mechanisms through which minimum wage standards influence the textile industry GTFP via innovation

Minimum wage standards can affect GTFP through two primary mechanisms. As China's overall living standards improved, employment opportunities increased, and the demographic dividend diminished, the textile industry, a labour-intensive sector, gradually lost its competitive edge based on low-cost labour [14].

On the one hand, minimum wage standards can force firms to innovate, thereby enhancing GTFP. First, the cost-effect suggests that increases in minimum wage standards raise absolute labour costs, compelling firms to shift towards technology-driven growth. This, in turn, promotes GTFP growth and green transformation in China's textile industry [15]. Second, the selection effect indicates that higher minimum wages encourage low-productivity firms to exit the market while deterring potential entrants with low production potential. Efficient firms typically engage in innovation to maintain their competitive edge, and increased R&D investment and innovation activities contribute to GTFP improvements [16, 17]. Third, according to the efficiency wage theory, minimum wages can reduce worker shirking, incentivise employees to pursue education and training, and attract higher-calibre talent. These factors enhance human capital within firms, leading to improved labour productivity and innovation motivation [18]. Fourth, minimum wage standards can enhance resource allocation efficiency. The mobility of capital and labour across regions improves resource utilisation, technical efficiency, and overall GTFP [19]. Finally, from the demand side, higher minimum wages increase average income levels, promoting consumption upgrades. As local consumers' purchasing power strengthens, their demand for innovative products rises, incentivising firms to innovate and boost GTFP [20].

On the other hand, while minimum wage standards can promote firm innovation and GTFP through these mechanisms, they may also inhibit innovation and GTFP growth. First, increases in minimum wages can crowd out innovation funding. To compensate for higher wage costs, firms may reduce R&D budgets. Given the high risks and vulnerability of innovation to infringement, especially in China's underdeveloped intellectual property protection regime, this can create a double squeeze on firm profits, discouraging innovation [21, 22]. Second, the employment effect of minimum wages is significant. Innovation relies on diverse, non-redundant information and resources, often sourced from lower-level employees who support R&D activities. However, higher minimum wages can lead to job losses among low-skilled workers, disrupting the balance of skills within firms and impeding technological progress [23, 24]. Third, according to the export learning hypothesis, firms facing intense international competition often learn from global experiences to improve technology and efficiency. However, higher minimum wages can reduce exports and lower product quality, weakening the export learning effect and inhibiting innovation and GTFP growth in the textile industry [25, 26]. Fourth, minimum wage increases can spill over to employees earning above the minimum wage, raising overall labour costs and reducing firms' R&D investment [27]. Finally, according to the social exchange theory, firms may reduce non-wage benefits such as training to offset higher wage costs. This can weaken employee loyalty and increase work intensity, reducing workers' motivation to innovate and negatively impacting GTFP. Based on the above analysis, the following hypothesis is proposed:

H1: When the "inhibitory" effect of minimum wage standards on technological innovation outweighs the "forcing" effect, it is detrimental to GTFP growth in the textile industry.

Mechanisms through which minimum wage standards influence the textile industry GTFP via factor substitution effects

Increases in minimum wage standards generate factor substitution effects, meaning that higher minimum wages lead to a relative price increase for labour. This compels profit-maximising firms to substitute capital or technology for labour [28]. The extent to which firms substitute capital or technology for labour depends not only on the price ratio between the substituting factor and labour but also on the elasticity of substitution between these factors [29].

On the one hand, minimum wage increases have a compensating effect on low-wage workers [28]. Firms are required to pay low-skilled workers wages above the market-clearing level, resulting in higher total wage payments to this group. As the price ratio between substituting factors and labour decreases, firms' incentives to substitute capital or technology for labour increase.

On the other hand, minimum wage increases also produce spillover effects on workers' earnings above the minimum wage [30]. This occurs because higher minimum wages increase the relative cost of low-skilled labour, prompting firms to substitute high-skilled labour for low-skilled labour. The increased

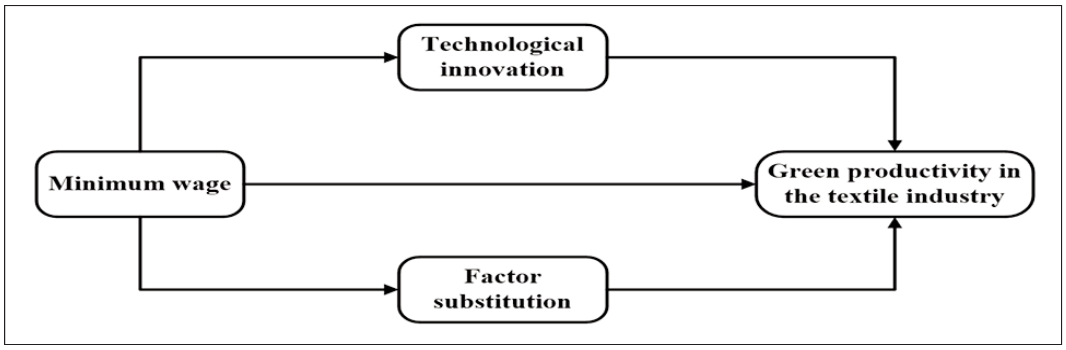

Fig. 1. Theoretical framework

demand for high-skilled workers leads to higher wages for this group [31]. Consequently, as the cost of labour-intensive production rises rapidly, firms are more inclined to substitute capital for labour and high-skilled workers for low-skilled workers [32]. For example, the "machine-for-human" strategy implemented by coastal firms involves replacing labour with advanced fixed assets. This not only accesses the embedded cutting-edge production technologies within machinery but also significantly improves production efficiency and reduces costs. While this appears to be a substitution of equipment and technology for labour, it is essentially a substitution of capital for labour. This factor substitution effect is more pronounced when the elasticity of substitution between capital and labour is high [33].

However, the sustained increase in the capital-to-labour ratio in China has primarily been driven by extensive industrial scale expansion, particularly in heavy and chemical industries [34]. The heavy industrialisation characteristic exacerbates environmental degradation, which in turn has a negative impact on green total factor productivity. Based on the above analysis, the following hypothesis is proposed:

H2: Minimum wage standards inhibit GTFP growth in the textile industry through factor substitution effects.

The theoretical framework of this paper is shown in figure 1.

RESEARCH DESIGN

Model specification

Drawing on prior research, it has been established that, in addition to minimum wage standards, factors such as the level of economic development, government actions, industrial structure, consumer demand, foreign direct investment, and human capital levels all influence green total factor productivity (GTFP) in the textile industry [35]. Based on these findings, we denote textile green total factor productivity as CGTFP and minimum wage standards as MW. We also select the following control variables: level of economic development (GDP), government actions (GOV), industrial structure (STRU), consumer demand (CR), foreign direct investment (FDI), and human capital levels (HCL). Using these variables, we construct Model (1) to assess the impact of minimum wage standards on green total factor productivity in the textile industry:

$$CTFP_{it} = \alpha_0 + \alpha_1 MW_{it} + \gamma Control + \mu_i + \varphi_t + \varepsilon_{it} \quad (1)$$

In equation 1, i denotes the city, and t denotes the time period (t = 2004–2023). The terms α_1 and γ represent the corresponding elasticity coefficients, while α_0 and ε_{it} represent the intercept and error term, respectively. *Control* is a set of control variables. μ_i represents the city fixed effects, and φ_t represents the year fixed effects, which are included to control for unobservable city-specific and time-specific factors.

Data sources and processing

Data from 276 prefecture-level and above cities in China over the period 2004–2023 were employed for analysis, yielding a total sample size of 5,264 observations. The following section provides details on the data sources, processing methods, and relevant statistical yearbooks for the variables used in this study.

Dependent variable

The dependent variable in this study was measured in two ways. First, the ACF method was used to measure productivity, with each city serving as a decision-making unit to assess green total factor productivity (GTFP) in the textile industry across Chinese regions. This measure of textile GTFP is denoted as CGTFP1 [36]. Given the availability of textile industry data, the following proxies were used: textile value-added to measure total output; net fixed asset investment (original value of fixed assets minus accumulated depreciation) to measure capital stock [37]; the number of employees in the textile industry in each city to measure labour input; and the total amount of coal input to measure intermediate inputs in the textile industry [38].

The second method employed the GML (Generalised Malmquist Luenberger) index for measurement. The panel data encompassed K (k = 1, 2, ..., 256) provinces (autonomous regions, municipalities directly under the central government) and t (t = 1, 2, ..., 15) time periods. The variables x, y, and b represent input variables, desired output variables, and undesired output variables, respectively. Each decision-making unit includes N types of inputs, $x \in R_+^N$, M types of desired outputs, $y \in R_+^M$, and J types of undesired outputs, $b \in R_+^J$. The production possibility set $P(x)$ can be expressed as $P(x) = \{(y, b) \mid \text{inputs } x \text{ produce } (y, b)\}$. The set $P(x)$ must satisfy the following conditions: $(0, 0) \in P(x)$, $x \in R_+^N$. If $x' \geq x$, then $P(x') \supseteq P(x)$. If $(y, b) \in P(x)$ and $0 \leq \theta \leq 1$, $(\theta y, \theta b) \in P(x)$. If $(y, b) \in P(x)$ and $b = 0$, then $y = 0$. The formula for the GML index is as follows:

$$GML^{\prime,+1}(x^t, y', b', x^{t+1}, y^{t+1}, b^{t+1}) = \frac{1 + D^G(x', y', b^t)}{1 + D^G(x'^{+1}, y^{t+1}, b'^{+1})} \tag{2}$$

In the formula, $D^G(x, y, b)$ represents the directional distance function, defined as $D^G(x, y, b) = \max\{\beta \mid (y + \beta y, b - \beta b) \in P^G(x)\}$. This function seeks to maximise the increase in desired outputs while simultaneously reducing undesired outputs. The directional vector used is $g = (y, b)$, where $g \in R_+^M \times R_+^J$.

The core of the GML index is to build on the ML index by utilising the entire set, that is, $P^G = P^1 \cup P^2 \cup \ldots \cup P^T$, to construct the production frontier and address the issue of infeasible solutions. The formula is presented as follows:

$$\begin{aligned} GML^{t,+1}(x^t, y', b^t, x^{t+1}, y^{t+1}, b^{t+1}) &= \\ &= \frac{1 + D^G(x^t, y^t, b^t)}{1 + D^G(x^{t+1+}, y^{++1}, b^{b+1})} = \\ &= \frac{1 + D^t(x^t, y^t, b^t)}{1 + D^{+1}(x^{t+1}, y^{t+1}, b^{++1})} \times \\ &\times \frac{[1 + D^c(x^t, y', b^t)] / [1 + D^t(x^t, y^t, b^t)]}{[1 + D^G(x^{t+1}, y^{t+1}, b^{+1})] / [1 + D^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})]} = \\ &= \frac{TE^{t+1}}{TE^t} \times \frac{BPG_{t+1}^{t,t+1}}{BPG_t^{t,+1}} = TEC^{t,t+1} \times TC^{t,t+1} \end{aligned} \tag{3}$$

In the formula, TE represents technical efficiency; BPG represents the technical change between two time periods; TEC represents the index of technical efficiency change; and TC represents the index of technical change.

Regarding the measurement of inputs and outputs for the green total factor productivity (CGTFP2) in the textile industry, existing literature varies in the selection of indicators for green total factor productivity. The CO_2 emissions of the textile industry were calculated based on the consumption of various types of energy, the standard coal conversion coefficients for these energies, and the CO_2 emission coefficients [39]. The measurement indicators for the GML index of the textile industry are presented in table 1.

Core explanatory variable

The minimum wage standard (MW) refers to the lowest remuneration that employers are legally required to pay workers for normal labour provided within the statutory working hours or the working hours stipulated in a legally binding employment contract [40], measured in yuan. Data on the minimum wage standard were manually collected and collated through various means, including browsing the websites of human resources and social security bureaus of prefecture-level cities, policy documents, statistical bulletins, and official newspapers. This process yielded minimum wage data for 276 cities from 2004 to 2023, which were subsequently log-transformed.

Other control variables

Factors that typically influence the dependent variable include the level of infrastructure, government actions, and external influences of economic development. The control variables selected in this study are as follows:

- Level of economic development (GDP): Measured by the gross regional product of each city (in ten thousand yuan), with log-transformation applied.
- Government actions (GOV): Measured by the ratio of educational and scientific expenditures in the city's fiscal spending to the regional gross product.
- Industrial structure (STRU): Measured by the proportion of employees in the secondary industry relative to the total number of employees in the region.
- Consumer demand level (CR): Measured by the retail sales of consumer goods in each city (in ten thousand yuan), with log-transformation applied.
- Foreign direct investment (FDI): Measured by the total amount of foreign direct investment in China

Table 1

MEASUREMENT INDICATORS FOR THE GML INDEX OF THE TEXTILE INDUSTRY IN EACH CITY

Type of indicators	Name	Units	Calculation method
Factor inputs	Energy inputs to the textile sector	Ten thousand tonnes	Energy consumption of various types of energy in the textile industry×the coefficient of converted standard coal for various types of energy
	Employees of textile enterprises	Millions of people	Number of employees in textile enterprises
	Total assets of textile enterprises	Billions of yuan	Textile industry enterprise assets
Desired outputs	Gross value of textile output	Ten billions of yuan	Gross textile output
Undesired outputs	CO_2 emissions from the textile industry	Ten thousand tonnes	Σ Energy consumption by type in the textile industry × standard coal factor for each type of energy conversion × CO_2 emission factor

Table 2

VARIABLE PROCESSING AND DESCRIPTIVE STATISTICS							
Variable	**Name**	**Abbreviation**	**Obs**	**SD**	**Mean**	**Min**	**Max**
Explanatory variables	Green total factor productivity in textile (ACF)	CGTFP1	1264	2.224	13.988	3.210	25.544
	Green total factor productivity in textile (GML)	CGTFP2	1264	0.872	2.678	0.078	6.153
Explained variable	Minimum wage standard	MW	1264	4.293	4.101	3.372	7.782
Control variables	Level of economic development	GDP	1264	3.308	6.984	4.263	8.909
	Government behaviour	GOV	1264	6.110	9.402	7.877	12.984
	Industrial structure	STRU	1264	0.783	4.953	4.004	7.922
	Consumer demand level	CR	1264	11.024	1.980	0.782	4.376
	Foreign direct investment	FDI	1264	2.872	9.290	4.555	13.089
	Human capital level	HCL	1264	4.444	1.454	0.117	3.562
Mechanism variables	Technological innovation	CII	1264	16.235	1.781	0.545	3.987
	Labour input	ZL	1264	8.820	3.765	2.897	6.113

(in ten thousand US dollars), with log-transformation applied.

- Human capital level (HCL): Measured by the ratio of the number of students enrolled in higher education institutions to the regional population.

Data for the above control variables were sourced from the China Urban Statistical Yearbook. Specific variables and descriptive statistics are presented in table 2.

EMPIRICAL TESTS AND RESULTS ANALYSIS

Benchmark regression results

Table 3 reports the benchmark regression results of the impact of the minimum wage standard on green total factor productivity (GTFP) in the textile industry. Columns (1) and (3) present the regression results considering only the changes in the minimum wage standard (MW), while controlling for city and time effects. Columns (2) and (4) present the results after including all city-level control variables. The findings indicate that the estimated coefficient of the minimum wage standard is significantly negative, suggesting that increases in the minimum wage standard are detrimental to the growth of GTFP in the textile industry. Theoretically, higher minimum wages may inhibit corporate technological innovation and induce factor substitution effects. The continuous increase in the capital-to-labour ratio, driven by the “inhibitory” effect of technological innovation, further exacerbates pollution, energy consumption and pollutant emissions in the textile industry, thereby impeding the improvement of GTFP.

Table 3

BENCHMARK REGRESSION RESULTS				
Variable	**(1)**	**(2)**	**(3)**	**(4)**
	GGTFP1	**GGTFP1**	**GGTFP2**	**GGTFP2**
MW	–0.217*** (–3.056)	–0.309*** (–3.587)	–0.188*** (–3.924)	–0.255*** (–4.100)
GDP		0.032** (2.158)		0.019*** (3.343)
GOV		0.239** (2.255)		0.188*** (3.017)
STRU		–0.333 (–1.277)		–0.416*** (-3.300)
CR		–0.089** (–2.155)		–0.067*** (–2.940)
FDI		0.190** (2.079)		0.216*** (3.080)
HCL		0.136* (1.921)		0.234*** (3.455)
Control	NO	YES	NO	YES
City fixed	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES
N	1264	1264	1264	1264
R^2	0.0382	0.0205	0.0680	0.0441

Note: Parentheses indicate robust standard errors. *, **, *** denote significance levels of 1%, 5%, and 10%, respectively. This notation applies to the following tables.

Robustness tests

Robustness tests were conducted in two main aspects. First, the sample was adjusted. Regions with high levels of industrial agglomeration typically exhibit higher minimum wages and greater innovation output. These areas differ significantly from other cities in terms of economic development, environmental regulation, and the efficiency and level of technological innovation. Given that a large number of high-tech company headquarters in China are concentrated in Beijing, Shanghai, Guangzhou, and Shenzhen, samples from these cities were excluded. The model was then re-estimated based on the adjusted sample, with results shown in columns (1) and (2) of table 4. The regression coefficient for the minimum wage standard remained significantly negative.

Second, the impact of the COVID-19 pandemic was considered. The data period was set as 2004–2019 and 2023 to exclude the influence of the pandemic. During the pandemic, economic activities were severely disrupted, and the textile industry faced issues such as work stoppages, supply chain interruptions, and labour shortages. These factors obscured or distorted the relationship between green total factor productivity (GTFP) fluctuations and the minimum wage standard. After excluding samples from the relevant years, the model was re-estimated based on the adjusted sample, with results shown in columns (3) and (4) of table 4. The regression coefficient for the minimum wage standard remained significantly negative.

Third, outliers were removed. To mitigate the impact of outliers on the empirical results, a 1% truncation and winsorisation were applied to the green total factor productivity in the textile industry at both ends of the distribution. As shown in columns (5) to (8) of table 4, the estimated coefficient for the minimum wage standard remained significantly negative after both truncation and winsorisation.

In summary, after a series of robustness tests, the conclusion remained valid: increases in the minimum wage standard were detrimental to the growth of green total factor productivity in the textile industry.

Endogeneity tests

Endogeneity tests were conducted in two main aspects. First, to address the potential reverse causality between green total factor productivity (GTFP) in the textile industry and the control variables, all control variables were lagged by one period and included in the estimation of equation 1. The results, shown in columns (1) and (2) of table 5, indicate that the estimated coefficient for the minimum wage standard remained significantly negative.

Second, to mitigate estimation bias arising from endogeneity, we followed the approach of Li et al. and selected the average of the highest and lowest minimum wage standards within the province where the city is located (LZ) as an instrumental variable [41]. The estimation was conducted using Two-Stage Least Squares (2SLS). The first-stage regression results of the 2SLS, shown in columns (3) and (4), demonstrate that the instrumental variable (LZ) is significant at the 1% level, with an F-statistic of 23.45, indicating no weak instrument problem. The second-stage regression results of the 2SLS, shown in columns (5) and (6), reveal that the estimated coefficient for the minimum wage standard remains significantly negative at the 5% level.

The above results confirm that, after controlling for endogeneity, the conclusion that the minimum wage standard inhibits the improvement of green total factor productivity in the textile industry still holds.

Table 4

ROBUSTNESS TESTS

Variable	Sample adjustments		Year of removal of the epidemic		Bilateral cut-offs		Bilateral indentations	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	GGTFP1	GGTFP2	GGTFP1	GGTFP2	GGTFP1	GGTFP2	GGTFP1	GGTFP2
MW	–0.0243*** (–3.111)	–0.0450*** (–3.499)	–0.0389*** (–4.045)	–0.0211*** (–4.230)	–0.0155** (–2.140)	–0.0171*** (–3.077)	–0.0158** (–2.167)	–0.0188*** (–3.178)
GDP	0.175*** (3.719)	0.222 (1.123)	0.210 (1.288)	0.114*** (2.982)	0.236** (2.100)	0.159*** (3.100)	0.188** (2.341)	0.149*** (3.123)
GOV	0.116** (2.104)	0.245*** (3.278)	–0.560 (–1.245)	0.555 (1.544)	0.222** (2.133)	0.299** (2.031)	0.227** (2.183)	0.253** (2.149)
STRU	–0.072*** (–3.115)	–0.054 (–1.026)	–0.039** (–2.203)	0.041 (1.490)	–0.030*** (–3.155)	–0.055** (–2.180)	–0.028** (–2.167)	–0.065*** (–3.109)
CR	–0.121*** (–2.889)	–0.139 (–1.155)	–0.224*** (–3.180)	–0.318 (–1.246)	0.360** (2.044)	0.225 (1.330)	–0.360* (–1.844)	–-0.222* (–1.840)
FDI	0.176*** (3.012)	0.155* (1.871)	0.209** (2.174)	0.330*** (3.215)	0.222** (2.033)	–0.266 (–1.115)	0.129*** (3.160)	0.234 (1.068)
HCL	0.365*** (3.879)	0.278** (2.021)	0.166*** (3.300)	0.199 (1.244)	–0.190 (–1.186)	0.222* (1.855)	0.135** (2.066)	0.144 (1.567)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1180	1180	986	986	1064	1064	1088	1088
R^2	0.039	0.045	0.028	0.034	0.041	0.049	0.027	0.032

Table 5

ENDOGENEITY TESTS						
Variable	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	GGTFP1	**GGTFP2**	**MW**	**MW**	**GGTFP1**	**GGTFP2**
MW	–0.044*** (–4.123)	–0.050** (–4.315)			–0.049** (–2.177)	–0.056** (–2.285)
AW			0.367*** (4.108)	0.430*** (4.322)		
GDP	0.123*** (2.799)	–0.245 (–1.110)	0.144*** (3.214)	0.150** (2.339)	0.257*** (3.122)	0.339*** (2.890)
GOV	0.255*** (3.046)	0.230** (2.311)	–0.115 (–1.344)	0.122** (2.169)	–0.136 (–1.800)	0.158** (2.045)
STRU	–0.045*** (–3.167)	–0.022*** (–2.919)	–0.102 (–1.125)	–0.119*** (–3.031)	–0.066** (–3.350)	0.072 (3.211)
CR	–0.221*** (–3.190)	–0.233*** (–3.228)	–0.121** (–2.093)	–0.144*** (–2.855)	–0.326** (–2.199)	0.310 (1.585)
FDI	0.188*** (3.123)	0.217 (1.175)	0.145** (2.180)	0.166** (2.012)	0.190* (1.851)	0.202** (2.139)
HCL	1.065*** (5.175)	0.322** (2.009)	0.289** (2.050)	0.199*** (2.928)	0.256 (1.230)	–0.178 (–1.555)
Control	YES	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES	YES	YES
N	1042	1042	1264	1264	1264	1264
R^2	0.013	0.082	0.066	0.024	0.075	0.080

Note: The F-statistic for the first-stage 2SLS regression results in columns (3) and (4) is 23.45.

Mechanism tests

The preceding sections have thoroughly examined the impact of the minimum wage standard on green total factor productivity (GTFP) in the textile industry. To further elucidate the intrinsic relationship between the minimum wage standard and GTFP in the textile industry, Equations 4 and 5 were formulated. For technological innovation, the city innovation index (CII) was used as a measure, with data sourced from the China City and Industry Innovation Report 2024. For the capital-to-labour ratio change (ZL), following the common practice in the literature, the perpetual inventory method was employed to estimate the capital stock of each city from 2004 to 2023. The total number of employees, including private and individual workers, at the end of each year from 2004 to 2023, was used as the measure of labour input. In equation 4, Med represents the mediating variables, namely the city innovation index and the capital-to-labour ratio change, with other variables defined consistently with Equation (1). This approach was used to investigate the roles of technological innovation and factor substitution effects in the impact of the minimum wage standard on GTFP in the textile industry.

$$Med_{it} = \alpha_0 + \alpha_1 MW_{it} + \gamma Control + \mu_i + \varphi_t + \varepsilon_{it} \quad (4)$$

$$CTFP_{it} = \alpha_0 + \alpha_1 MW_{it} + \alpha_1 Med_{it} + \gamma Control + \mu_i + \varphi_t + \varepsilon_{it} \quad (5)$$

Table 6, column (1), reports that the minimum wage standard has a significantly positive effect on the city innovation index. This suggests that the “inhibitory” effect of the minimum wage standard on technological innovation outweighs its “forcing” effect, thereby impeding the improvement of GTFP in the textile industry. Thus, Hypothesis 1 (H1) is empirically supported.

Column (2) shows that the minimum wage standard has a significantly negative effect on the capital-to-labour ratio change. This indicates that the minimum wage standard also inhibits the improvement of GTFP in the textile industry through an increase in the capital-to-labour ratio. Therefore, Hypothesis 2 (H2) is confirmed.

HETEROGENEITY ANALYSIS

Regional heterogeneity

Given the significant differences in economic development levels and locational advantages among cities in different regions, the impact of the minimum wage standard on green total factor productivity (GTFP) in the textile industry may vary across regions [42]. To examine this, cities were categorised into eastern, central, and western regions. As shown in table 7, the minimum wage standard had a significantly negative effect on GTFP in the textile industry in the western region, while no significant impact was observed in the eastern and central regions.

Table 6

MECHANISM TESTS						
Variable	(1)	(2)	(3)	(4)	(5)	(6)
	CII	CGTFP1	CGTFP2	ZL	CGTFP1	CGTFP2
MW	–0.211*** (–3.088)	–0.117*** (–3.155)	–0.098** (–2.220)	0.380*** (3.192)	–0.244*** (–3.053)	–0.367*** (–3.148)
CII		–0.123*** (–3.561)	–0.350*** (–3.788)			
ZL					–0.355*** (–3.058)	–0.417*** (–3.113)
GDP	0.398** (2.143)	0.224*** (2.865)	0.310 (1.122)	0.255*** (2.719)	0.176** (2.054)	0.409 (1.146)
GOV	0.267** (2.011)	0.145** (2.065)	0.333 (1.446)	0.299*** (3.200)	0.311 (1.104)	0.288*** (3.221)
STRU	–0.102** (–2.132)	–0.095 (–1.268)	–0.088*** (–3.200)	–0.079*** (–3.117)	–0.066 (–1.365)	–0.114 (–1.101)
CR	–0.131** (–2.220)	–0.227** (–2.119)	–0.208*** (–3.355)	–0.129*** (–3.004)	–0.115 (–1.106)	–0.233*** (–3.199)
FDI	0.181*** (3.730)	0.174*** (3.501)	0.216** (2.111)	0.209* (1.899)	0.313*** (5.022)	0.255 (1.215)
HCL	0.365 (1.167)	0.442 (1.122)	0.228** (2.109)	0.254 (1.465)	0.349** (2.215)	0.444*** (3.775)
Control	YES	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES	YES	YES
N	1264	1264	1264	1264	1264	1264
R^2	0.022	0.018	0.035	0.055	0.040	0.033

Table 7

REGIONAL HETEROGENEITY						
Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Eastern	Central	Western	Eastern	Central	Western
	CGTFP1	CGTFP1	CGTFP1	CGTFP2	CGTFP2	CGTFP2
MW	0.037 (1.144)	0.024 (1.183)	–0.058** (–3.562)	0.055 (1.237)	–0.062 (–1.208)	–0.045*** (–3.455)
GDP	0.198 (1.344)	0.220** (2.050)	0.311** (2.122)	0.255*** (3.067)	0.229 (1.448)	0.333 (1.100)
GOV	0.167 (1.130)	0.311 (1.255)	0.422*** (3.789)	0.235** (2.021)	0.336 (1.577)	0.244** (2.154)
STRU	0.312*** (3.211)	–0.178** (–2.055)	–0.221 (–1.034)	–0.165 (–1.110)	–0.237** (–2.187)	–0.244** (–2.030)
CR	–0.145** (–2.341)	–0.231 (–1.410)	–0.220*** (–2.088)	–0.187** (–2.154)	–0.334* (–1.872)	0.131 (1.310)
FDI	0.229* (1.871)	0.188*** (3.124)	0.193*** (3.164)	0.215 (1.610)	0.313** (2.065)	0.234** (2.113)
HCL	0.312*** (3.289)	0.443** (2.166)	0.116 (1.100)	0.252** (2.066)	0.440 (1.222)	0.225** (2.141)
Control	YES	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES	YES	YES
N	386	536	342	386	536	342
R^2	0.043	0.082	0.055	0.016	0.037	0.044

The likely reason is that the eastern and central regions of China can mitigate the dual pressures of rising labour costs and increasingly stringent environmental regulations, both caused by increases in the minimum wage, through industrial relocation. Moreover, these regions have higher technological progress efficiency compared to the Western region. Additionally, the green transformation of the textile industry is still in its developmental stage across all regions, which further explains the insignificant impact of the minimum wage standard on GTFP in the textile industry in these regions. In contrast, the western region has a relatively lower level of economic development. The setting and adjustment of the minimum wage standard are closely related to the regional economic development level. The relatively low labour costs in the western region attract the relocation of labour-intensive and polluting industries from the eastern and central regions. Coupled with a development model that relies on resource endowments to boost economic growth and low pollution control technology levels, these factors collectively exert a more adverse impact on GTFP in the textile industry.

Urban scale heterogeneity

Given the significant differences among cities of varying scales in terms of agglomeration economies and economies of scale, the impact of the minimum wage standard on green total factor productivity (GTFP) in the textile industry may vary across cities of different sizes. To investigate this, following the approach of Zou et al., cities were categorised into small and medium-sized cities [43], Type II large cities, Type I large cities, and megacities or special large cities, based on the total population at the end of 2023 in each city's jurisdiction. As shown in columns (1) to (8) of table 8, the minimum wage standard had a significantly negative effect on GTFP in the textile industry in small and medium-sized cities and Type II large cities, while no significant impact was observed in Type I large cities and megacities or special large cities.

The reason is that China's megacities, special large cities, and Type I large cities tend to relocate high-energy-consuming and highly polluting industries to Type II large cities and small and medium-sized cities. Therefore, the impact of the minimum wage standard on these larger cities is insignificant. In contrast, small and medium-sized cities and Type II large cities, which receive the transfer of polluting industries, suffer from irrational industrial structures and imperfect environmental regulatory systems. The continuous increase in pollution emissions significantly suppresses GTFP. This indicates that industrial relocation in China occurs not only between regions but also among cities of different scales.

Urban administrative heterogeneity

Given the significant differences among cities of varying administrative levels in terms of human capital reserves, technological development, preferential

Table 8

URBAN SCALE HETEROGENEITY								
Variable	Small and medium-sized cities	II large cities	I large cities	Super and mega cities	Small and medium-sized cities	II large cities	I large cities	Super and mega cities
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
MW	–0.156*** (–3.172)	–0.289** (–2.354)	–0.540 (–1.101)	–0.333 (–1.088)	–0.120** (–2.020)	–0.244* (–1.822)	–0.477 (–1.380)	–0.500 (–1.477)
GDP	0.155 (1.209)	0.255*** (3.333)	0.222 (1.562)	0.188*** (3.245)	0.311** (2.304)	0.255** (2.116)	0.410 (1.200)	0.211 (1.188)
GOV	0.222** (2.134)	0.311 (1.498)	0.145 (1.199)	0.220** (2.046)	0.306 (1.216)	0.189* (1.802)	0.421 (1.527)	0.509*** (3.871)
STRU	–0.111** (–2.232)	–0.165 (–1.309)	–0.120 (–1.045)	–0.244 (–1.440)	0.133 (1.124)	–0.289 (–0.934)	–0.252** (–2.110)	–0.200*** (–3.312)
CR	–0.055*** (–3.313)	–0.234 (–1.509)	0.387 (1.144)	–0.187** (–2.022)	–0.120* (–1.840)	–0.222 (–1.221)	–0.140** (–2.154)	–0.288*** (–3.100)
FDI	0.210*** (3.206)	0.333 (1.319)	0.406* (1.822)	0.199 (1.110)	0.311*** (3.610)	0.422 (1.514)	0.152 (1.019)	0.134** (2.115)
HCL	0.222** (2.165)	0.334*** (2.778)	0.252 (1.533)	0.252** (2.025)	0.344** (2.112)	0.213 (1.345)	0.240** (2.369)	0.188** (2.030)
Control	YES	YES	YES	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES	YES	YES	YES	YES
N	442	386	228	208	442	386	228	208
R^2	0.075	0.081	0.040	0.066	0.052	0.033	0.044	0.038

Table 9

URBAN ADMINISTRATIVE HETEROGENEITY								
Variable	**Prefecture-level Cities**	**Provincial Capital Cities**	**Sub-provincial Cities**	**National Centre Cities**	**Prefecture-level Cities**	**Provincial Capital Cities**	**Sub-provincial Cities**	**National Centre Cities**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
MW	–0.225*** (–2.790)	0.119 (1.154)	0.133 (1.226)	–0.222 (–1.208)	–0.091** (–2.110)	0.144 (0.829)	0.077 (1.176)	0.150 (1.245)
GDP	0.111*** (3.199)	0.167* (1.831)	0.200 (1.328)	0.128** (2.155)	0.360** (2.039)	–0.155 (–1.044)	0.222 (1.110)	0.310 (0.988)
GOV	0.310*** (3.219)	0.222 (1.288)	0.144** (2.111)	0.335*** (3.460)	0.166 (1.333)	0.218* (1.770)	0.192 (1.245)	0.333* (1.800)
STRU	–0.210*** (–3.167)	–0.178 (–1.200)	0.122 (1.144)	–0.156*** (–3.209)	0.222 (1.055)	–0.183 (–0.994)	–0.155** (–2.219)	–0.320*** (–3.013)
CR	–0.188*** (–3.011)	–0.234** (–1.999)	0.385 (1.141)	–0.127** (–2.100)	0.120 (0.888)	–0.222** (–2.120)	0.140 (1.315)	–0.288*** (–3.222)
FDI	0.089** (2.369)	0.131 (1.113)	0.076 (1.120)	0.119* (1.834)	0.082*** (3.212)	0.144 (1.312)	0.155 (1.201)	0.100*** (3.252)
HCL	0.129*** (3.154)	0.231** (2.189)	0.155 (1.430)	0.220** (2.115)	0.146*** (3.422)	0.117 (1.244)	0.233 (1.232)	0.188** (2.111)
Control	YES	YES	YES	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES	YES	YES	YES	YES
N	860	214	86	104	860	214	86	104
R^2	0.154	0.110	0.088	0.072	0.159	0.105	0.243	0.100

policies, and environmental regulations, the impact of the minimum wage standard on green total factor productivity (GTFP) in the textile industry may vary across cities. Therefore, following the approach of Qi & Deng, cities were categorised into prefecture-level cities, provincial capitals, sub-provincial cities, and national central cities [44]. Sub-provincial cities include Guangzhou, Wuhan, Harbin, Shenyang, Chengdu, Nanjing, Xi'an, Changchun, Jinan, Hangzhou, Dalian, Qingdao, Shenzhen, Xiamen, and Ningbo. Among these, Shenzhen, Dalian, Qingdao, Xiamen, and Ningbo are planned single-list cities, while the others are provincial capitals. National central cities include Shanghai, Beijing, Guangzhou, Tianjin, Chongqing, Chengdu, Wuhan, Zhengzhou, and Xi'an.

As shown in columns (1) to (8) of table 9, the minimum wage standard had a significantly negative effect on GTFP in the textile industry in prefecture-level cities, while its impact on provincial capitals, sub-provincial cities, and national central cities was positive but insignificant. The likely reason is that important production factors in China's urbanisation process, such as capital, infrastructure investment, human capital, advanced technology, and preferential policies, are allocated progressively from the central to local governments and from higher to lower-level cities. As a result, national central cities, sub-provincial cities, and provincial capitals have more developed transportation and information infrastructure, and they cluster universities and scientific research institutions. These factors make it easier to stimulate agglomeration economies in cities, rendering the crowding-out and employment effects of the minimum wage insignificant. In contrast, for cities with lower administrative levels, as the minimum wage standard increased, local governments and enterprises mostly responded by increasing fiscal subsidies and capital investment to achieve economic growth targets and to alleviate market competition pressures caused by rising costs. The increased capital investment is likely to manifest directly as the development of heavy and chemical industries, which in turn has an adverse impact on GTFP in the textile industry.

CONCLUSIONS AND POLICY IMPLICATIONS

Conclusions

Based on manually collected data on minimum wage standards from 276 Chinese cities between 2004 and 2023, and panel data from these cities, this study examined the impact of the minimum wage standard on green total factor productivity (GTFP) in the textile industry in Chinese cities. The results indicate that the minimum wage standard has a significantly negative effect on GTFP in the textile industry. This conclusion remains valid after conducting multiple robustness tests and addressing endogeneity issues. Mechanism tests reveal that the minimum wage standard inhibits the growth of GTFP in the textile industry through two channels: technological innovation and factor substitution effects. Heterogeneity analysis shows that the impact of the minimum wage standard on GTFP in the textile industry varies by region, city size, and administrative level. Specifically, it has a significantly negative effect on the western region but not on the eastern and central regions. The negative impact is more pronounced in smaller cities, particularly small and medium-sized cities and Type II large cities, while no significant effect is observed in Type I large cities and megacities or special large cities. Similarly, the negative impact is more significant in prefecture-level cities compared to provincial capitals, sub-provincial cities, and national central cities.

Policy implications

Refine the minimum wage system. Given the negative impact of the minimum wage standard on GTFP in the textile industry, it is essential to refine a minimum wage system that suits China's national conditions. This should promote a shift in the economic development model, encouraging a transition from factor-driven growth, such as reliance on labour, to innovation-driven growth. This will enhance energy-saving and emission reduction levels and improve GTFP in the textile industry.

Accelerate the transformation of factor endowment structure. Since the minimum wage standard has a more pronounced "inhibitory" effect on technological innovation compared to its "forcing" effect, and the current factor endowment structure exacerbates environmental burdens in cities, it is necessary to accelerate the transformation of the factor endowment structure. This can be achieved by enhancing human capital and technological innovation capabilities to drive productivity changes. For example, tax exemptions and rebates on pollution fees for corporate innovation and energy-saving emission reductions can optimise the allocation of innovative factors and guide enterprises to shift from relying on resource and cost advantages to relying on technological and human capital advantages.

Implement regionally differentiated environmental regulations and technology upgrading policies. Adopt a "negative list" management model to restrict the transfer of highly polluting and energy-intensive industries to the western region. Implement talent development strategies to attract high-tech, low-pollution enterprises through preferential policies and incentive mechanisms.

Strengthen regional economic linkages and collaboratively promote the overall improvement of green GTFP. It is crucial to promote upstream and downstream industrial agglomeration between large cities and surrounding small and medium-sized cities, enhancing the division of labour and collaboration across regional industrial chains. Additionally, leveraging the human capital reserves and technological development levels of higher administrative level cities, cities should implement horizontal differentiated development and vertical division of labour to radiate and drive surrounding lower administrative level cities. This will achieve coordinated progress in improving GTFP in the textile industry across cities of all sizes.

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Bridging the gap: Environmental regulation and carbon productivity in the textile industry amid dual carbon targets

DOI: 10.35530/IT.077.01.202568

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ABSTRACT – REZUMAT

Bridging the gap: Environmental regulation and carbon productivity in the textile industry amid dual carbon targets

This research assessed the carbon productivity within the textile industry and utilised spatial Durbin and threshold regression models to empirically examine the relationship between environmental regulation and carbon productivity in this sector. The findings demonstrate that, at the national level, environmental regulation has generally enhanced the carbon productivity of China's textile industry. However, the local impact and spatial spillover effects of environmental regulation exhibit significant differences. At the regional level, environmental regulation has had a more substantial positive effect on the carbon productivity of the textile industry in the eastern and central regions, while it has hindered the improvement of carbon productivity in the western region. Additionally, the local and spatial spillover effects of environmental regulation vary greatly across different regions. The threshold effect analysis indicates that the impact of environmental regulation on the carbon productivity of the textile industry is contingent upon the level of textile technology. In provinces where the threshold value of textile technology has not been met, strengthening environmental regulation may impede the improvement of carbon productivity in the textile industry. Environmental regulation can boost the carbon productivity of the textile industry through two pathways: attracting foreign direct investment and optimising the energy structure.

Keywords: *textile technology, environmental regulation, carbon productivity, FDI, energy structure*

Reducerea decalajului: reglementările de mediu și productivitatea carbonului în industria textilă în contextul obiectivelor duble privind emisiile de carbon

Această cercetare a evaluat productivitatea carbonului în industria textilă și a utilizat modele spațiale Durbin și de regresie prag pentru a examina empiric relația dintre reglementările de mediu și productivitatea carbonului în acest sector. Rezultatele demonstrează că, la nivel național, reglementările de mediu au îmbunătățit în general productivitatea carbonului în industria textilă din China. Cu toate acestea, impactul local și efectele de propagare spațială ale reglementărilor de mediu prezintă diferențe semnificative. La nivel regional, reglementările de mediu au avut un efect pozitiv mai substanțial asupra productivității carbonului în industria textilă din regiunile estice și centrale, în timp ce au împiedicat îmbunătățirea productivității carbonului în regiunea vestică. În plus, efectele locale și spațiale ale reglementărilor de mediu variază foarte mult de la o regiune la alta. Analiza efectului de prag indică faptul că impactul reglementărilor de mediu asupra productivității carbonului în industria textilă depinde de nivelul tehnologiei textile. În provinciile în care valoarea pragului tehnologiei textile nu a fost atinsă, consolidarea reglementărilor de mediu poate împiedica îmbunătățirea productivității carbonului în industria textilă. Reglementările de mediu pot stimula productivitatea carbonului în industria textilă prin două căi: atragerea investițiilor străine directe și optimizarea structurii energetice.

Cuvinte-cheie*: tehnologia textilă, reglementări de mediu, productivitatea carbonului, investiții străine directe, structura energetică*

INTRODUCTION

The global textile industry faces unprecedented environmental challenges as international climate commitments intensify. The Paris Agreement's goal of limiting global warming to 1.5°C above pre-industrial levels has prompted nations worldwide to adopt ambitious carbon reduction targets. The European Union's Green Deal aims for climate neutrality by 2050, while the United States has committed to achieving net-zero emissions by 2050. These international frameworks have created a global imperative for industries to fundamentally transform their production models, with the textile sector, responsible for approximately 10% of global carbon emissions, under particular scrutiny.

The textile industry's environmental impact extends far beyond carbon emissions, encompassing water consumption (20% of global industrial water pollution), chemical usage, and waste generation. Major textile-producing countries, including India, Bangladesh, Vietnam, and Türkiye, are implementing increasingly stringent environmental regulations, creating a global competitive landscape where carbon productivity becomes a critical determinant of industrial competitiveness. The Ellen MacArthur Foundation's Make Fashion Circular initiative and the United Nations' Sustainable Development Goals have further elevated the urgency of sustainable textile production on the global agenda.

Within this global context, China has set ambitious goals to achieve peak carbon emissions before 2030 and carbon neutrality by 2060. The introduction of these dual carbon goals has had a profound impact on the textile industry, presenting both significant challenges and substantial development opportunities. Under the dual carbon framework, it is essential to vigorously promote new textile methods characterised by greening, intelligentisation, and industrialisation to facilitate the green development of the textile industry [1]. As a pillar industry of the national economy, the textile sector has driven rapid economic growth while causing severe environmental degradation [2]. In response, the government has implemented a series of environmental regulations to constrain corporate pollution emissions.

With the increasing severity of climate change and environmental pollution, China has been committed to advancing green development and pursuing a low-carbon, sustainable development path [3]. A low-carbon economy represents an economic model that achieves low-carbon development by balancing economic growth with carbon dioxide emission reduction targets [4]. The textile industry, as a foundational and pillar sector of economic development, consumes a large amount of energy and generates significant carbon dioxide emissions [5]. According to the Intergovernmental Panel on Climate Change (IPCC), the textile industry accounts for 36% of total carbon emissions, making reducing emissions from this sector an urgent priority. Current approaches to emission reduction include either reducing absolute carbon emissions or improving carbon productivity. The former approach, which sacrifices economic development, is inconsistent with the principles of sustainable development. In contrast, the latter approach, which is central to a low-carbon economy, represents a crucial pathway for sustainable carbon reduction [6].

China's position as the world's largest textile producer and exporter, accounting for over 50% of global textile production, makes its environmental regulatory effectiveness crucial for global sustainability goals. The country's textile industry not only serves domestic markets but also supplies major international brands, creating ripple effects throughout global supply chains. As international buyers increasingly demand sustainable production practices and implement supplier environmental standards, Chinese textile manufacturers face mounting pressure to improve their carbon productivity while maintaining competitive advantages.

In fact, the Chinese government has implemented a range of environmentally restrictive measures to protect the environment. These measures include regional joint prevention and control, as well as air pollution prevention and control plans aimed at reducing carbon emissions. The goal is to enhance carbon productivity and improve environmental quality through environmental regulation [7]. Given that the textile industry accounts for one-third of China's total industrial emissions, it is essential to determine whether environmental regulation has improved the carbon productivity of the domestic textile industry and its spillover effects on adjacent regions. Furthermore, it is necessary to explore whether a threshold value exists for the impact of environmental regulation on carbon productivity and whether other factors may constrain this relationship. Understanding how environmental regulation affects carbon productivity in the textile industry is crucial. This study addresses these questions by measuring the carbon productivity of the textile industry and analysing the relationship between environmental regulation and carbon productivity using spatial econometric and threshold regression models. This research is significant for informing region-specific environmental regulation policies and enhancing the carbon productivity of China's textile industry.

While existing literature has not specifically focused on the relationship between environmental regulation and carbon productivity in the textile industry, several studies have examined the broader relationship between environmental regulation and carbon productivity [8]. Cheng and Kong used provincial industrial data from China to explore the relationship between environmental regulation, industrial structural changes, and carbon productivity, concluding that increased environmental regulation intensity is beneficial for improving industrial carbon productivity [9]. Zhang et al. analysed the relationship between environmental regulation, economic growth, and regional carbon productivity in China, arguing that environmental regulation currently inhibits the improvement of carbon productivity [10]. Li et al. examined the non-linear impact of environmental regulation on regional carbon productivity under local government competition, suggesting that the effect of environmental regulation on carbon productivity can change with factors such as technological innovation [11]. These studies provide a theoretical foundation for further research on the relationship between environmental regulation and carbon productivity in the textile industry. However, several gaps remain: First, there is a lack of examination of the spillover effects of carbon productivity. As inter-regional competition and cooperation deepen, it is necessary to analyse the spatial spillover effects of carbon productivity. Second, there is insufficient research at the industry and regional levels. In addition to industry differences, regional disparities are also prevalent in China.

In light of these gaps, this study makes the following contributions based on provincial panel data from China between 2004 and 2022:

(1) Pioneering analysis of spatial spillover effects in textile manufacturing. This study was the first to systematically explore the spillover effects of environmental regulation on regional carbon productivity, specifically within the textile industry. Using spatial econometric models, the analysis captured interdependencies among textile-producing provinces and examined how environmental regulations in one textile hub affected carbon productivity in neighbouring textile regions. This addressed pollution haven effects commonly observed in labour-intensive manufacturing and provided insights for coordinated regional policy design through identification of textile technology diffusion, production facility relocation, and competitive spillover mechanisms across China's textile manufacturing belt.

(2) Multi-level comprehensive impact assessment of textile industry dynamics. The study conducted a comprehensive examination of overall, local, and spatial spillover effects at both national and regional levels within China's textile sector. The multi-dimensional framework differentiated between direct effects (within textile clusters), indirect effects (cross-regional textile supply chain spillovers), and total effects, providing granular insights into environmental regulation effectiveness across different textile manufacturing regions. Decomposition techniques separated local textile production effects from inter-regional spillover effects, enabling precise quantification of impact sources within the textile industry ecosystem.

(3) Advanced threshold effect analysis with textile technology interaction. The investigation explored non-linear relationships between environmental regulation and carbon productivity in textile manufacturing, identifying critical regulatory intensity levels where marginal effects on textile production efficiency changed dramatically. Incorporating textile-specific technology levels (including automation, clean production technologies, and energy-efficient machinery) as threshold variables revealed how regulation effectiveness varied across different stages of textile technological development. This dual-threshold approach employed Hansen's (1999) methodology with bootstrap procedures, contributing to the non-linear environmental economics literature whilst providing practical guidance for calibrating regulatory stringency in textile manufacturing contexts.

(4) Comprehensive transmission mechanism analysis for textile industry transformation. The study explored transmission mechanisms through which environmental regulation affected carbon productivity in textile manufacturing via multiple industry-specific channels: innovation (R&D stimulation in clean textile technologies), industrial restructuring (textile firm entry/exit dynamics and value chain reorganisation), scale effects (compliance costs impact on textile production capacity), competition (market dynamics alteration within textile segments), and investment reallocation (capital shifts toward energy-efficient textile machinery and sustainable production processes). Multi-mechanism analysis employed structural equation modelling and instrumental variables to establish causal relationships specific to textile industry transformation patterns.

(5) Methodological innovation and robustness in textile industry analysis. The study advanced methodological frontiers through: developing textile industry-specific carbon productivity measurement frameworks that accounted for fibre processing, dyeing, and finishing processes; combining spatial Durbin models with threshold regression techniques tailored to textile manufacturing characteristics; and implementing multiple robustness checks, including alternative spatial weight matrices reflecting textile supply chain linkages and instrumental variable approaches using textile-specific instruments. The framework could be adapted for other labour-intensive manufacturing industries, contributing to the spatial environmental analysis literature.

(6) Policy-relevant insights for global textile sustainability. The research generated actionable policy insights extending beyond China's textile industry through the identification of optimal regulatory intensity levels for textile manufacturing, spatial coordination requirements among textile-producing regions, and technology-conditional policy design principles for sustainable textile production. Findings contributed to international textile industry sustainability discussions and climate policy debates, offering evidence-based recommendations for balancing carbon reduction goals with textile industry competitiveness in developing economies, whilst supporting global textile supply chain decarbonisation efforts.

THEORETICAL ANALYSIS AND HYPOTHESIS DEVELOPMENT

Current academic research on the impact of environmental regulation on carbon productivity is primarily based on two theories: the Compliance Cost Theory [12] and the Innovation Compensation Theory [13]. The former argues that environmental regulation increases managerial complexity, pollution fees, and environmental investments, thereby reducing profitable production investments and capital returns. This ultimately has a negative impact on carbon productivity. In contrast, the latter, represented by the "Porter Hypothesis", posits that appropriate environmental regulation can drive technological progress in enterprises by reducing waste, pollution, and input costs. This, in turn, improves product quality and production efficiency, thereby compensating for and even exceeding compliance costs through innovation spillovers. Whether the impact of environmental regulation on carbon productivity is dominated by compliance costs or innovation compensation depends on the net effect of local effects (direct effects) and spatial spillover effects (indirect effects) [14].

In the context of the textile industry, carbon emissions consist of both direct emissions from textile activities and indirect emissions from the production of related materials, with the latter accounting for approximately 80% of total emissions [15]. Therefore, carbon emissions in the textile industry must consider not only emissions from textile activities but also those from the production of textile materials [16]. Given the currently high level of carbon emissions in the textile industry and the lack of significant technological breakthroughs [17], the innovation spillover effect of environmental regulation within a region is not pronounced [18]. Moreover, stringent environmental regulation in a region can lead to reduced output and increased costs for local textile material manufacturers, thereby increasing demand for textile materials from neighbouring regions [19]. This, in turn, promotes the development of textile material producers in neighbouring regions, particularly those with advanced technologies and broader market coverage. These enterprises can achieve economies of scale, improve production efficiency, and enhance carbon productivity in the textile industry in adjacent areas. Based on this analysis, the following hypothesis is proposed:

H1: Environmental regulation improves carbon productivity in the textile industry in Chinese regions.

The above analysis assumes homogeneity in macroeconomic factors such as economic levels. However, in China, there are significant differences in factor endowments, economic development levels, and geographical locations. Therefore, regional differences cannot be ignored when examining the impact of environmental regulation on carbon productivity in the textile industry. The eastern region, with its concentration of high-tech industries and higher economic development levels, also benefits from advanced technologies in textile-related auxiliary industries and textile material manufacturing [20]. This context is conducive to leveraging the innovation compensation effect of environmental regulation to improve local carbon productivity in the textile industry [21]. In contrast, the central and western regions, despite rapid development in the textile industry, still lag behind the eastern region in terms of economic and technological levels. Strengthening environmental regulation in these regions may inhibit industry expansion and result in significant compliance costs, thereby negatively impacting carbon productivity [22]. Based on these considerations, the following hypothesis is proposed:

H2: The impact of environmental regulation on carbon productivity in the textile industry varies across regions.

Existing studies have shown that the effect of environmental regulation on carbon productivity is also influenced by technological levels. When technological levels are high, environmental regulation can effectively promote innovation spillovers and enhance carbon productivity. In the textile industry, increased mechanisation and automation can improve energy efficiency. Currently, the production technology in China's textile industry is relatively mature. The key to effectively leveraging innovation compensation lies in the accumulation of incremental technological innovations [23]. Therefore, the impact of environmental regulation on carbon productivity in the textile industry is constrained by a technological threshold. Only when the technological level in the textile industry reaches this threshold can environmental regulation effectively promote improvements in carbon productivity. Based on this reasoning, the following hypothesis is proposed:

H3: The technological level in the textile industry acts as a threshold in the relationship between environmental regulation and carbon productivity.

Environmental regulation not only directly affects carbon productivity in the textile industry but also indirectly influences it through various channels. The "Pollution Haven Hypothesis" suggests that developed countries, in pursuit of profit maximisation, tend to shift pollution-intensive industries to developing countries with weaker environmental regulations [24]. Consequently, on one hand, stringent environmental regulation can deter some foreign direct investment (FDI) and increase pollution control costs for foreign enterprises. This may lead to a crowding-out effect on research and development (R&D) and management investments, weakening local firms' ability to absorb management knowledge and advanced technologies from foreign firms and thereby impeding the spillover effects of FDI. On the other hand, strict environmental regulation helps to screen out environmentally friendly firms and prevent the entry of pollution-intensive enterprises, which is conducive to the sustainable development of the textile industry [25]. Thus, environmental regulation can influence carbon productivity in the textile industry through the screening effect of FDI.

Reducing coal consumption and increasing the proportion of clean energy are important pathways to establishing a green production model in the textile industry [26]. The implementation of environmental regulation can encourage firms to reduce their demand for high-carbon energy sources such as coal and oil and increase the use of clean energy sources such as wind, solar, and geothermal energy. This guides firms towards establishing rational energy consumption patterns, which is particularly important for the sustainable development of the textile industry. Therefore, environmental regulation can improve carbon productivity in the textile industry by optimising the energy structure. Based on this analysis, the following hypothesis is proposed:

H4: Environmental regulation improves carbon productivity in the textile industry by increasing foreign direct investment and optimising the energy structure.

The theoretical framework diagram of the research in this paper is shown in figure 1.

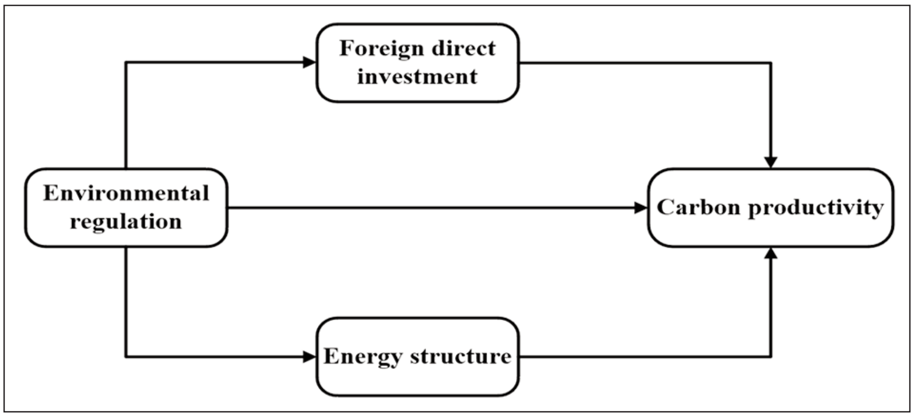

Fig. 1. Theoretical framework diagram

MODEL TEXTILE AND VARIABLE DESIGN

Model textile

Spatial Durbin Model (SDM)

Spatial econometric models mainly include the Spatial Lag Model (SLM), the Spatial Error Model (SEM), and the Spatial Durbin Model (SDM). The SLM and SEM are used to analyse spatial spillover effects on the dependent variable and spatial impacts of error shocks, respectively. The SDM is more general and incorporates both the SLM and SEM. Therefore, this study employs the SDM. The specific form is as follows:

$$\ln CP_{it} = \delta\Sigma_{j=1}^{n} w_{ij} \ln CP_{jt} + \beta \ln ER_{it} + \sigma\Sigma_{j=1}^{n} w_{ij} \ln ER_{jt} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where CP_{it} is an explanatory variable indicating the carbon productivity of the textile industry in province i in year t, ER_{it} is a core explanatory variable indicating the intensity of environmental regulation in province i in year t, w_{ij} is a weight matrix, X_{it} is a control variable, and δ, β, σ and γ are parameters to be estimated.

Threshold effect model

To further examine whether there is a threshold effect on the impact of environmental regulation on carbon productivity in the textile industry, this paper selects environmental regulation and the level of science and technology in the textile industry as the threshold variables, respectively, and analyses them by using a nonlinear panel threshold model, which is set as follows:

$$\ln CP_{it} = \alpha_0 + \alpha_1 \ln ER_{it} \cdot I(\ln T_{it} \le \gamma) + \alpha_2 \ln ER_{it} \cdot I(\ln T_{it} > \gamma) + \beta X_{it} + \mu_i + \varepsilon_{it} \quad (2)$$

where T is the threshold variable, γ – the threshold to be estimated, and $I(\cdot)$ denotes the indicator function.

Mechanism effect model

Meanwhile, in order to measure the indirect effect of environmental regulation on the carbon production efficiency of the textile industry, the following model is constructed.

$$\ln CP_{it} = \delta\Sigma_{j=1}^{n} w_{ij} \ln CP_{jt} + \beta_1 \ln ER_{it} + \beta_2 \ln ER_{it} \times \ln fdi_{it} + \beta_3 \ln ER_{it} \times \ln ener_{it} + \sigma\Sigma_{j=1}^{n} w_{ij} \ln ER_{jt} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

where $\ln ER_{it} \times \ln fdi_{it}$, $\ln ER_{it} \times \ln ener_{it}$ denote the interaction terms of environmental regulation with FDI and energy structure, respectively.

Indicator selection

Carbon productivity

Carbon productivity refers to the economic output generated per unit of carbon emissions, encompassing both economic growth and carbon dioxide emissions [27]. Based on this concept, this study first estimated the carbon emissions of the textile industry and then calculated its carbon productivity.

Existing methods for estimating carbon emissions in the textile industry primarily employ the material balance approach. Li et al. introduced the concept of associated carbon emissions in the textile industry, which includes both direct and indirect emissions [28]. They further specified the scope of carbon dioxide emissions in the textile industry as those directly generated by textile activities and those arising from the production of five major textile materials: steel, aluminium, glass, timber, and cement. Drawing on this approach, this study categorised textile industry carbon emissions into three types: (i) emissions from the consumption of 15 types of fossil fuels, including raw coal, washed coal, crude oil, and gasoline, during the textile process; (ii) emissions from electricity and heat consumption; and (iii) emissions from the production of five major textile materials, including cement and steel. Using the associated carbon emissions method, a model for estimating carbon emissions in the textile industry was established as follows:

$$E = E_1 + E_2 = 12/44 \times \left[\Sigma\alpha_i C_i + \Sigma\beta_i(1 - \delta_i)M_j\right] \quad (4)$$

where E is the total carbon emission from the textile industry, E_1 – the direct carbon emission, E_2 – the indirect carbon emission, and C – the corresponding energy consumption, α – the carbon emission coefficient of the corresponding energy source; M – the material usage, β – the carbon emission coefficient of the textile materials, and δ – the recycling coefficient of the corresponding textile materials. The coefficient 12/44 represents the molecular weight conversion factor from CO_2 to carbon. This conversion is necessary because: Molecular composition: Carbon dioxide (CO_2) has a molecular weight of 44 atomic mass units (carbon = 12, oxygen = 16 × 2 = 32, total = 44), whilst pure carbon has a molecular weight of 12 atomic mass units. Conversion rationale: Energy consumption data and emission coefficients typically measure CO_2 emissions. However, to calculate pure carbon emissions for carbon productivity analysis, the CO_2 values must be converted to their carbon equivalent by multiplying by 12/44 (≈ 0.273).

After estimating the carbon emissions of the textile industry in each province based on equation 4, the carbon productivity of the textile industry was calculated using GDP data adjusted to the base year of 2004. Carbon productivity was defined as the ratio of economic output to carbon emissions.

Environmental regulation intensity. Existing literature has identified three main approaches to measuring environmental regulation intensity: (i) using environmental policies as a proxy; (ii) estimating it based on pollutant emissions; and (iii) measuring it as the proportion of pollution control investment to relevant industrial output [29]. Since environmental policies are not always aligned with the growth of carbon emissions in the textile industry [30], and technological progress is a significant factor in reducing pollutant emissions, emissions data alone cannot accurately reflect the intensity of environmental regulation [31]. Therefore, this study adopted the third approach, measuring environmental regulation intensity as the ratio of pollution control costs to industrial output. Drawing on the method proposed by Azam et al., the study adjusted pollution control costs by the proportion of industrial output in the gross national product and used the adjusted value relative to the proportion of industrial output in the regional gross domestic product as the indicator of environmental regulation intensity [32].

Control variables

Given the multiple factors influencing carbon productivity in the textile industry, this study selected the following control variables based on relevant research: technological level in the textile industry, development level of the textile industry, development level of supporting industries, energy consumption structure of the textile industry, and openness of the textile industry to foreign investment. The technological level in the textile industry, as reflected in its mechanisation and automation, enhances resource utilisation efficiency [33]. In regions with a more developed textile industry, effective market competition promotes the rational allocation of production factors and improves industry productivity. The development of supporting industries, such as surveying and design, encourages the rationalisation of design plans and the adoption of new materials, thereby conserving resources [34]. The energy consumption structure significantly affects energy efficiency, with a higher proportion of primary energy sources, such as coal, reducing overall energy efficiency. Foreign investment in developing countries can introduce advanced management practices and technologies, generating demonstration and spillover effects that enhance domestic production efficiency.

The raw data used in this study were sourced from the *China Textile Industry Statistical Yearbook*, *China Energy Statistical Yearbook*, and *China Statistical Yearbook*. Due to significant data gaps for Tibet and the Hong Kong, Macao, and Taiwan regions, these areas were excluded from the analysis. Descriptive statistics for the variables are presented in table 1.

Table 1

STATISTICAL DESCRIPTION OF VARIABLES

Variable name	Variable explanation	Mean	SD	Min	Max
Carbon productivity in textile (CP)	Gross National Product/Carbon Emissions from textiles	4.215	2.103	0.850	9.880
Intensity of environmental regulation (ER)	Industrial Pollution Control Costs/Industrial Output Value	1.851	0.920	0.210	4.501
Level of technology in the textile industry (TL)	Technical equipment rate of the textile industry	8.450	3.200	2.100	18.500
Degree of development of the textile industry (CD)	Gross output value of the textile industry/Gross national economic output value	4.250	2.850	0.150	12.500
Degree of development of the ancillary Industries (AD)	Number of employees in the survey and design/Number of employees in the textile industry	2.150	1.120	0.350	5.200
Structure of energy consumption in the textile industry (EC)	Coal consumption converted to standard coal in the textile industry/Energy consumption in the textile industry	52.340	14.800	18.200	85.500
Level of opening up of the textile industry to the outside world (OL)	Gross output value of foreign investment in the textile industry/GDP of the textile industry	0.420	0.310	0.010	1.850

EMPIRICAL ANALYSIS

Spatial econometric estimation results and analysis

Before conducting a spatial econometric analysis, it is necessary to examine the spatial correlation in carbon productivity in the textile industry. This study employed Moran's I index to assess spatial autocorrelation using three matrices: an adjacency matrix, a distance matrix, and a spatial weights matrix. The results of Moran's I index were consistent across all three matrices. Therefore, only the results based on the adjacency matrix are presented in this study, as shown in table 2. The Moran's I index for carbon productivity in the textile industry from 2004 to 2022 was greater than zero and statistically significant, indicating positive spatial correlation. This result confirms that carbon productivity in the textile industry exhibits spatial dependence, justifying the use of spatial econometric models for further analysis.

Full sample estimation. In accordance with the selection rules for spatial econometric models, the study first conducted Lagrange Multiplier (LM) and robustness tests. When the LM-lag test was significant compared to the LM-error test, and the robust LM-lag test was significant while the robust LM-error test was not, the Spatial Autoregressive (SAR) model was preferred. Conversely, the Spatial Error Model (SEM) was selected if the LM-error test was more significant. The Spatial Durbin Model (SDM) was chosen based on further Wald and Likelihood Ratio (LR) tests to determine the final model. The Hausman test yielded a Z-value of 51.39 (P=0.000), significantly rejecting the null hypothesis and indicating the use of a fixed-effects model. Subsequent Wald and LR tests (P=0.006) rejected the null hypotheses of degeneration into SAR or SEM models, supporting the selection of the SDM model. To mitigate potential heteroscedasticity, all variables were transformed using logarithms. For statistical variables expressed in current prices, adjustments were made based on corresponding price indices. Given that ordinary least squares estimation in the SDM model may produce biased results, this study employed maximum likelihood estimation.

The estimation results in table 3 indicate the following: (1) Environmental regulation intensity passed the 5% significance test, showing a positive effect on the carbon productivity of the textile industry in adjacent regions but a negative effect in the local region, highlighting the prominence of compliance costs. Overall, environmental regulation contributed to the improvement of carbon productivity in China's textile industry to some extent. (2) The technological level of the textile industry had a positive effect on carbon productivity in both local and adjacent regions at the 1% significance level, confirming its importance in enhancing carbon productivity. (3) The energy consumption structure of the textile industry had significant positive direct and indirect effects on carbon productivity, indicating that a clean energy-oriented consumption pattern is a key factor in improving carbon productivity. Environmental regulation has effectively promoted

Table 2

MORAN'S I INDEX FOR CARBON PRODUCTIVITY IN THE TEXTILE INDUSTRY, 2004–2022

Index	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
I-value	0.321	0.345	0.378	0.364	0.346	0.333	0.320	0.317	0.346	0.355
P-value	0.002	0.001	0.000	0.001	0.000	0.004	0.001	0.002	0.001	0.008
Index	2014	2015	2016	2017	2018	2019	2020	2021	2022	-
I-value	0.358	0.352	0.363	0.365	0.371	0.378	0.382	0.390	0.388	-
P-value	0.001	0.005	0.001	0.000	0.002	0.001	0.000	0.001	0.004	-

Table 3

ESTIMATED RESULTS OF THE SAMPLE SPATIAL MEASUREMENT MODEL

Explanatory variable	Direct effect		Indirect effect		Total effect	
	Estimated value	Z value	Estimated value	Z value	Estimated value	Z value
ER	–0.021**	–1.979	0.045**	–2.105	0.024**	–2.178
TL	0.205***	3.120	0.337***	3.672	0.542***	3.594
CD	–0.222	–1.447	–0.175	–1.234	–0.397	–1.149
AD	0.529***	3.122	0.569***	3.455	1.099***	3.566
EC	0.044**	2.096	0.128**	2.001	0.172**	1.980
OL	0.005	0.878	–0.038	–1.234	–0.034	–1.143
R^2	0.567					
logL	167.789					

Note: The superscripts ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively. The same applies to the following tables.

carbon emission reductions through the low-carbon transformation of the energy consumption structure. The negative indirect effect of the energy consumption structure, which did not pass the significance test, suggests that its spillover effect on carbon productivity in the textile industry is not significant. (4) The development level of the textile industry had a positive effect at the 1% significance level, indicating that higher industry development levels enhance carbon productivity in the textile industry and drive improvements in adjacent regions. (5) The development level of supporting industries had positive direct and indirect effects at the 5% significance level, suggesting that rationalised surveying and design practices effectively reduce resource wastage and improve carbon productivity in the textile industry. (6) The openness of the textile industry to foreign investment had no significant effect on carbon productivity in China's textile industry and did not pass the significance test. This result is attributed to the continuous improvement of domestic textile technology and management practices, which have diminished the impact of foreign investment on the industry. Hypothesis 1 was thus validated.

Regional spatial econometric model estimation. To mitigate the impact of regional spatial development imbalances and reveal the regional characteristics of the effect of environmental regulation on carbon productivity in the textile industry, this study divided the 30 provinces into eastern, central, and western regions [35]. The estimation results are presented in table 4. As shown in table 4, in the eastern region, the direct and indirect effects of environmental regulation intensity on carbon productivity in the textile industry were positive. In contrast, in the central and western regions, the direct effects of environmental regulation intensity were negative, while the indirect effects were opposite, with a positive effect in the central region and a negative effect in the western region. This finding confirms the theoretical analysis that the impact of environmental regulation on carbon productivity in the textile industry exhibits regional heterogeneity. Regarding the control variables, the technological level of the textile industry, the development level of the textile industry, and the development level of supporting industries had positive direct and indirect effects on carbon productivity across all regions. Meanwhile, the energy consumption structure had negative direct and indirect effects on carbon productivity in all regions, consistent with the overall sample estimation results. The openness of the textile industry to foreign investment had negative direct and indirect effects on carbon productivity in the eastern and central regions, but did not pass the significance test. In the western region, however, the openness of the textile industry had positive direct and indirect effects on carbon productivity. This is primarily because the textile industry in the western region is relatively underdeveloped, and foreign investment in the textile sector can generate demonstration effects that enhance domestic productivity and improve carbon productivity. Hypothesis 2 was thus validated.

Threshold effect regression results and analysis

The empirical analysis in the preceding section primarily examined the impact of explanatory variables on carbon productivity in the textile industry. Subsequently, this study further investigated whether environmental regulation has a threshold effect on carbon productivity in the textile industry by separately selecting the intensity of environmental regulation and the technological level of the textile industry as threshold variables. Before the threshold effect analysis, it was necessary to examine the corresponding number and values of thresholds for the

Table 4

REGIONAL SPATIAL ECONOMETRIC MODEL ESTIMATION RESULTS

Explanatory variable	Eastern			Central			Western		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
ER	0.023** (2.110)	0.039** (2.223)	0.062*** (3.078)	–0.039*** (–3.444)	0.091*** (3.879)	0.052* (1.782)	–0.041** (–2.101)	–0.198** (–2.326)	–0.239*** (–3.227)
TL	0.044*** (2.789)	0.118** (2.117)	0.162*** (3.332)	0.210 (1.270)	0.456** (2.054)	0.666*** (3.468)	0.037 (1.112)	0.151* (1.876)	0.188** (2.325)
CD	–0.218** (–2.102)	–0.276** (–2.054)	–0.494*** (–3.487)	–0.350** (–2.110)	–0.912* (–1.875)	–1.263*** (–3.565)	–0.051*** (–3.780)	–0.049 (–1.291)	–0.101** (–2.222)
AD	0.665* (1.770)	0.541** (2.183)	1.206*** (3.399)	1.048* (1.823)	1.110 (1.308)	2.158** (2.055)	1.032** (2.118)	0.611** (2.355)	1.643*** (3.448)
EC	0.004*** (2.987)	0.039** (2.116)	0.043*** (3.119)	0.002 (1.083)	0.009* (1.778)	0.011** (2.234)	0.156** (2.158)	0.006* (1.766)	0.162** (2.085)
OL	–0.014** (–1.988)	–0.114** (–2.221)	–0. 128*** (–3.356)	–0.015** (–2.067)	–0.056** (–2.011)	–0.071** (–2.232)	0.018* (1.870)	0.033** (2.039)	0.051*** (3.867)
R^2	0.763			0.509			0.688		
logL	123.782			56.905			85.149		

threshold variables. Table 5 presents the threshold values for the intensity of environmental regulation and the technological level of the textile industry obtained using the BS bootstrap sampling method. The results indicate that the threshold tests for the intensity of environmental regulation were not significant. That is, when the intensity of environmental regulation is used as a threshold variable, there is no significant threshold effect between environmental regulation and carbon productivity in the textile industry. This suggests that, at present, environmental regulation still has considerable potential to enhance carbon productivity in the textile industry. In contrast, the F-statistic for the single threshold of the technological level of the textile industry passed the 1% significance test, while the double and triple thresholds were not significant. Therefore, when the technological level of the textile industry is used as a threshold variable, a single threshold effect exists in the relationship between environmental regulation and carbon productivity.

Based on the threshold effect tests described above, this study employed a single-threshold panel model with the technological level of the textile industry as the threshold variable. The estimation results are presented in table 6. The results show that when the technological level of the textile industry is used as a threshold variable, the impact of environmental regulation on carbon productivity in the textile industry exhibits a V-shaped pattern. Specifically, when the technological level of the textile industry exceeds the threshold value, environmental regulation has a positive effect on improving carbon productivity. Conversely, when the technological level is below the threshold value, environmental regulation inhibits the improvement of carbon productivity. This indicates that in the textile industry, the innovation compensation effect of environmental regulation can only be effectively realised when the technological level reaches a certain standard. This effect not only offsets the compliance costs incurred by enterprises but also enhances carbon productivity. Further, based on the threshold value, the sample was divided into two groups: provinces with relatively high and relatively low technological levels in the textile industry, as shown in table 6. Provinces with technological levels below the threshold value have relatively low technological capabilities in the textile industry, which are not conducive to the realisation of innovation compensation effects. As a result, environmental regulation cannot effectively promote improvements in carbon productivity. Hypothesis 3 was thus validated.

Mechanism regression tests

To further investigate the indirect effects of heterogeneous environmental regulation on carbon productivity in the textile industry, interaction terms between environmental regulation and various mediating variables were introduced. The results are presented in table 7.

The interaction term between environmental regulation and foreign direct investment (ER×FDI) was positive, indicating that environmental regulation can exert a screening effect through foreign direct investment by attracting clean and environmentally friendly

Table 5

THRESHOLD EFFECT TESTS

Threshold variable	Number of thresholds	Threshold value	F value	P value	BS times	Threshold value		
						10%	5%	1%
Intensity of environmental regulation	Single threshold	0.456	2.982	0.672	500	8.234	10.789	15.110
	Double threshold	0.411 0.456	4.110	0.588	500	11.345	10.789	15.110
	Triple threshold	2.980	12.255	0.387	500	10.882	16.587	27.145
Level of science and technology	Single threshold	2.455***	29.107	0.000	500	18.565	22.909	29.816
	Double threshold	2.619 3.011	18.998	0.333	500	17.448	21.785	28.222
	Triple threshold	2.989	7.374	0.456	500	31.204	40.666	59.188

Table 6

SAMPLE GROUPING RESULTS OF TEXTILE INDUSTRY TECHNOLOGY LEVEL THRESHOLDS

Threshold variable	Threshold value	Coefficient	Equivalent provinces
Level of technology in the textile industry	TL≤2.455	–0.275**	Hebei, Liaoning, Anhui, Fujian, Jiangsu, Zhejiang Jiang, Jiangxi, Shandong, Henan, Hubei, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Shanxi, Ningxia
	TL>2.455	0.467***	Beijing, Tianjin, Shanghai, Inner Mongolia, Jilin, Heilongjiang, Hunan, Guangdong, Qinghai

Table 7

ESTIMATION RESULTS OF THE INDIRECT EFFECTS OF ENVIRONMENTAL REGULATION ON CARBON PRODUCTIVITY IN THE TEXTILE INDUSTRY						
Explanatory variable	**Direct effect**	**Indirect effect**	**Total effect**	**Direct effect**	**Indirect effect**	**Total effect**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
ER	0.002* (1.786)	0.011*** (3.283)	0.073** (2.190)	0.023** (2.110)	0.039** (2.223)	0.062*** (3.078)
ER×FDI	0.111* (1.877)	0.203** (2.122)	0.128*** (3.589)	0.178** (2.113)	0.211** (2.089)	0.389*** (3.025)
ER×ENER	0.088* (1.783)	0.030** (2.29)	0.128*** (3.766)	0.110* (1.879)	0.166 (1.234)	0.276** (2.117)
TL	-	-	-	0.056** (2.111)	0.110* (1.887)	0.166*** (3.155)
CD	-	-	-	–0.134* (–1.812)	–0.211** (–2.149)	–0.345** (–2.147)
AD	-	-	-	0.459* (1.825)	0.446 (1.218)	0.905 (1.399)
EC	-	-	-	0.014*** (3.015)	0.023* (1.719)	0.037*** (3.230)
OL	-	-	-	–0.022* (–1.780)	–0.099** (–2.115)	–0. 120*** (–3.226)
R^2	0.673			0.666		
logL	123.45			110.255		

enterprises, thereby accelerating the green development of the textile industry. From the perspective of environmental regulation, this finding may be attributed to the fact that China's market mechanisms are not yet fully developed, necessitating the implementation of effective market incentive policies [36].

The interaction term between environmental regulation and energy structure (ER×ENER) was also positive, suggesting that environmental regulation can enhance carbon productivity in the textile industry by promoting the use of clean energy through the optimisation of the energy structure. From the perspective of environmental regulation, this outcome may be primarily driven by policy requirements and market guidance, with minimal influence from public preferences [37]. Hypothesis 4 was thus validated.

CONCLUSIONS AND POLICY IMPLICATIONS

This study estimated the direct and indirect effects of environmental regulation on carbon productivity in the textile industry at both the national and regional levels, based on provincial panel data from 2004 to 2022. Using spatial panel Durbin models and threshold panel models, the study also explored the threshold variables and values influencing the relationship between environmental regulation and carbon productivity in the textile industry. The results demonstrate the following:

(1) At the national level, environmental regulation has an overall positive effect on improving carbon productivity in China's textile industry. However, the local effect and spatial spillover effect differ significantly. While local environmental regulation has a significant positive spatial spillover effect on the carbon productivity of adjacent regions, its impact within the local region is less pronounced due to the compliance costs incurred by enterprises. Additionally, technological level, development level of the textile industry, and the development level of supporting industries positively influence carbon productivity. In contrast, a coal-dominated energy consumption structure hampers improvements in carbon productivity.

(2) Regionally, environmental regulation in the eastern and central regions has a more pronounced positive effect on carbon productivity in the textile industry. In contrast, environmental regulation in the western region inhibits improvements in carbon productivity. Significant differences exist in the local and spatial spillover effects of environmental regulation across regions. In the eastern region, both local and spatial spillover effects are positive, while in the central and western regions, the local effects are negative. The spatial spillover effects are opposite, with a positive effect in the central region and a negative effect in the western region. However, increased openness to foreign investment in the textile industry can promote improvements in carbon productivity in the western region.

(3) Regarding threshold effects, no significant nonlinear threshold relationship was found between environmental regulation and carbon productivity when environmental regulation intensity was used as the threshold variable. However, when the technological level of the textile industry was used as the threshold variable, a single V-shaped threshold effect was observed. That is, when the technological level exceeds the threshold value, the innovation spillover

effect of environmental regulation can offset the negative impact of compliance costs and enhance carbon productivity. Two-thirds of the provinces did not meet the technological threshold value, indicating substantial room for improvement in the technological level of the textile industry.

(4) Environmental regulation can improve carbon productivity in the textile industry through foreign direct investment and the optimisation of the energy structure.

The conclusions of this study offer the following policy implications:

- First, further promotion of the development and implementation of environmental regulation policies, particularly those related to the textile industry, is necessary to enhance the overall level of carbon productivity nationwide. Strengthening inter-regional coordination in the implementation of environmental regulations can prevent local textile industries in regions with stricter regulations from losing opportunities due to avoidance behaviours related to investment activities. This approach also protects the enthusiasm of local governments in implementing energy-saving and emission-reduction measures.
- Second, considering the varying development needs of the textile industry and environmental urgency across regions, region-specific measures should be adopted to balance ecological protection and economic development. The eastern region should focus on the scientific formulation and effective implementation of textile industry environmental regulations. In contrast, the central and western regions should prioritise improving the development level of the textile industry while gradually implementing environmental regulations.

  Encouraging foreign textile enterprises and high-tech textile firms from the eastern region to invest in the western region can enhance carbon productivity in the textile industry through technology spillovers and demonstration effects.
- Third, aligning environmental regulation with the technological level of the textile industry is essential to fully leverage the innovation compensation effect of environmental regulation. The improvement in carbon productivity driven by innovation compensation aligns with China's requirements for high-quality and regional innovative development. Therefore, in addition to implementing reasonable environmental regulation measures, regions should continuously enhance the technological level of the textile industry, especially in provinces that have not yet reached the threshold value. Optimising the energy consumption structure of the textile industry and related sectors, reducing the use of inefficient energy sources such as coal, and increasing the proportion of green energy consumption are also critical steps.

RESEARCH LIMITATIONS AND FUTURE RESEARCH PROSPECTS

Research limitations

Although this study utilised comprehensive provincial panel data spanning from 2004 to 2022, several data limitations were encountered. Firstly, the provincial-level aggregated data may have masked firm-level heterogeneous responses and variations in carbon productivity performance. Secondly, whilst the temporal scope was substantial, it may not have fully captured the long-term dynamic effects of environmental regulations.

The study employed spatial econometric and threshold regression techniques; however, certain methodological constraints remained. The construction of the spatial weight matrix was based on geographical proximity, which may not have comprehensively reflected the complex economic linkages between provinces. The threshold identification method assumed that threshold effects remained consistent across all provinces and time periods, potentially overlooking temporal variations and inter-provincial heterogeneity.

Future research prospects

Future research should extend to firm-level data to analyse the heterogeneous responses of different types of textile enterprises to environmental regulations, thereby providing a foundation for precise policy design.

The analytical framework should be expanded to include other major textile-producing countries, such as India, Bangladesh, Vietnam, and Turkey, to enhance the generalisability of the research findings. The effectiveness of different regulatory instruments (command-and-control versus market-based mechanisms) should be investigated, exploring the optimal design of policy combinations including carbon pricing, environmental taxes, and emissions trading systems.

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Weaving the green thread: configurational drivers of sustainable transformation in the textile industry

DOI: 10.35530/IT.077.01.202576

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ABSTRACT – REZUMAT

Weaving the green thread: configurational drivers of sustainable transformation in the textile industry

Green transformation is a critical strategy for promoting sustainable development in the textile industry. Drawing on the TOE framework, we construct a theoretical model encompassing technological, organisational, and environmental dimensions. Using panel data from Chinese textile enterprises spanning 2016 to 2024, we apply a combination of dynamic Qualitative Comparative Analysis (QCA), Necessary Condition Analysis (NCA), one-way ANOVA, and the Kruskal–Wallis rank-sum test to explore configurational pathways influencing green transformation. The findings reveal that no single factor constitutes a necessary condition for high-level green transformation. However, the necessity of digital transformation and government subsidies has shown a rising trend. Three distinct pathways are identified that facilitate green transformation: technology–environment driven, technology–organisation driven, and hybrid multi-factor driven. Inter-group analysis indicates that the consistency scores of these configurations declined collectively in 2020, followed by a rebound from 2021 onward, with the hybrid pathway demonstrating the greatest stability and effectiveness. Intra-group analysis suggests that the effectiveness of each configuration varies depending on enterprise size. Our study demonstrates that the green transformation of textile enterprises is not the result of a single driving force but emerges from the interplay of multiple factors, offering practical insights for firms pursuing green innovation.

Keywords: *textile industry, green transformation, TOE framework, dynamic QCA*

Conturând dimensiunea ecologică: factori de configurare ai transformării durabile în industria textilă

Transformarea ecologică este o strategie esențială pentru promovarea dezvoltării durabile în industria textilă. Pe baza cadrului TOE, construim un model teoretic care cuprinde dimensiuni tehnologice, organizaționale și de mediu. Folosind date panel de la întreprinderi textile chineze din perioada 2016-2024, aplicăm o combinație de analiză comparativă calitativă dinamică (QCA), analiză a condițiilor necesare (NCA), ANOVA unidirecțională și testul Kruskal-Wallis pentru a explora căile configuraționale care influențează transformarea ecologică. Rezultatele arată că niciun factor singular nu constituie o condiție necesară pentru o transformare ecologică la nivel înalt. Cu toate acestea, necesitatea transformării digitale și a subvențiilor guvernamentale a înregistrat o tendință ascendentă. Sunt identificate trei căi distincte care facilitează transformarea ecologică: bazată pe tehnologie-mediu, bazată pe tehnologie-organizație și bazată pe factori multipli hibrizi. Analiza intragrup indică faptul că scorurile de coerență ale acestor configurații au scăzut colectiv în 2020, urmate de o revenire începând cu 2021, calea hibridă demonstrând cea mai mare stabilitate și eficacitate. Analiza intragrup sugerează că eficacitatea fiecărei configurații variază în funcție de dimensiunea întreprinderii. Studiul nostru demonstrează că transformarea ecologică a întreprinderilor textile nu este rezultatul unei forțe singulare, ci rezultă din interacțiunea mai multor factori determinanți, oferind perspective practice pentru firmele care urmăresc inovarea ecologică.

Cuvinte-cheie: *industria textilă, transformare ecologică, cadru TOE, QCA dinamic*

INTRODUCTION

As one of the world's oldest industries [1], the textile sector plays a vital role in many developing countries by generating substantial employment and enhancing women's economic status and social participation [2]. However, the rise of fast fashion and its demand for low-cost textiles has led to intensified fabric consumption and shortened garment life cycles, resulting in numerous environmental challenges, including greenhouse gas emissions, global warming, and air pollution [3]. According to the International Energy Agency (IEA), the textile and apparel industry accounts for approximately 10% of global carbon emissions, making it the second-largest industrial polluter after the petroleum sector. Producing one ton of textiles results in nearly 200 tons of wastewater, while each kilogram of fabric emits around 23 kilograms of carbon dioxide. Some studies predict that, with the global population expected to reach 8.5 billion by 2030, the clothing industry may overtake petrochemicals as the world's largest polluter. In the current global movement toward harmony between humans and nature, addressing the environmental and health challenges posed by the textile industry has become a core agenda of sustainable development [4].

Green transformation is widely regarded as a key pathway for achieving sustainable development in the textile sector, as it enhances resource efficiency and significantly reduces pollutant emissions [5, 6]. However, due to its public-good nature and generally low financial returns, firms often lack adequate incentives to invest in green initiatives [7]. In response, researchers have increasingly sought to identify the driving forces behind green transformation [8, 9]. From a technological perspective, digital technologies provide promising avenues by optimising resource allocation, facilitating knowledge sharing, and supporting innovation to address environmental challenges [10]. Nevertheless, the widespread application of digital tools may lead to increased energy consumption, which could undermine their intended environmental benefits [11]. On the environmental front, regions with stricter regulatory standards tend to experience lower levels of pollution [12]. When formal environmental regulations prove ineffective in certain areas, informal mechanisms based on public environmental awareness can serve as valuable supplements to compensate for regulatory gaps [13].

Although existing studies have provided valuable insights into the green transformation of the textile industry, a core question remains insufficiently addressed: why do the same influencing factors result in markedly different transformation outcomes across enterprises or contexts? This issue partly arises from the methodological limitations of conventional research approaches. Most prior studies rely on linear regression and other traditional quantitative techniques that focus on identifying the "net effect" of individual variables, which refers to the marginal contribution of a single variable while controlling for the influence of others. However, these approaches are based on several assumptions, including the independence of variables, the symmetry of causal relationships, and the constancy of marginal effects. In complex management environments, such assumptions are often unrealistic [14].

In practice, green transformation is a complex process influenced by the dynamic interaction of multiple conditions, which may exhibit complementarity, substitutability, or even mutual inhibition [15]. Qualitative Comparative Analysis (QCA), rooted in set theory, provides a powerful framework for analysing such complexity. It takes a holistic and configurational perspective, viewing each case as a set of interrelated conditions, and systematically compares different combinations across cases to identify multiple causal pathways that lead to a common outcome [16]. Unlike traditional methods that assume variable independence, QCA emphasises the interdependence among factors and the logic of configurations. This makes it particularly effective in explaining why distinct pathways may produce the same result, or why a single pathway might lead to different outcomes depending on the context [14, 17].

China presents an ideal empirical setting for investigating the green transformation of the textile industry. On one hand, as the world's largest producer, consumer, and exporter of textiles and garments, China plays a pivotal role in the global textile value chain [18]. According to data from the China National Textile and Apparel Council (CNTAC) and related institutions, the textile and apparel sector emits approximately 230 million tons of greenhouse gases each year, accounting for about 2 per cent of the country's total emissions. The industry has long been under substantial pressure to improve energy efficiency and reduce pollution, which has generated strong internal momentum for green transformation. On the other hand, the industry has recently been shaped by increasingly stringent environmental regulations and policies promoting industrial restructuring. Since China's official announcement of its "carbon peak and carbon neutrality" goals at the 75th United Nations General Assembly in September 2020, targeting peak carbon dioxide emissions by 2030 and carbon neutrality by 2060, the textile industry, as a high-emission sector, has become a priority in national policy efforts toward green upgrading.

For instance, the "14th Five-Year Plan for the Development of the Textile Industry", released in June 2021, explicitly called for substantial progress in energy conservation, cleaner production, and resource recycling, and elevated green development to a strategic level for the sector.

This study makes several contributions. First, it enriches the understanding of green transformation pathways. Previous studies have mainly relied on traditional statistical models to examine the impact of single factors on green transformation [12, 19], while paying limited attention to how different factors interact or substitute for each other under specific conditions to influence corporate green innovation. Drawing on configuration theory [20], this study integrates the Technology–Organisation–Environment (TOE) framework and finds that the green transformation of textile firms is not driven by any single factor, but instead results from the synergistic interaction of multiple conditions. This insight offers managers a new theoretical lens for understanding the complex mechanisms that drive green transition and responds to recent calls in the literature to explore the coupling of ecological elements [20, 21]. Second, by applying one-way analysis of variance and the Kruskal–Wallis rank-sum test, we identify the heterogeneous effects of different configurational paths on green transformation. Our findings emphasise the importance of selecting adaptive, multi-factor strategies based on a firm's stage of development in order to enhance the feasibility and effectiveness of green transformation.

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

TOE Framework

The TOE (Technology–Organisation–Environment) framework was first proposed by Tornatzky and Fleischer in 1990 [22]. This analytical framework focuses on the factors influencing technological application conditions from three levels: technology, organisation, and environment. It is essentially a comprehensive analytical framework used to explain organisational behaviour related to technological integration and adoption. The technological dimension often includes factors such as the level of informatisation, technological innovation capability, and technological integration capability [23]. The organisational dimension commonly covers factors such as executive tenure, executive background, organisational climate, and organisational slack [24]. The environmental dimension generally includes factors such as market competition, policy changes, and external pressures [25]. As the TOE framework has been continuously applied, its connotations, subdimensions, and application scenarios have been constantly adjusted and refined. Based on its application in technological innovation research, it has now been extended to various fields such as education, e-government, healthcare, and post-pandemic organisational governance [26].

We choose the TOE framework for two reasons: first, according to the existing literature, the influencing factors of green transformation mostly fall within the dimensions of technology, organisation, and environment. Using the TOE framework facilitates the integrated analysis of existing factors. Second, the TOE framework is a highly generalizable theoretical model that can be further refined according to specific research questions and contexts. It has strong flexibility, operability, and broad applicability.

TOE Framework for Construction Green Innovation

(1) Technological conditions

This dimension includes digital transformation and investment in R&D personnel. The widespread application of digital technologies provides crucial support for textile enterprises undergoing green transformation. Specifically, tools such as big data, cloud computing, and the Internet of Things enable precise management of energy, water, and raw materials, which enhances resource efficiency and reduces environmental burdens. In addition, digitalisation improves firms' access to external information on markets, policies, and technologies, thereby strengthening their ability to acquire and apply green production knowledge and reducing uncertainty and cost during the transition [27]. Investment in R&D personnel reflects a firm's technical capacity in developing green technologies and designing environmentally friendly products. According to endogenous growth theory, R&D is a critical driver of sustained innovation and technological progress. In the textile industry, technical staff engaged in R&D often focus on energy conservation, pollution control, and sustainable materials, providing practical green solutions. Higher R&D input is associated with greater progress in green transformation and improved market competitiveness alongside reduced environmental risk.

(2) Organisational conditions

This dimension includes organisational slack and the environmental awareness of top executives.

Organisational slack functions as a resource buffer that enables firms to absorb the costs of green transformation. When facing policy pressure or market uncertainty, companies with available slack are more capable of allocating resources to green R&D, cleaner production, and sustainable product development, thereby enhancing the feasibility and stability of transformation [28]. Nevertheless, excessive slack may lead to inefficiencies, resource misallocation, or even path dependence on high-emission practices, which can undermine responsiveness to environmental challenges and hinder progress [29, 30]. The environmental awareness of executives plays a vital role in guiding strategic decisions related to green transformation. Since this process often requires major strategic shifts and resource realignment, strong support from top management is essential for successful implementation [31]. In the textile sector, environmentally conscious leaders are more inclined to adopt green strategies such as energy reduction, material substitution, and eco-certification, thereby enhancing firms' initiative and execution capacity in green practices [32].

(3) Environmental conditions

This dimension includes market competition and perceived government support. Market competition significantly shapes firms' green strategies. In highly competitive markets, firms may prioritise short-term profit and defer green investment due to intense cost pressures [33]. Conversely, moderate competition can motivate firms to pursue green innovation as a means of differentiation, strengthening their competitive advantage in emerging green markets [34]. Perceived government support refers to firms' awareness of external policy incentives. Given the high upfront costs and uncertainty associated with green transformation in the textile industry [11], firms' perception of stable policy support, such as subsidies, green credit, and tax incentives, can significantly influence their willingness to invest. Nevertheless, some scholars argue that government subsidies may alter firms' innovation behaviour. When innovation costs remain constant, firms may reduce their own investment in R&D, suggesting that subsidies could potentially suppress rather than promote innovation [35].

In conclusion, the TOE framework identifies six key sub-dimensions that influence green transformation in the textile industry. These technological, organisational, and environmental factors do not operate in isolation but interact dynamically as part of a configurational system. To better understand these interdependencies, this study employs a dynamic QCA approach to examine complementary and substitutive relationships across dimensions and to identify distinct configurational pathways that drive green transformation. The overall research framework is presented in figure 1.

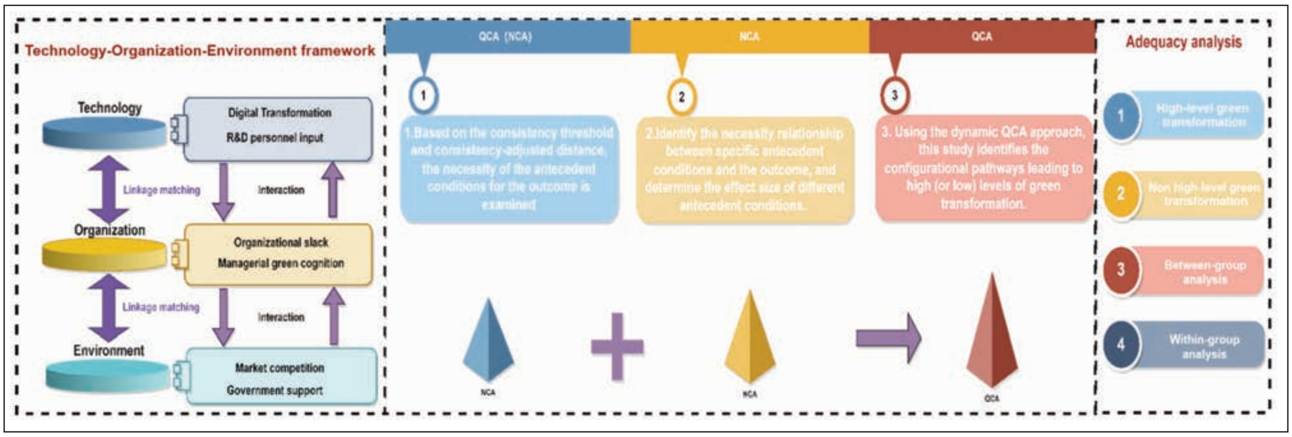

Fig. 1. Theoretical framework

RESEARCH DESIGN

To systematically explore the multiple pathways of green transformation in Chinese textile enterprises, we adopted a two-stage research paradigm integrating Dynamic Qualitative Comparative Analysis (Dynamic QCA) and Necessary Condition Analysis (NCA). This combination of methods allows for a comprehensive and in-depth revelation of complex causal relationships from both sufficiency and necessity perspectives.

Dynamic Qualitative Comparative Analysis (QCA)

Qualitative Comparative Analysis (QCA) is a set-theoretic and Boolean algebra-based configurational method. Its core advantage lies in its ability to identify how multiple antecedent conditions combine to lead to a certain outcome, rather than examining the net effect of individual variables in isolation. However, traditional QCA typically performs static analysis at a single time point, a method with clear limitations when analysing certain industries.

For China's textile industry, the policy environment, market demand, and technological conditions it faces are in continuous flux. For instance, in recent years, the state has successively introduced policies such as "carbon peaking" and "carbon neutrality" targets, the "14th Five-Year Green Development Plan", and "pollution prevention and control battles", guiding enterprises to accelerate their transformation towards low-carbon, efficient, and intelligent operations. This policy orientation not only drives continuous adjustments in corporate strategies but also leads to green practices exhibiting phased characteristics across different periods. Furthermore, the rapid evolution and replacement of digitalisation and green technologies further shorten enterprises' adaptation cycles. Enterprises often need to complete the leap from basic environmental compliance to systematic green innovation within a few years. Therefore, the green transformation of the textile industry is not a one-time, static event, but rather a long-term, cumulative, and phased dynamic process.

Specifically, concerning the result variable defined in this study – "green transformation" – its evolutionary trajectory encompasses multiple levels, from preliminary compliance-based pollution control, gradually progressing to cleaner production, resource recycling, and then establishing a green innovation system. This inherently represents a long-term, cumulative, and phased dynamic process, not a static, singular event. In this process, the combinations of driving conditions required at different stages may differ fundamentally. For example, early transformation might be more influenced by government subsidies and policy pressure, whereas later stages may rely more on internal technical capabilities, organisational slack, and green culture. Static QCA overlooks this longitudinal causal evolution and struggles to reveal the driving logic of enterprise green transformation pathways as they change over time.

Moreover, the sudden COVID-19 pandemic in 2020, as a significant environmental shock, also had a nonlinear impact on corporate green practices. Some enterprises faced resource constraints during the pandemic, temporarily reducing green investments, while others seized the opportunity to accelerate their green transformation initiatives. Such episodic and discontinuous event characteristics cannot be fully identified through static QCA.

Consequently, a static analysis at an isolated time point fails to capture the macro-level dynamics of the textile industry, nor can it reveal the staged characteristics and the evolution of driving factors inherent to the "green transformation" process itself. To address this, our study employs Dynamic QCA, as proposed by Garcia-Castro and Ariño (2016) [36], which, through its cross-period analytical capabilities, accurately characterises the true trajectory of enterprise green transformation. This method treats each enterprise's observations across multiple years as independent cases, thereby introducing the time dimension. It systematically examines the influence of different condition combinations on the outcome variable at various time points, and further analyses the consistency, stability, and trend changes of configurational pathways over time. This approach thus extends beyond the explanatory boundaries of static configurational methods and aligns more closely with the dynamic nature of green transformation.

The technical implementation of Dynamic QCA in this study followed these steps: 1. Data Reorganisation and Calibration: We first organised the panel data from 2016 to 2024. In the R language environment, we used "enterprise-year" as the unit of analysis, converting the condition and outcome values of each enterprise in each year into fuzzy set membership scores (between 0 and 1) to construct the QCA truth table format. 2. Configuration Solving and ESA Method: When solving configurations, we adopted Enhanced Standard Analysis (ESA). ESA is an improved version of QCA standard analysis that produces more robust and credible parsimonious and intermediate solutions by excluding logically contradictory "logical remainders" during the Boolean minimisation process. This ensures the logical rigour of the causal paths we identify. 3. Dynamic Evaluation: We used R packages such as QCA and SetMethods to perform configurational analysis for each annual time slice separately, and calculated the consistency adjustment distance between groups and within groups. This enables us to quantify whether the explanatory power of a specific path changes significantly over time or with enterprise size, thereby capturing the dynamic mechanisms driving green transformation.

It is worth noting that, unlike traditional QCA, Dynamic QCA requires measuring consistency from three dimensions: between-group, within-group, and overall, and captures the trend of consistency changing with time and cases through consistency adjustment distance. Specifically, when analysing with the R language, the system defaults to outputting consistency Euclidean distance, which must be converted into consistency adjustment distance using the following formulas:

$$\textit{BECONS adjusted distance} = \frac{\textit{BECONS distance}}{\sqrt{\dfrac{n}{n^2 + 3n + 2}}} \quad (1)$$

$$\textit{WICONS adjusted distance} = \frac{\textit{WICONS distance}}{\sqrt{\dfrac{n}{n^2 + 3n + 2}}} \quad (2)$$

where n in formula 1 represents time (9 in this study), used to calculate BECONS adjusted distance; n in formula 2 represents cases (51 in this study), used to calculate WICONS adjusted distance.

Necessary Condition Analysis (NCA)

Although QCA can identify the necessity of certain conditions, its judgment is primarily qualitative. In management practice, policymakers are often more concerned with quantitative questions, such as: "To what extent must a certain condition be met to provide the necessary assurance for achieving a specific objective?" To address this, we introduced Necessary Condition Analysis (NCA) as a complement to QCA. NCA is a quantitative analytical technique that precisely identifies the minimum threshold (often referred to as a bottleneck) of each driving factor required to achieve a certain target level. It does this by measuring the effect size of necessary conditions and constructing a ceiling regression line. For fuzzy set membership scores that continuously vary between 0 and 1, NCA can describe the degree of necessity more finely than traditional QCA. For example, NCA can formulate quantitative necessary condition statements such as: "To achieve a certain level of green transformation performance, condition X must reach at least level Xc". This provides richer information for analysis, allowing us to explicitly determine the level at which each driving factor becomes a limiting bottleneck for transformation. In this study, we simultaneously employed both the stepped CE-FDH and the smoother CR-FDH methods to estimate the ceiling line, ensuring the robustness of our results. To evaluate the strength of necessity, we further reported the effect size d, which indicates constraint strength, and obtained p-values through 10,000 permutation resamples to assess its statistical significance. The combination of QCA and NCA enables us to gain a more comprehensive understanding of causal relationships from both sufficiency and necessity dimensions.

Case selection and data collection

Based on the 2012 industry classification standard issued by the China Securities Regulatory Commission (CSRC), we select textile companies listed on the Shanghai and Shenzhen A-share markets from 2016 to 2024 as the study sample. During the screening process, we exclude ST and *ST firms as well as companies with significant missing data. The final dataset includes 459 firms with balanced panel data. Annual report information is obtained from the official websites of the Shanghai and Shenzhen Stock Exchanges, while financial data is retrieved from the CSMAR database provided by GTA. Considering the lag in green transformation behaviour, all antecedent variables are lagged by one period.

Outcome Variable

We measure green transformation based on textual information disclosed in firms' annual reports [37]. Specifically, we identify 113 green transformation keywords from five dimensions: advocacy and initiatives, strategic orientation, technological innovation, pollution control, and environmental monitoring. We calculate the frequency of each keyword appearing in the annual report text of listed companies. The total frequency count, plus one, is then transformed using the natural logarithm to construct the firm's green transformation score.

Antecedent Variables

Technological conditions include two sub-conditions: digital transformation and investment in R&D personnel. For digital transformation, we follow a textual analysis approach [38]. First, we define digital transformation behaviour based on two categories: the adoption of foundational digital technologies and the implementation of technological practices.

Foundational technologies include four typical types: artificial intelligence (A), blockchain (B), cloud computing (C), and big data (D). Technological practices (E) are categorised based on their real-world applications. Figure 2 illustrates the keyword map. Then, using Python, we extract the annual report texts of sample firms to create a text corpus. Based on the keywords in Figure 2, we perform word matching, frequency counts, and keyword grouping to construct a composite indicator of digital transformation. The final total frequency is log-transformed to produce a quantitative index of each firm's digital transformation level. R&D personnel investment is measured by the proportion of R&D staff (number of R&D employees divided by total employees), which reflects the firm's input of technical human capital for green innovation. Organisational conditions include two sub-conditions: organisational slack and executives' green awareness. Organisational slack is measured using the quick ratio, which better reflects a firm's short-term solvency and its ability to absorb transformation-related costs. For executives' green awareness, we identify 19 keywords related to environmental strategy, green competitiveness, corporate social responsibility, and sensitivity to external environmental pressure [39, 40]. These keywords include energy conservation, environmental strategy, low-carbon development, and environmental governance. Using Python, we scrape and analyse keyword frequencies

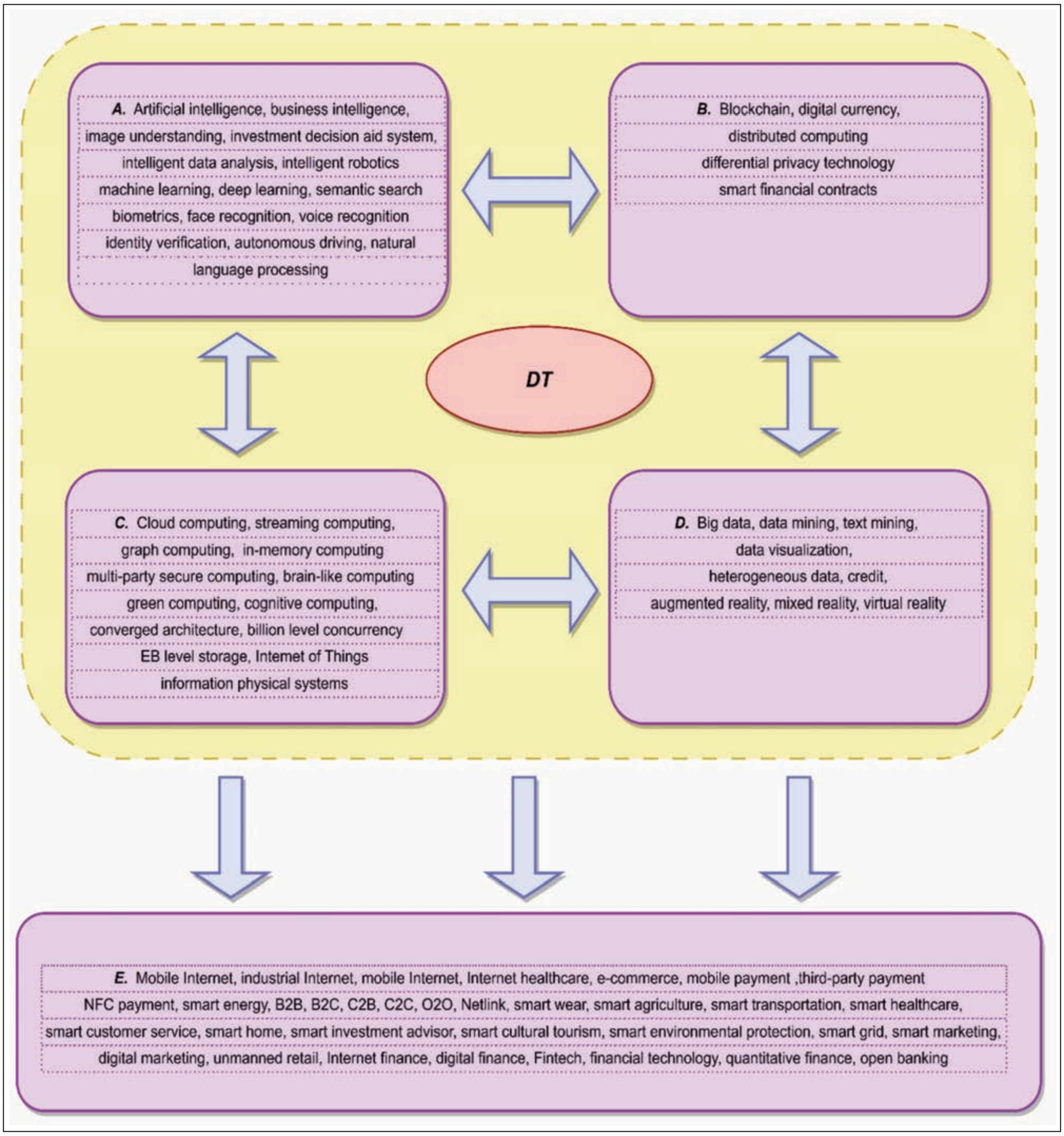

Fig. 2. Characteristic keyword map

from each firm's annual report texts. The natural logarithm of keyword frequency plus one is used as the indicator of green awareness among executives.

Environmental conditions include market competition and perceived government support. Market competition is measured using the Lerner Index, which effectively captures a firm's market power relative to peers in the same industry. For government support, we use the natural logarithm of the total amount of government subsidies received, which reflects the firm's perception of policy incentives for R&D.

RESULTS AND ANALYSIS

Variable calibration

Unlike traditional empirical research, QCA requires variable calibration before analysis. Based on case characteristics and the distribution of raw values, we define three anchor points: full membership, the crossover point, and full non-membership. These anchors are used to convert original values into fuzzy-set membership scores ranging from 0 to 1. Following established practice [14], we apply the direct calibration method, setting the 95th, 50th, and 5th percentiles as thresholds. Since all variables follow a unified quantile calibration rule, listing the specific anchor values for each variable individually does not provide additional information, so the calibration table will no longer be reported separately.

Necessary condition analysis

Qualitative Comparative Analysis (QCA)

In conventional QCA, a condition is deemed necessary if its consistency exceeds 0.9. In dynamic QCA, a condition can also be considered necessary if the consistency is high and the difference in consistency across groups is less than 0.1. When this threshold is exceeded, further investigation is required.

As shown in table 1, digital transformation, organisational slack, and government support exhibit consistency differences across groups greater than 0.1, suggesting that further analysis is warranted. By examining their consistency and coverage across different cases (table 2), we observe that the consistency scores in Cases A through D remain below 0.9 for all years, indicating that these variables are not necessary conditions [41].

Nonetheless, in Cases A and D, both digital transformation and government support show an upward trend in necessity over time (figure 3). This finding is consistent with previous research that underscores the increasing importance of these two factors in enabling green transformation [42].

Necessary Condition Analysis (NCA)

Since QCA assesses necessity from a qualitative perspective, we complement our analysis using Necessary Condition Analysis (NCA), as recommended by Dul et al. NCA includes two ceiling estimation techniques: Ceiling Regression (CR) and Ceiling Envelopment (CE). We assess necessity using two diagnostic procedures [43].

First, we examine the scatter plots between each antecedent condition and the outcome. A visible space in the upper-left corner suggests potential necessity, with larger empty areas implying stronger constraints. Second, we analyse the effect size and perform a Monte Carlo permutation test. A condition is considered necessary only if it exhibits both a statistically significant effect size and a significant permutation result ($p<0.05$).

Table 1

NECESSARY CONDITION ANALYSIS

Causal condition variable	High energy-saving innovation level				Low energy-saving innovation level			
	Overall consistency	Overall coverage	Inter-group adjusted distance	Intra-group adjusted distance	Overall consistency	Overall coverage	Inter-group adjusted distance	Intra-group adjusted distance
Digital Transformation	0.658	0.679	0114A	0.084	0.395	0.398	0.087	0.091
~Digital Transformation	0.772	0.675	0.083	0.009	0.534	0.625	0.196B	0.037
R&D Personnel Ratio	0.613	0.602	0.085	0.091	0.491	0.495	0.088	0.093
~ R&D Personnel Ratio	0.489	0.484	0.095	0.068	0.605	0.609	0.091	0.013
Organizational Slack	0.607	0.504	0.007	0.036	0.439	0.393	0.153C	0.006
~ Organisational Slack	0.611	0.609	0.091	0.095	0.393	0.401	0.093	0.072
Executives' Green Cognition	0.592	0.671	0.018	0.062	0.443	0.419	0.093	0.099
~ Executives' Green Cognition	0.429	0.428	0.091	0.096	0.674	0.693	0.096	0.098
Market Competition	0.515	0.602	0.096	0.049	0.384	0.396	0.093	0.027
~ Market Competition	0.625	0.573	0.096	0.083	0.698	0.506	0.097	0.059
Government Support	0.701	0.605	0.171D	0.066	0.488	0.494	0.094	0.014
~ Government Support	0.578	0.471	0.098	0.047	0.609	0.622	0.094	0.026

Note: "~" denotes the absence of a condition.

Table 2

INTER-GROUP RESULTS WITH ADJUSTED CONSISTENCY DISTANCE > 0.1										
Causal configuration		**Year**								
		2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Case A	Inter-group consistency	0.311	0.326	0.498	0.561	0.637	0.791	0.796	0.875	0.898
	Inter-group coverage	0.862	0.775	0.761	0.656	0.615	0.583	0.635	0.575	0.635
Case B	Inter-group consistency	0.692	0.715	0.664	0.623	0.531	0.469	0.421	0.314	0.409
	Inter-group coverage	0.415	0.392	0.505	0.611	0.606	0.434	0.713	0.665	0.675
Case C	Inter-group consistency	0.623	0.327	0.415	0.526	0.545	0.385	0.255	0.386	0.419
	Inter-group coverage	0.312	0.677	0.315	0.265	0.21	0.345	0.616	0.623	0.406
Case D	Inter-group consistency	0.304	0.329	0.483	0.575	0.657	0.788	0.792	0.838	0.845
	Inter-group coverage	0.825	0.730	0.615	0.585	0.591	0.515	0.482	0.351	0.455

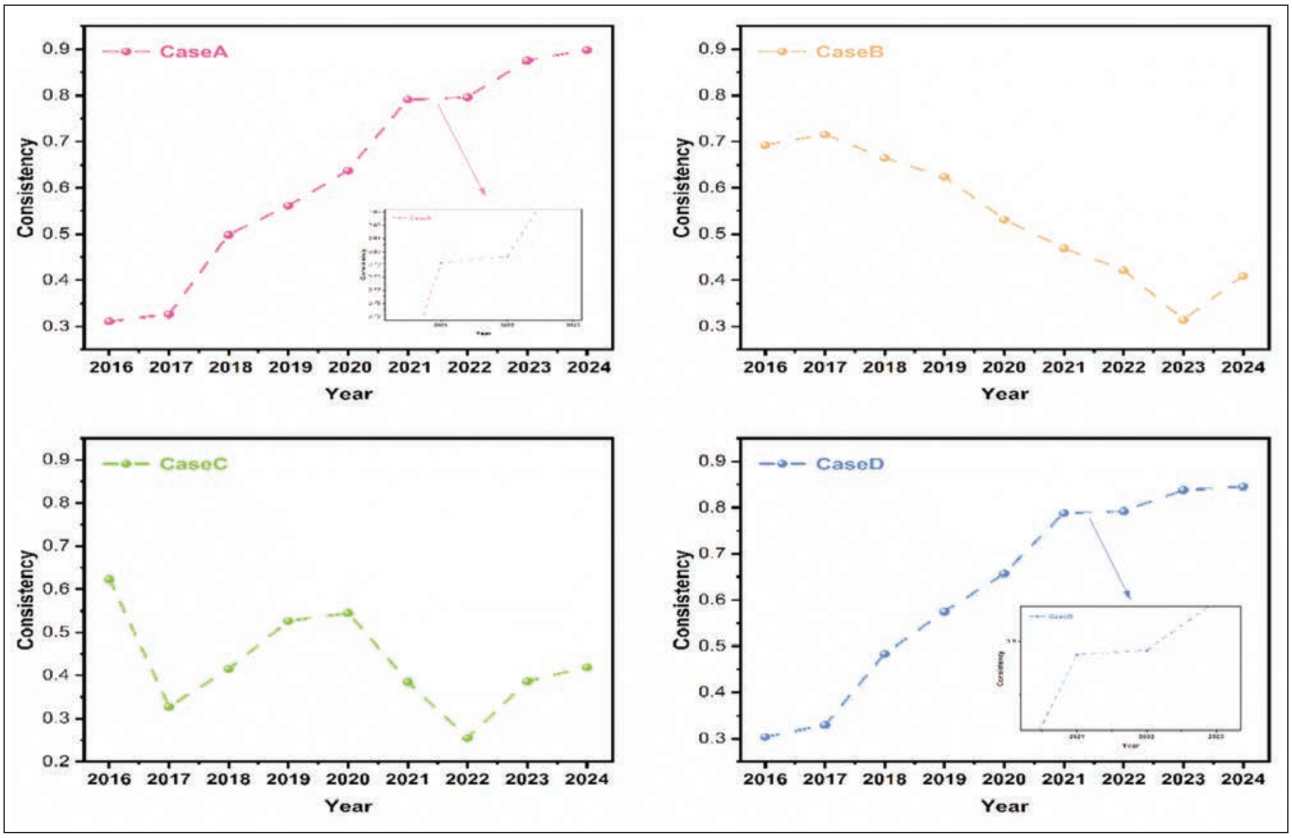

Fig. 3. Trend of inter-group consistency

Based on the scatter plots, no evident empty area is observed in the upper-left region for any of the variables, suggesting preliminarily that they do not constitute necessary conditions for green transformation. Moreover, according to the effect size and Monte Carlo permutation test results, none of the six variables simultaneously meets both the effect size criterion (Effect size > 0.1) and statistical significance in the Monte Carlo simulation permutation test (p-value < 0.05), indicating that none of them satisfies the criteria for being identified as a necessary condition for green transformation.

In summary, the results show that no single antecedent condition is necessary for achieving green transformation. Table 4 further presents the bottleneck thresholds for each condition. To ensure full green transformation among textile enterprises, the following minimum levels are required: 8.3% for digital transformation, 3.0% for R&D personnel input, 5.8% for organisational slack, and 8.0% for government support. Executive green awareness and market competition do not exhibit bottleneck effects.

Sufficiency analysis of configurational conditions

Configuration analysis constitutes the core of QCA and seeks to uncover how various combinations of antecedent conditions influence the emergence of the outcome. According to established standards, the consistency threshold for sufficiency is typically set at a minimum of 0.75 [41]. In this study, we set the consistency threshold at 0.85, the frequency threshold

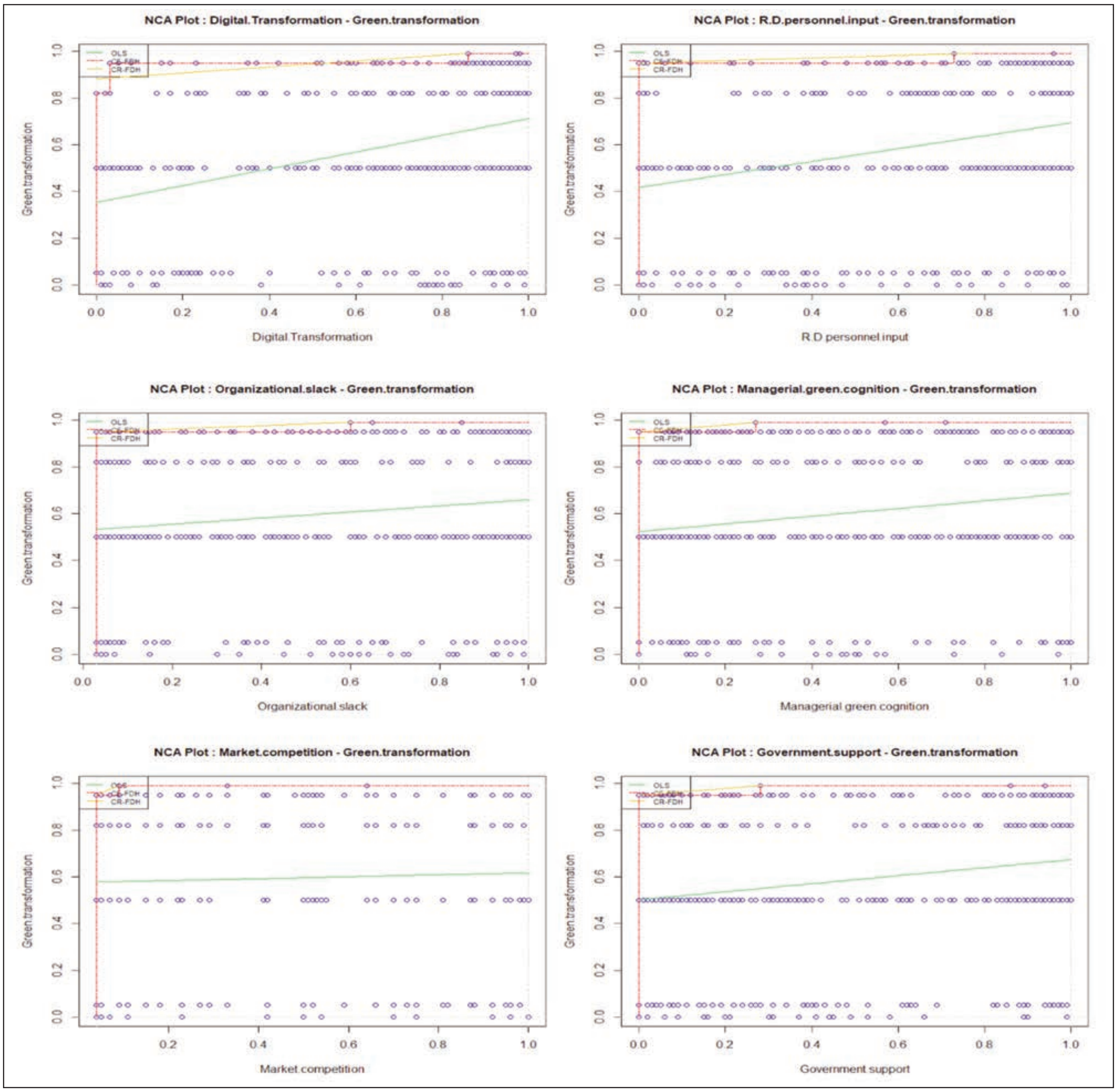

Fig. 4. Scatter plot of influencing factors

Table 3

NECESSARY CONDITION ANALYSIS (NCA)						
Antecedent condition[a]	**Methods**	**Accuracy (%)**	**Ceiling Zone**	**Scope**	**Effect (d)**	**p value[b]**
Digital Transformation	CR	97.4%	0.046	0.99	0.046	0.021
	CE	100%	0.038	0.99	0.039	0.015
R&D Personnel Ratio	CR	100%	0.015	0.99	0.015	0.156
	CE	100%	0.029	0.99	0.029	0.155
Organizational Slack	CR	100%	0.011	0.96	0.012	0.091
	CE	100%	0.023	0.96	0.024	0.091
Executives' Green Cognition	CR	100%	0.005	0.99	0.005	0.195
	CE	100%	0.011	0.99	0.011	0.195
Market Competition	CR	100%	0.001	0.95	0.001	0.622
	CE	100%	0.002	0.95	0.002	0.622
Government Support	CR	100%	0.006	0.99	0.006	0.321
	CE	100%	0.011	0.99	0.011	0.319

Note: [a] – Based on calibrated fuzzy-set data; [b] – Results obtained using permutation testing with 10,000 resamples.

Table 4

BOTTLENECK LEVELS (%) IDENTIFIED BY NCA METHOD						
Green transformation	**Digital transformation**	**R&D staff proportion**	**Organizational slack**	**Executives' green cognition**	**Market competition**	**Government support**
0	NN	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN	NN
30	NN	NN	NN	NN	NN	NN
40	NN	NN	NN	NN	NN	NN
50	NN	NN	NN	NN	NN	NN
60	NN	NN	NN	NN	NN	NN
70	NN	NN	NN	NN	NN	NN
80	NN	NN	NN	NN	NN	NN
90	7.1	NN	NN	NN	NN	NN
100	8.3	3.0	5.8	NN	NN	8.0

Note: The table uses a CAP regression analysis, CR; NN indicates not necessary.

at 2, and the RPI threshold at 0.75 to enhance the robustness of the results. During counterfactual analysis, we excluded simplifying assumptions that would lead to logical contradictions. Given the hetero geneity in enterprise development, the impact of antecedent conditions on the outcome cannot be uniformly determined. Accordingly, we analysed without preset directional expectations, allowing each condition to appear as either present or absent. As a result, we obtained enhanced parsimonious, intermediate, and complex solutions.

Based on the enhanced intermediate and parsimonious solutions, we identified core and peripheral conditions following the approach proposed by Fiss (2011). Table 5 reports the results of the configuration analysis. Specifically, four configurations were identified as leading to high-level green transformation, which can be categorised into three types: technology–environment-driven, technology–organisation-driven, and hybrid-driven configurations (figure 5).

Summary of configurations

(1) Technology and Environment Driven Configuration (H1)

Configuration H1 shows a consistency of 0.907 and a raw coverage of 0.468, explaining approximately 47% of the sample cases. Within this configuration, digital transformation, R&D staffing, and government support are core conditions. This indicates that some textile enterprises advance green transformation by upgrading their technologies and leveraging policy support. For example, through the adoption of smart equipment, the enhancement of technical personnel,

Table 5

CONFIGURATIONAL ANALYSIS				
Causal condition	**High-level Green transformation**			
	H1	**H2**	**H3a**	**H3b**
	Technology–environment-drive	**Technology–organisation-driven**	**Multi-dimensional driven**	
Digital transformation	◈	◈	◈	◎
R&D personnel input	◈	◈	◉	◈
Organizational slack	◎	◉	◈	◈
Executives' green cognition		◈	◉	
Market competition	◉			◈
Government support	◈	◎	◈	◈
Consistency	0.907	0.921	0.887	0.912
PRI	0.901	0.802	0.769	0.794
Raw coverage	0.468	0.393	0.297	0.322
Unique coverage	0.101	0.059	0.102	0.125
Inter-group adjusted distance	0.013	0.002	0.054	0.049
Intra-group adjusted distance	0.075	0.082	0.080	0.014
Overall consistency	0.904			
Overall coverage	0.658			

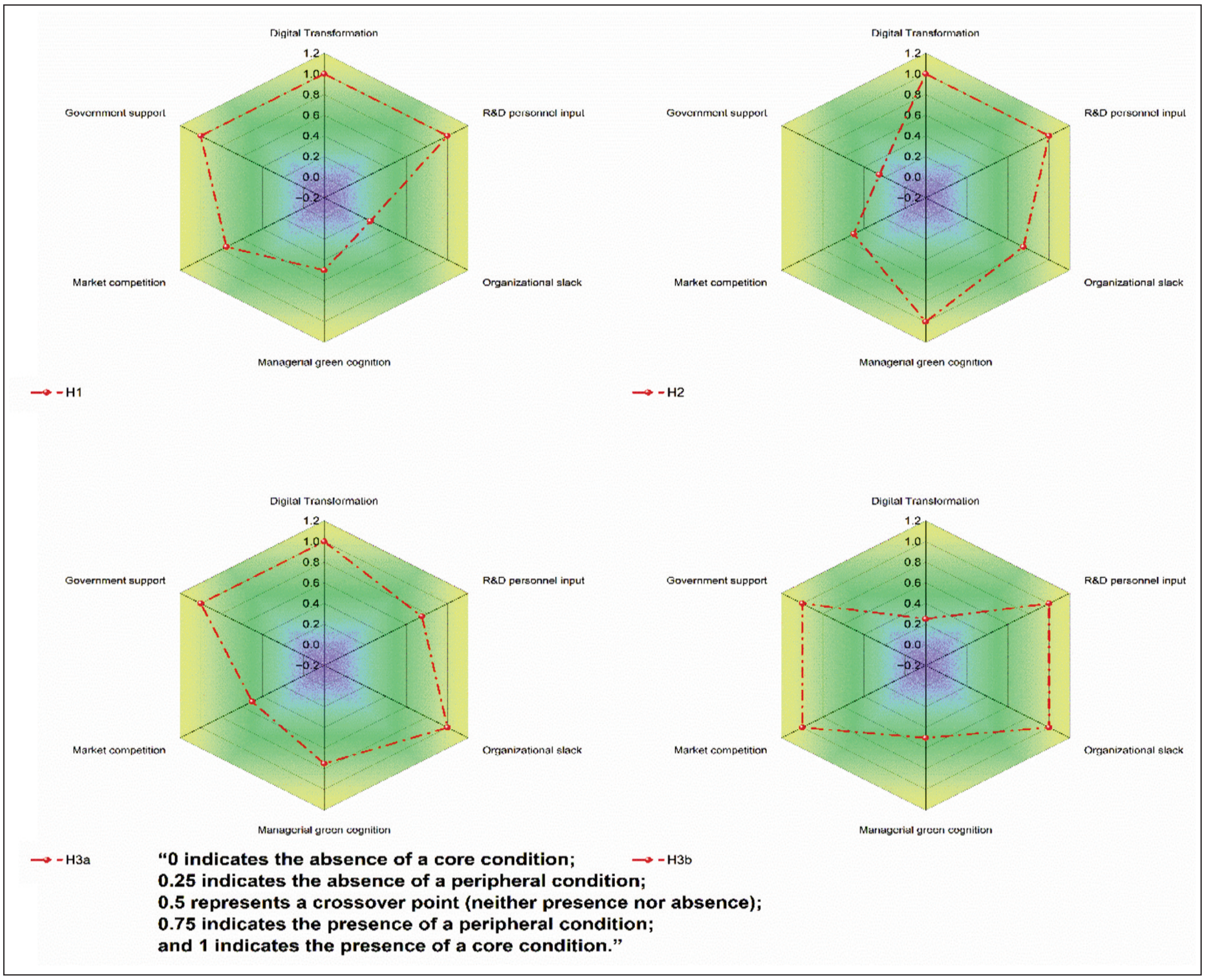

Fig. 5. Radar chart of configurations

and the utilisation of government subsidies, firms can effectively reduce energy consumption and emissions. Market competition serves as a peripheral condition, suggesting that firms in more competitive environments are more motivated to pursue transformation in order to enhance their public image. Since this configuration primarily emphasises technological and environmental factors, it is referred to as technology and environment-driven.

(2) Technology and Organisation Driven Configuration (H2)

Configuration H2 has a consistency of 0.921 and a raw coverage of 0.393, accounting for approximately 39% of the sample cases. In this configuration, digital transformation, R&D staffing, and executives' green awareness are core conditions, suggesting that firms promote green transformation by combining technological upgrading with managerial attention to environmental issues. Digital technologies and R&D investment improve energy efficiency and enable cleaner production, while green-oriented executives help translate environmental visions into concrete actions. Organisational redundancy acts as a peripheral condition, indicating that a firm's internal resource buffer provides support for implementing green practices. Given the emphasis on technological and organisational dimensions, this configuration is labelled as technology and organisation-driven.

(3) Multi-Factor Hybrid Driven Configuration (H3a + H3b)

Configuration H3a demonstrates a consistency of 0.887 and a raw coverage of 0.297, covering around 30% of the sample. Configuration H3b has a consistency of 0.912 and a raw coverage of 0.322, explaining about 32% of the sample. In H3a, the core conditions include digital transformation, organisational redundancy, and government support, while R&D staffing and executives' green awareness serve as peripheral conditions. This suggests that firms can promote green transformation by relying on internal technological capacity and resource redundancy, combined with external policy incentives and managerial orientation. In H3b, the core conditions consist of R&D staffing, organisational redundancy, market competition, and government support. This configuration indicates that under high competitive pressure, firms accelerate the development and application of green technologies by integrating internal innovation capabilities and external policy instruments. Overall, both H3a and H3b reflect a mode of green transformation that relies on the interaction of multiple dimensions. Therefore, this configuration is classified as multi-factor hybrid driven.

Inter-group analysis

Although the inter-configuration consistency deviation of the four high-level green transformation configurations does not exceed 0.1, indicating no significant time effects, a closer examination of the temporal trend reveals that all four paths experienced a notable decline in consistency in 2020, followed by a gradual recovery starting from 2021 (figure 6). It should be noted that this fluctuation concentrated in 2020 is a systematic rather than a random disturbance, and thus does not qualify as a benign deviation [36]. This inter-configuration analysis addresses the lack of temporal perspective in previous cross-sectional studies and demonstrates that the four configurations are robust over 2016–2024.

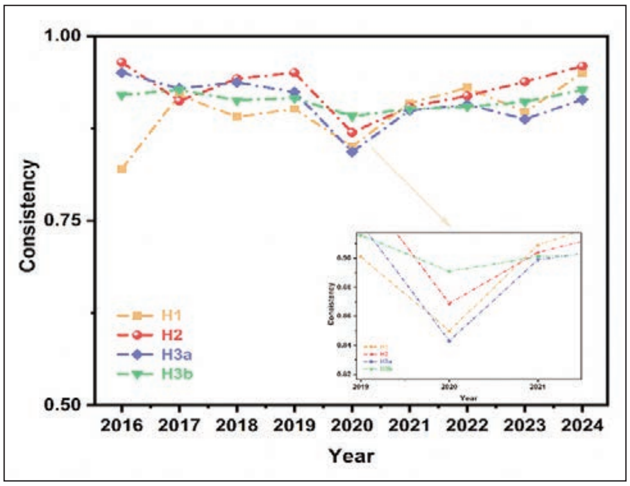

Fig. 6. Variation in inter-group consistency

As for the sharp drop in 2020, it may be attributed to the outbreak of COVID-19 that year, during which enterprises prioritised operational stability over green transformation. Although this short-term disruption occurred, all inter-configuration deviation values remain below 0.1 and do not substantially affect the explanatory power of the model. Therefore, the results remain valid under normal conditions. It is noteworthy that configuration H3b was less affected by the pandemic, indicating that the "Multi-Factor Hybrid Driven Type" exhibits greater stability.

Intra-group analysis

Consistent with the results of inter-configuration deviation, the intra-configuration deviation of all four configurations is also below 0.1, suggesting that the explanatory power of the four configurations does not differ significantly across firm sizes. Given the overall comparability of explanatory power, a further examination of firm size coverage across configurations can help identify their distribution among different firm sizes.

As current QCA methods lack indicators for measuring firm size coverage differences, we rank sample firms by firm size (natural log of total assets) and divide them into small, medium, and large-scale groups based on terciles. Configuration 2 failed the normality test and was analysed using the non-parametric Kruskal-Wallis rank-sum test. Configurations H1 and H3b passed both the normality and homogeneity of variance tests, making them suitable for one-way ANOVA. Configuration H3a, which barely failed the normality test, was tested using both methods to ensure robustness.

The specific results are shown in tables 6 and 7. The p-values for configurations H1 and H3b are both below 0.1 and are statistically significant, indicating notable differences across firm sizes. The remaining configurations have p-values above 0.1 and are not statistically significant. To further explore configuration preferences by firm size, we calculated the mean firm size coverage for each configuration. As shown in table 8, configuration H1 performs better among large firms, while configuration H3b is more effective for smaller ones (see selected case examples in figure 7).

Table 6

KRUSKAL-WALLIS TEST

Configuration	Mean	SD	F	P
H2	0.414	0.253	2.147	0.341
H3a	0.331	0.176	1.492	0.476

Table 7

ONE-WAY ANALYSIS OF VARIANCE FOR CONFIGURATIONS

Configuration	Mean	SD	F	P
H1	0.337	0.172	3.14	0.06*
H3a	0.372	0.216	0.67	0.536
H3b	0.357	0.192	7.02	0.004***

Table 8

MEAN COVERAGE OF CONFIGURATIONAL PATHS

Category	H1	H2	H3a	H3b
Small-scale	0.322	0.309	0.316	0.489
Medium-scale	0.351	0.354	0.409	0.352
Large-scale	0.502	0.403	0.397	0.245

CONCLUSION AND DISCUSSION

This study investigates the complex driving mechanisms in the green transformation process of China's A-share textile industry. Utilising panel data from 2016 to 2024 and a two-stage method combining Dynamic QCA and NCA, we identified three distinct configurational pathways leading to high-level green transformation: technology-environment driven, technology-organisation endogenously driven, and multi-factor integrated. All identified pathways exhibit high consistency and coverage, suggesting that no single optimal path exists for green transformation, thereby demonstrating the typical characteristic of equifinality. Inter-group analysis further reveals that the

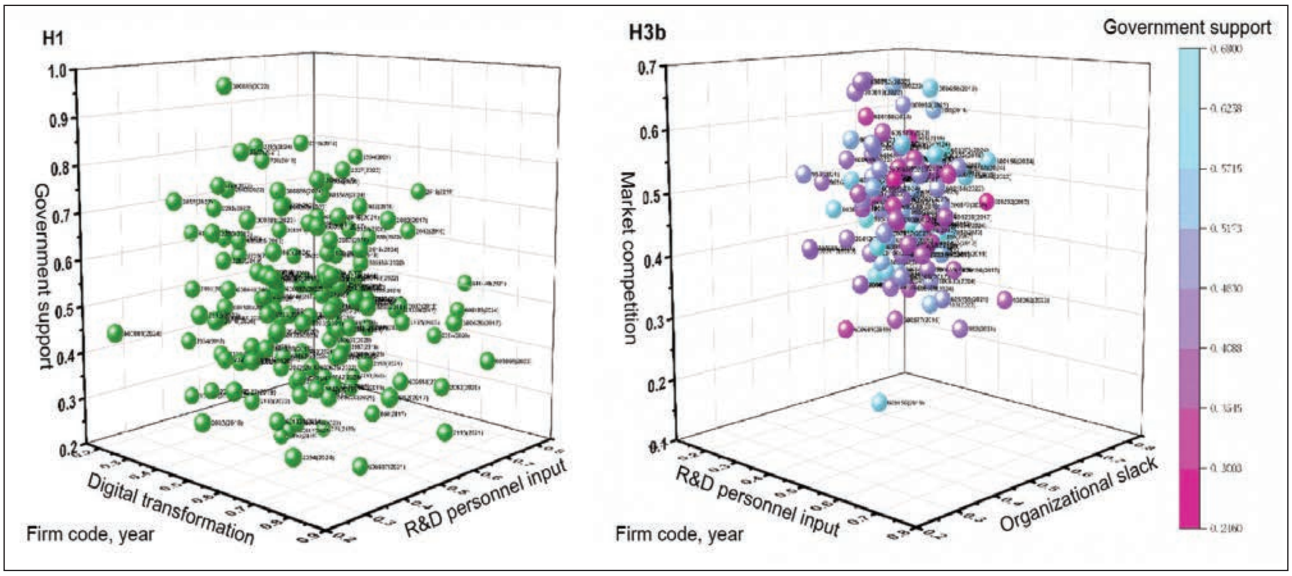

Fig. 7. Representative sample cases of Green transformation

consistency levels of these three configurations significantly declined in 2020 before gradually rebounding in 2021. Notably, the multi-factor integrated pathway demonstrated greater stability and the most effective transformation outcomes amidst these fluctuations. Intra-group analysis, in turn, indicates that the driving effects of these configurations vary to some extent across different enterprise scales.

Our research offers several significant contributions. First, we broaden the research perspective on green transformation, moving beyond the existing literature's predominant focus on the linear impact of single variables. From a theoretical standpoint, this study deepens the understanding of the "configurational logic of green transformation". Consistent with Fiss's (2011) three core principles of configurational theory, the three high-performance pathways identified in this paper exemplify equifinality, illustrating that diverse combinations of conditions can lead to superior green transformation performance, thereby responding to recent calls for configurational research [20, 21]. Second, this study elucidates the complex substitution and complementarity relationships among driving factors. For instance, executive green awareness and organisational slack within the technology-organisation endogenously driven pathway can functionally compensate for government support in the technology-environment driven pathway. This vividly illustrates the intricate interplay between internal corporate resources and the external institutional environment in fostering green transformation. Finally, our research substantiates the logic of causal asymmetry prevalent in social sciences. Although digital transformation emerges as a core condition in multiple pathways, NCA analysis demonstrates that it is not a necessary condition for achieving high-level green transformation. This implies that the impact of a single condition on the outcome differs across various factor combinations, challenging the symmetry assumption of variable effects in traditional regression methods and deepening our comprehension of green transformation's complex causal mechanisms. Furthermore, our findings align closely with China's current green industrial policy orientation, confirming the "green + digital" integrated development logic emphasised in policies such as the "14th Five-Year Plan for the Textile Industry Development", "Industrial Green Development Plan", and "Green Manufacturing System Construction Guide". These insights also offer valuable implications for economies and regions at similar levels of economic development.

From a policy-making perspective, governments should shift from relying on "single tools" to implementing precise policies through a "policy toolbox". For enterprises exhibiting characteristics of the technology-environment driven pathway, policies should extend beyond mere subsidies to include integrated incentive schemes. For example, a fast-track system for green approvals or credit could be established for firms meeting specific standards in digital transformation, R&D personnel proportion, and effective utilisation of government subsidies. Second, supporting digital infrastructure and green finance in the textile industry should not be a one-time investment but rather a long-term, sustained strategic commitment. Moreover, our study indicates that the multi-factor integrated pathway is particularly effective for small and medium-sized enterprises (SMEs) and demonstrates greater stability during external shocks. This suggests that government support for SMEs should not solely rely on direct financial injections (e.g., subsidies) but, more critically, focus on optimising their business ecosystem. For instance, establishing national green textile certification and procurement platforms could strengthen market signals for green consumption, enabling SMEs that pursue green innovation to gain quicker market returns and thus activate their endogenous motivation.

From an enterprise management perspective, managers should act as "resource integrators" rather than "executors of isolated initiatives". Enterprises should select the most suitable transformation pathway based on their specific conditions. For example, large enterprises with substantial technical and financial strength might prioritise the technology-organisation endogenously driven pathway (H2), with executive green awareness as the core driver, leveraging top-level design and internal culture as the bedrock for transformation. Conversely, SMEs with relatively limited resources should actively seek external support, adeptly utilising external forces such as government subsidies and market competition to pursue a multi-factor integrated compensatory growth strategy (H3b), leveraging external factors to offset internal constraints. Furthermore, the strong resilience demonstrated by the multi-factor integrated pathway during the 2020 pandemic offers a crucial lesson in risk management for all enterprises. This implies that the most robust strategy involves building a diversified capability portfolio: while pursuing technological innovation, maintaining healthy organisational slack (e.g., cash flow) is essential to buffer uncertainty, alongside a keen ability to capitalise on external policies and market opportunities. Finally, our study unequivocally highlights that no single condition offers a permanent solution; managers must regularly review and adjust their resource allocation, perceiving green transformation as a collaborative process that necessitates continuous attention and dynamic adaptation.

Despite achieving preliminary results in identifying green transformation pathways and exploring their underlying mechanisms, our study has certain limitations. First, regarding variable selection, we adopted the TOE framework and identified multiple empirically supported antecedent variables from existing literature, aiming to construct a relatively comprehensive explanatory model. However, constrained by data availability and the characteristics of the industry sample, some potentially key factors may not have been included in the analysis, thus failing to fully capture all complex driving mechanisms underpinning green transformation. Future research could explore the inclusion of new, more endogenous variables, such as corporate culture and governance structure, to further refine model construction. Second, this paper's analysis primarily relies on publicly available data, such as corporate annual reports. Future research could integrate qualitative methods, such as interviews or surveys, to delve into the underlying logical mechanisms driving corporate green transformation, thereby further enhancing the theoretical explanatory power and practical relevance of the research.

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Green threads: a bibliometric review of sustainable manufacturing practices in the fashion industry

DOI: 10.35530/IT.077.01.2025111

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ABSTRACT – REZUMAT

Green threads: a bibliometric review of sustainable manufacturing practices in the fashion industry

The significance of sustainable manufacturing has increased, especially in the fast-fashion sector, amid the growing urgency of resource depletion, environmental degradation, and unsustainable industrial practices. To map the thematic and intellectual landscape of research in sustainable fashion and manufacturing, this study performs a thorough bibliometric analysis. This study uses quantitative and qualitative bibliometric techniques using Biblioshiny (R Studio) to identify important trends, powerful authors, high-impact publications, prestigious journals, and emerging research themes based on 194 research documents that were pulled from the Scopus database. The results show that scholarly interest increased significantly after 2015, with significant increases in publications from 2020 to 2023. Two prominent sources are Sustainability (Switzerland) and the Journal of Cleaner Production. Key motor themes like recycling, sustainable development, and the circular economy are highlighted by thematic mapping, and co-authorship networks show prominent collaborative clusters headed by writers like Shamsuzzaman M. and Islam M.T. There are still gaps in regional diversity, interdisciplinary integration, and real-world implementation studies, despite an expanding body of research. For academics, professionals, and legislators hoping to promote sustainable change in the global fashion manufacturing industry, this paper offers strategic insights.

Keywords: *circular economy, green practices, Scopus, sustainability, textile industry, co-authorship network, thematic mapping*

Fire ecologice: o analiză bibliometrică a practicilor de producție sustenabilă în industria modei

Importanța producției durabile a crescut, în special în sectorul modei rapide, din cauza urgenței crescânde legate de epuizarea resurselor, degradarea mediului și practicile industriale nesustenabile. Pentru a cartografia peisajul tematic și intelectual al cercetării în domeniul modei și producției durabile, acest studiu realizează o analiză bibliometrică aprofundată. Acest studiu utilizează tehnici bibliometrice cantitative și calitative folosind Biblioshiny (R Studio) pentru a identifica tendințe importante, autori influenți, publicații cu impact ridicat, reviste prestigioase și teme de cercetare emergente pe baza a 194 de documente de cercetare extrase din baza de date Scopus. Rezultatele arată că interesul academic a crescut semnificativ după 2015, cu creșteri importante ale publicațiilor între 2020 și 2023. Două surse proeminente sunt Sustainability (Elveția) și Journal of Cleaner Production. Teme cheie precum reciclarea, dezvoltarea durabilă și economia circulară sunt evidențiate prin cartografierea tematică, iar rețelele de coautorat arată clustere colaborative proeminente conduse de scriitori precum Shamsuzzaman M. și Islam M.T. Există încă lacune în diversitatea regională, integrarea interdisciplinară și studiile de implementare în lumea reală, în ciuda unei activități de cercetare în expansiune. Pentru academicieni, profesioniști și legiuitori care speră să promoveze schimbări durabile în industria globală a modei, acest articol oferă perspective strategice.

Cuvinte-cheie*: economie circular, practici ecologice, Scopus, sustenabilitate, industria textilă, rețea de coautorat, cartografiere tematică*

INTRODUCTION

Population growth, resource depletion, and environmental degradation are major global issues endangering human survival and advancement. When resources are used to produce goods, toxic environmental pollutants are released. Numerous programs are in place to encourage green practices in the industrial sector in response to growing concerns about resource scarcity and environmental degradation [1, 2]. The objective is to create and advance environmentally friendly production methods. Manufacturing will continue to play a significant role in wealth creation, job creation, and global economic growth for years to come. As a result, incorporating green practices into manufacturing has been a hot topic lately [3].

In the past ten years, there has been an increase in the number of green initiatives. It is possible for environmental management systems, green supply chain practices, environmental responsibility, and new circular economy practices to make a contribution to the implementation of green industrial policy [4].

“Green manufacturing” (GM) is an emerging method of production that embraces environmentally friendly practices in order to improve efficiency [5]. This technique is referred to as “green manufacturing for the first time”. GM is a method or system that maximises sustainability and minimises environmental impact by reusing materials and developing new products that are beneficial to the environment. This is accomplished through the production of environmentally friendly products [6].

According to Deif, General Motors is a paradigmatic example of a new manufacturing paradigm that includes a wide variety of environmentally friendly strategies, drivers, and procedures to maximise resource efficiency [7]. Green product design and green technology must be expressly integrated across the entire manufacturing process for GM to be considered environmentally responsible [8–13]. A great number of businesses have either already adopted genetically modified organisms or are making preparations to do so.

The general public is in agreement that we need to take action in order to protect the natural resources of our world; hence, businesses have the opportunity to improve their image by transitioning to production methods that are more environmentally friendly. In addition, this approach has the potential to save costs for the organisation over the course of time by facilitating the implementation of more efficient systems and the cultivation of a corporate culture that is dedicated to the development of innovative procedures. There is a possibility that the amount of waste that an organisation produces will reduce as a consequence of these more efficient practices [14].

Not only does the term “fast fashion” refer to the concept of speed, but it also refers to a set of practices that are implemented in the fashion market with the intention of achieving continuous growth based on the power and prosperity that the brand represents, as stated by Fletcher. In this sense, the reflection of the change was taken by the large-scale clothing production factories. There was a 6.2% growth in production in the global fashion sector (clothing) in the year 2020 [4]. In 2017, the largest fast fashion company, H&M, achieved 1.4% of the overall market. According to Pang and Zhang [3], the economic performance of the fast fashion business model is significant because of the low pricing and rapid product rotations that encourage excessive consumption, particularly among children and teenagers of the younger generation [15].

Therefore, businesses that had previously built a debut collection for each semester are now beginning to generate numerous entries during the same period of time. In addition, they are increasing the number of products that are created for each collection, which ultimately leads to an increase in the number of sales (markdown) [16]. There are various sustainability concerns, some of which are related to the low reuse and recycling rates during their life cycle, particularly in the post-use phase [17]. Global fashion delivers great economic benefits, but at the same time, there are many problems associated with sustainability. According to the European Materials Federation (2017), the recycling rate in the fashion business is approximately 1%, which is significantly lower than the recycling rate in the plastics sector, which is 14% [18].

Salcedo makes a comment in the social domain on the hazardous and risky working circumstances that are provided by the global textile industry [19]. These conditions are established for the most part in Third World countries such as India and China, where labour is more affordable and does not necessarily have a higher level of qualification. In addition, we bring attention to the fact that children and adolescents are frequently exposed to environments that are not conducive to their health, that employees receive a meager compensation (generally between one and two percent of the total sale price of a piece), and that they are also exposed to a variety of chemicals, insecticides, and other substances that are detrimental to human health and ecosystems.

Several understudied topics are revealed by a bibliometric analysis of the body of research on circular economy practices, sustainability in the fashion industry, and green manufacturing. First off, although the body of research on green manufacturing is expanding, there is still little interdisciplinary integration in the literature, especially when it comes to supply chain management, environmental science, and social sustainability studies. Research clusters typically concentrate primarily on technical or environmental issues, with fewer studies examining socioeconomic factors like consumer behaviour or labour welfare. There is also a clear geographic divide, with most research concentrated in developed economies and little research on developing nations, where fast fashion manufacturing is most common.

Furthermore, as evidenced by low citation counts and little keyword co-occurrence, emerging themes like post-consumer textile waste management and green fast fashion practices are still in their infancy. In order to capture the dynamic evolution of sustainable practices across industries, more real-world case studies, regulatory impact assessments, and longitudinal research are needed. Finally, policy-driven and empirical studies continue to be underrepresented. As a result, the following research questions have been framed:

RQ1: How has the volume of publications on green manufacturing and sustainability in the fashion industry evolved?

RQ2: Who are the most influential authors contributing to research on green manufacturing and sustainability in fast fashion?

RQ3: In which journals is research on green manufacturing and sustainable fashion most frequently published?

RQ4: What are the most frequent words used in green manufacturing research?

RQ5: Which documents have received the highest global citations in sustainability research, and what makes them influential?

RQ6: What are the key thematic clusters and interconnections in sustainability research, particularly in relation to manufacturing and the fashion industry?

RQ7: What are the most influential and emerging research themes in sustainability, based on their relevance and development over time?

RQ8: Which authors have collaborated on research related to sustainable manufacturing in the fashion industry?

To respond to the aforementioned queries, we employed bibliometric network analysis. The bibliometric analysis offers an easily extended perspective from micro to macro levels, in contrast to traditional narrative reviews of the literature based on the researchers' knowledge [20]. One of the best methods for conducting quantitative analyses of scientific findings is bibliometric analysis [21]. The best way to ascertain the conceptual framework of a field of study is through a bibliographic analysis [2, 22].

LITERATURE REVIEW

Human concerns about the environment served as the impetus for the early 1990s introduction of the GM concept [23]. Initially, GM's focus was entirely on processes in an effort to reduce manufacturing waste. After that, the focus switches to the final product, with steps being taken to preserve water, energy, and other natural resources. In a very specific sense, GM is typically understood to refer to the manufacturing of environmentally friendly goods, such as those used in clean technology equipment and renewable energy systems [24]. But in a much larger sense, GM is typically understood to be about putting green strategies into practice, such as waste and resource reduction strategies [3]. The idea is universal in its application, even though it is difficult in a broad sense. In fact, products made with eco-friendly production techniques are considered green [10]. The current body of research typically concentrates on the idea of greening manufacturing processes as a whole. From an economic perspective, "GM" aims to lessen or eradicate the adverse effects of "externalities" on the environment. Businesses view GM practices as advantageous [25].

In keeping with their GM experiments, Herva et al. developed a method to evaluate the environmental impact of a cotton jacket manufacturing facility [26]. A GM system model was presented by Deif [7]. Plans for a more environmentally friendly and efficient manufacturing process are depicted in the model. Businesses' GM practices may be validated based on their strategic goals, behaviour toward stakeholder demands, and stakeholder interests, according to the methodology created by Bigliardi and Bottani [27]. Rehman and Shrivastava conducted a thorough analysis of the GM literature review research [23]. They came to the conclusion that there were different areas of GM research. GM integrates a wide range of procedures into all business operations that have an effect on the environment. The GM framework for sustainable development in the Indian steel industry was validated by Shrivastava et al. [10]. The study detailed the organisation's GM implementation strategy and how it affected overall performance. Motivators for industrial GM implementation were identified and ranked by Mittal and Sangwan [28]. It was concluded that strong GM regulations and government incentives might aid industries in implementing GM. Arulrajah et al. offered a perspective that exhorts scholars to assess a company's human element in order to ascertain whether or not it adopts green practices [29].

There have been multiple attempts to implement it because of the success factors as well as technical and managerial issues. GM has surfaced in recent years and now covers every phase of the product life cycle, from design to end-use [30]. It refers to the particulars of environmentally friendly manufacturing practices, including pollution control, recycling, conservation, waste management, environmental protection, and regulatory enforcement [10]. In practically every manufacturing activity, green practices are crucial [24–40].

One of the most resource-intensive and environmentally damaging industries, the fashion sector uses a lot of energy, water, and chemicals. It also contributes significantly to greenhouse gas emissions and textile waste [41]. Researchers and policymakers have placed a greater emphasis on sustainable manufacturing practices in recent years as a way to lessen adverse social and environmental effects [33]. The application of circular economy concepts in fashion, which emphasise long-term, reusable, and recyclable design, is being highlighted in an expanding corpus of literature [37]. Waste reduction measures include product take-back programmes, textile-to-textile recycling, and new business models like clothing rental and resale [34].

However, fibre blends, expense, and inadequate infrastructure continue to be obstacles to the scaling of recycling technologies [35].

Sustainable fibres are becoming more popular as a substitute for conventional fibres. In an effort to lessen reliance on virgin polyester and cotton, studies show a growing use of recycled fibres, regenerated cellulosics, and bio-based textiles [40]. Although these materials have the potential to reduce life-cycle impacts, challenges with scalability and performance parity with conventional fibres still exist [42]. Due to the extensive use of chemicals and water, wet processing, especially dyeing and finishing, is a major environmental hotspot. Waterless dyeing techniques that can drastically lower effluent discharge include foam dyeing, enzymatic treatments, and supercritical CO_2 dyeing [36].

Despite their potential, supply-chain fragmentation, fibre compatibility, and cost prevent widespread adoption [40]. The most widely used technique for assessing environmental effects along the clothing value chain is still life cycle assessment, or LCA. Its function in locating hotspots is highlighted in recent reviews, especially during the stages of raw material production, dyeing, and consumer use [35]. However, accurate evaluations are hampered by inconsistent methodological approaches and a lack of supplier data [34]. For more comprehensive evaluations, the authors suggest incorporating social life cycle assessments (S-LCA) and harmonising LCA standards [41]. A growing priority is the electrification of heat-intensive processes and the adoption of renewable energy sources to decarbonise manufacturing [42]. Cleaner energy systems, like electric heat pumps, are being promoted to supplier factories that frequently use fossil fuel boilers (Vogue Business, 2025). It is believed that financing methods and brand-supplier partnerships are crucial to removing financial obstacles.

Increasingly, efforts are being made to improve efficiency and transparency through digital technologies such as AI-driven supply-chain optimisation, digital product passports, and blockchain-based traceability systems [33]. By decreasing overproduction, enhancing waste management, and facilitating recycling through material traceability, these tools promote sustainable manufacturing. Nevertheless, interoperability issues and implementation costs continue to exist [41]. Beyond environmental issues, fair wages, worker safety, and labour rights must all be considered in sustainable fashion manufacturing. The integration of environmental and social governance (ESG) measures into manufacturing practices is emphasised by scholars [39]. Without more extensive systemic changes like guaranteeing livable wages and increasing supplier capacity, implementing audits alone is insufficient [38].

According to recent studies (2023–2025), scalable applications of sustainable manufacturing practices are emerging in the fashion industry, moving beyond theoretical discussions. Recycling, materials, and cleaner processing innovations are progressing, but widespread adoption is still hampered by systemic issues with costs, policy, data accessibility, and social equity. Harmonised life cycle assessment (LCA) frameworks, supplier decarbonisation investments, extensive circularity infrastructure, and integrated environmental-social approaches must be the main focuses of future research and practices.

METHODOLOGY

Finding databases that support the study is the first stage in the bibliometric analysis process [12]. Information from the Scopus database as of July 12, 2025, served as the basis for this article. According to Chadegani et al., the Scopus database is the most searchable citation resource and the most comprehensive source for citations and abstracts of literature searches [31]. According to Zhao and Strotmann, Scopus has 60% more coverage than Web of Science. "Manufacturing" and "sustainable" are the two terms that make up the concept of "sustainable manufacturing". In order to guarantee that both terms are included in the results, we conducted separate searches for each of the terms [32]. In the first, all of the potentially relevant keywords linked with sustainable were included, and in the second, all of the sustainable manufacturing practices that were associated with keywords were included. In the end, the search term that we used was (Sustainability) and (sustainable manufacturing in the fashion sector). After conducting this search, a total of 332 documents were found. A total of 204 documents were produced after the first filters were applied to only include papers from the following subject areas: Business, Management and Accounting, Environmental Science, Social Sciences, and Arts and Humanities. Choosing only research articles, review papers, book chapters, and conference papers allowed for even more refinement.

This study's bibliometric analysis is a result of the final screening. A new and continuously evolving field of research serves as the foundation for our analysis; hence, we have concentrated on all of the references contained within the database, which includes conferences and papers from journals that have been subjected to peer review. According to Aria & Cuccurullo, we started the analysis by obtaining important bibliometric, qualitative and quantitative data. This included things like articles authored, authors, citations, country of origin, or keywords [5]. We did this by using a statistical tool that was available on R-Studio. In the realm of bibliometric analysis, Bibliometix is software that is based on R. R is an ecosystem program, which implies that it operates in

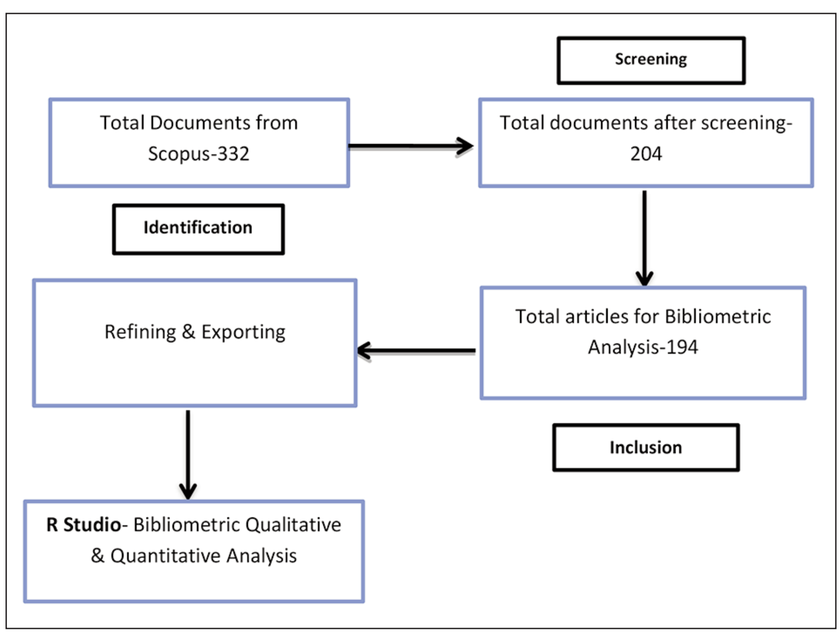

Fig. 1. Search and analysis flow diagram

a cohesive environment with the assistance of a group of open-source components. These components include open-source libraries, algorithms, and graphics applications.

ANALYSIS AND FINDINGS

To answer the research questions of the study, data were taken from the Scopus database and examined using Biblioshiny, the graphical user interface of the Bibliometrix package in R. Scopus was selected as a reliable source for bibliometric analysis due to its extensive coverage, which includes indexed journals, conference proceedings, and book series.

Annual scientific production

As a reflection of the early stages of scholarly interest in this field, the annual scientific production on sustainability in the fashion industry shows an initially modest research output between 2003 and 2014. From 2015 onward, there was a steady rise, indicating growing academic involvement.
Notably, publications increased significantly between 2020 and 2023, reaching a peak of over 40 articles in 2023. This highlights the increased research momentum that may have been fueled by current world events and a growing interest in interdisciplinary topics. Despite a drop in 2024 and 2025, production levels are still significantly higher than in previous years, indicating that the field of study has received ongoing scholarly attention (figures 2 and 3).

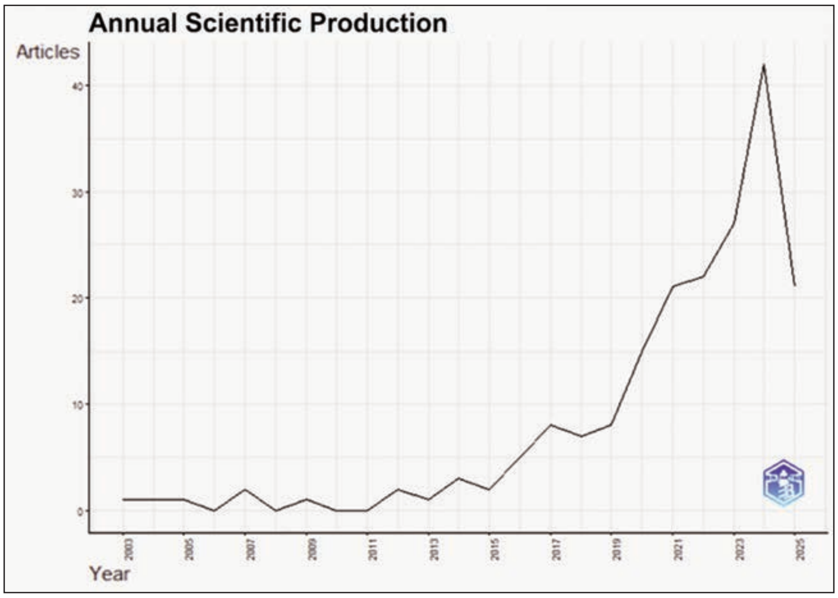

Fig. 2. Year-wise contribution

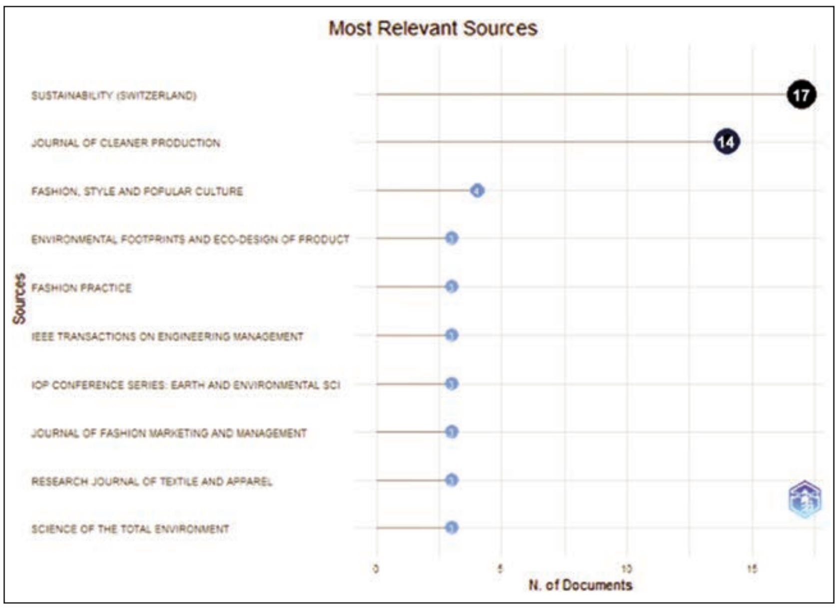

Fig. 3. Top contributing journals

Most relevant sources

The most pertinent sources supporting sustainability in fashion research are shown in figure 2. With 17 papers, Sustainability (Switzerland) is the most popular publication among the journals. The Journal of Cleaner Production comes in second with 14 papers (figure 3). This suggests that journals with an emphasis on sustainability and the environment are essential for sharing research in this field. A varied but less extensive range of publication venues was highlighted by the three to four articles each from the remaining sources, which included Food Quality and Preference, Environmental Engineering and Management Journal, and others. The concentration of publications in a small number of core journals indicates favoured platforms for academics and offers insightful information for upcoming researchers looking for significant publication opportunities.
Bradford's Law is used in figure 4 to show how core sources are distributed, highlighting the journals that make the biggest contributions to the body of knowledge on sustainable manufacturing in the fashion sector. According to the analysis, the Journal of Cleaner Production and Sustainability (Switzerland) are the main core source, publishing the most articles. Although they have fewer contributions, other journals such as Fashion, Style and Popular Culture, Environmental Footprints, and Fashion Practice are also included in the core zone. A significant amount of pertinent research is confined to a small number of journals, as evidenced by the steep drop in article numbers outside of the core sources. This focus identifies key publication platforms for academics and demonstrates the field's interdisciplinary character,

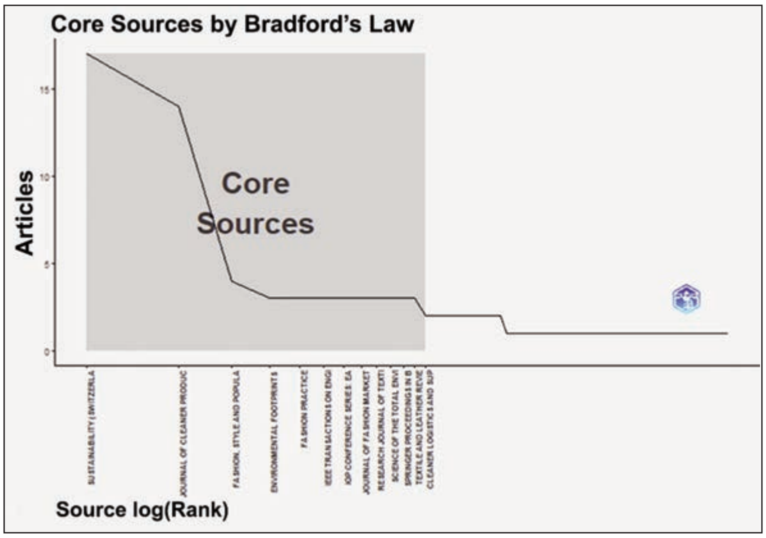

Fig. 4. Core sources by Bradford's Law

which includes sustainability, environmental science, fashion studies, and management research.

The dataset's most productive authors are highlighted in table 1. Four authors, Islam Mazed, Nayak Rajkishore, Niinimäki Kirsi and Shamsuzzaman MD, each contributed three publications, while one scholar leads the cohort with four publications. This implies that a small number of influential people are driving the field's advancement through a concentration of research activity. Ten more academics, including AkterMahmuida and Abbate Stefano, each wrote two articles, suggesting a growing network of up-and-coming authors (table 2).

Numerous highly influential papers in environmental management and sustainable fashion were found by the bibliometric review. As a pioneering study on the environmental effects of fast fashion, Niinimäki et al. (2020) is followed by Shirvanimoghaddam et al. (2020), Bick et al. (2018), Shen (2014), Jung (2014), and Fu (2018), all of whom make substantial contributions to topics like consumer behavior, sustainable supply chains, and the effects of fast fashion. A shift from theoretical reviews to applied and policy-oriented research is evident in recent publications, such as Khairul Akter et al. (2022) and Abbate (2024), which demonstrate growing interest in clean environmental systems and sustainable development (table 3).

According to the bibliometric keyword analysis, “sustainability” is the most prevalent theme and is closely followed by “sustainable development”. The textile and fashion sectors are the main subjects of research, with manufacturing and circular economy strategies receiving a lot of attention. Environmental impact and recycling are frequently discussed topics, suggesting a focus on eco-efficiency and resource management. All things considered, the keywords demonstrate a robust, system-level engagement with sustainability issues and solutions in the textile and fashion industries. By highlighting important thematic clusters and connections between commonly used keywords, the co-occurrence network visualisation demonstrates the intellectual framework of sustainability research. Terms like “sustainability”, “sustainable development”, and

Table 1

MOST PRODUCTIVE AUTHORS

Author	Articles
Islam Mazed	3
Nayak Rajkishore	3
Niinimäki Kirsi	3
Shamsuzzaman MD	3
Abbate Stefano	2
Akter Mahmuda	2
Atik Md Atiqur Rahman	2
Burak Cakmak	2
Casciani Daria	2

Table 2

MOST CITED PAPERS

Paper	Total Citations
Niinimäki K., 2020, Nat. Rev. EARTH Environ.	956
Shirvanimoghaddam K., 2020, Sci. Total. Environ.	400
Bick R., 2018, Environ. Heal. Glob. Access Sci. Source	272
Shen B., 2014, Sustainability	230
Jung S., 2014, Int. J. Consum. Stud.	195
Fu B., 2018, Sustainability	173
Khairul Akter M.M., 2022, Clean. Environ. Syst.	145
Cervellon M.C., 2012, J. Fash. Mark. Manag.	129
Islam M.M., 2021, J. Fash. Mark. Manag.	123
Abbate S., 2024, Environ. Dev. Sustain.	110

Table 3

MOST RELEVANT WORDS

Words	Occurrences
sustainability	67
sustainable development	49
textile industry	40
fashion industry	30
manufacturing	30
circular economy	29
textiles	22
environmental impact	19
recycling	16
sustainable fashion	16

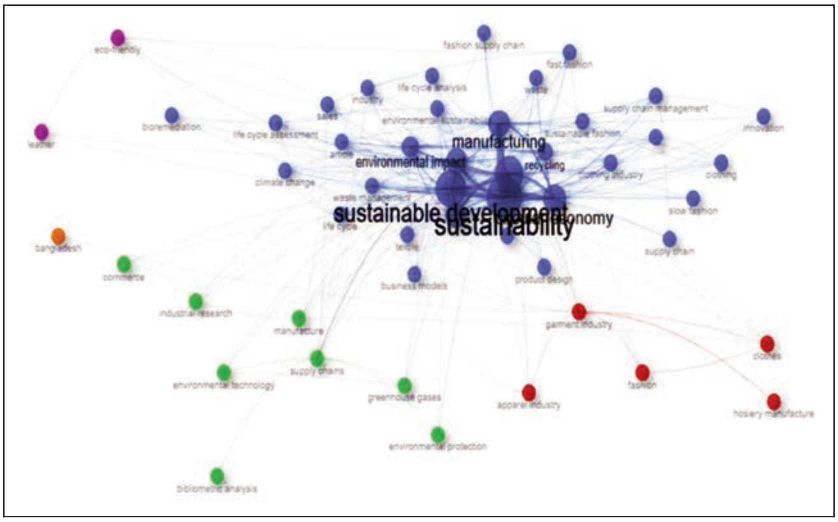

Fig. 5. Co-word networks

“manufacturing” predominate at the centre of the map, demonstrating their importance and frequent co-occurrence in academic literature. The focus on industrial and environmental sustainability is reflected in the various clusters that surround these central themes, such as recycling, life cycle assessment, and environmental impact. The fashion and garment industry is the focus of a noteworthy red cluster, with keywords like “fashion”, “apparel industry”, and “clothes”, indicating rising scholarly interest in environmentally friendly textile production methods. A research focus on technological and methodological advancements is suggested by the green cluster, which identifies themes associated with environmental technology, commerce, and bibliometric analysis. The inclusion of “Bangladesh” as a node highlights the geographic concentration of sustainability concerns in textile-producing regions, while other clusters delve into material-specific subjects like bioremediation and eco-friendly alternatives. With strong connections across the environmental, industrial, and geographic aspects of sustainability, the network map shows a well-developed but dynamic research landscape overall.

The structure and development of sustainability research themes, especially in the manufacturing and fashion industries, are depicted in the thematic map. Important motor themes like recycling, the fashion industry, the circular economy, sustainable development, and the textile sector are all well-developed and extremely pertinent, demonstrating their significant impact in the field. Although they are less developed, fundamental themes like supply chain management, manufacturing, and sustainability are crucial, indicating that they are areas that could use more in-depth research. Niche themes that cater to particular subfields, such as luxury consumption and manufacturing facilities, are well-developed but have little wider relevance. Digital fashion, customisation, and artificial intelligence, on the other hand, are underdeveloped and either gaining traction

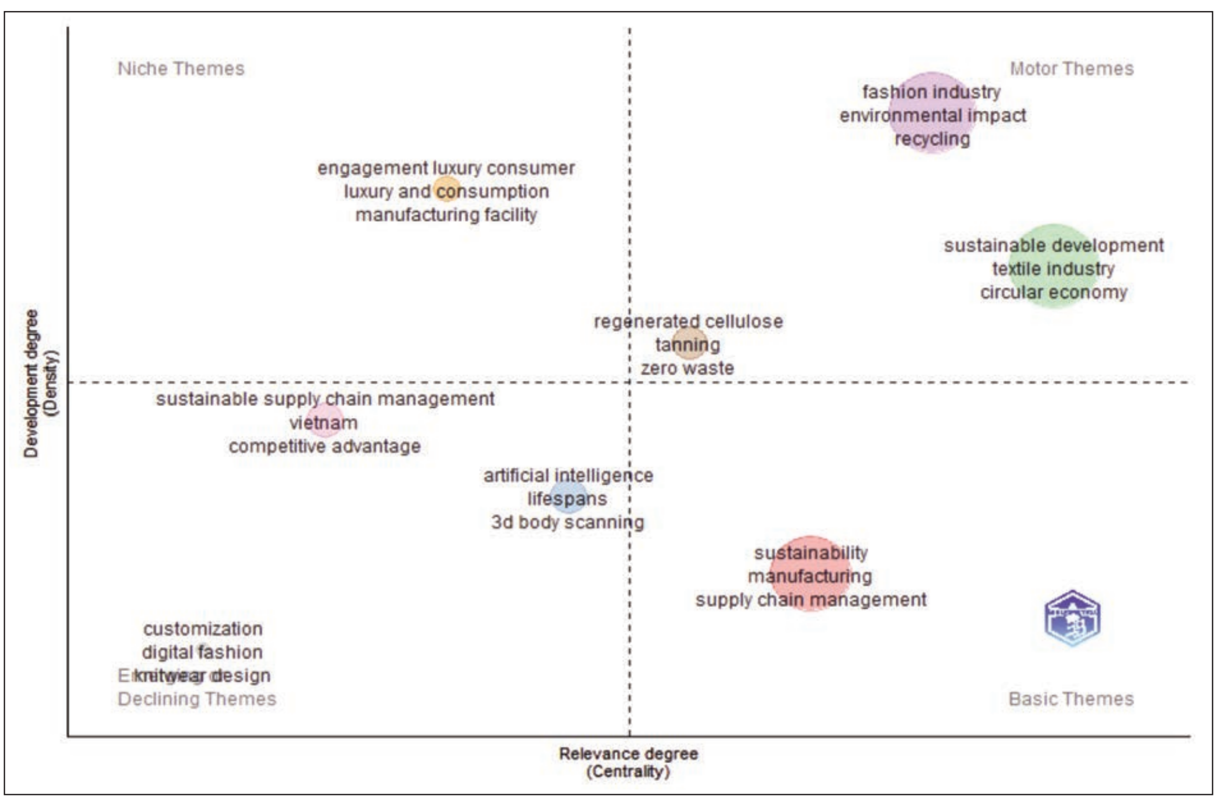

Fig. 6. Thematic map

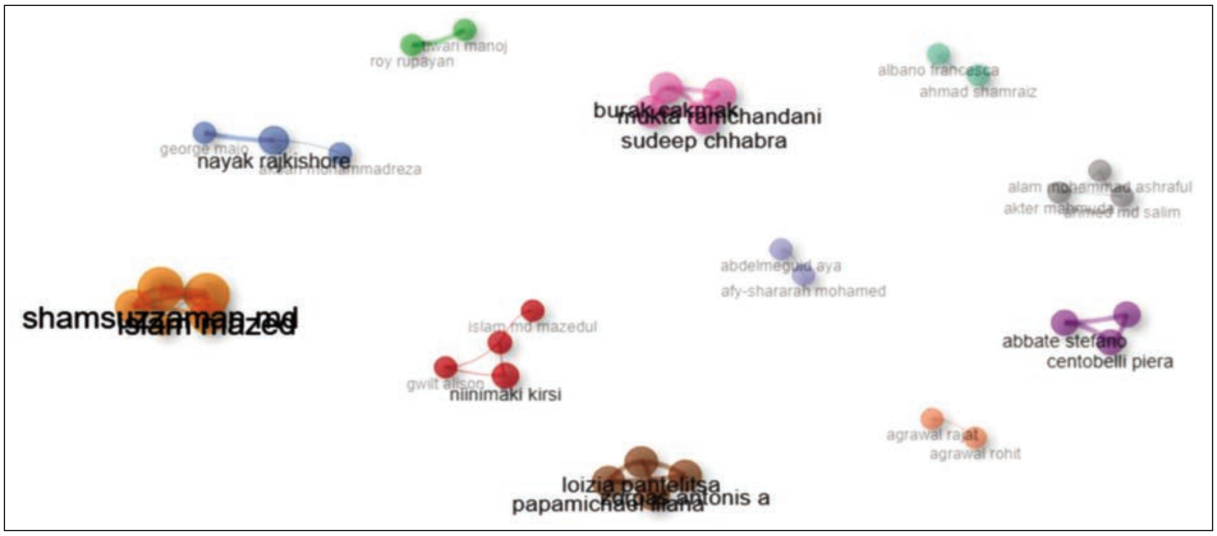

Fig. 7. Co-authorship network map

or losing relevance, as evidenced by their appearance in the emerging or declining themes quadrant. All things considered, the map offers a strategic summary of the main, emerging, and ancillary areas of sustainability research.

The co-authorship network map highlights different author clusters and shows the collaborative structure among researchers in the field. The most well-known group revolves around Zayed N.M., Islam M.T., and Shamsuzzaman M., suggesting a very active and significant research team.

Collaborations between Burak Erkayman and Sudeep Chhabra, as well as between Loizia P., Papamichael K., and Papadopoulos A., are other noteworthy clusters. These clusters indicate that specialised research teams are making major contributions to their fields. Smaller dyads indicate fewer partnerships with little cross-cluster connectivity. All things considered, the map shows a disjointed but fruitful research environment, with several important writers spearheading cooperative initiatives in their specialised fields.

DISCUSSION

The bibliometric analysis done for this study gives a full picture of how research in sustainable manufacturing in the fashion industry is changing over time. The big rise in publications after 2015, especially between 2020 and 2023, goes along with more people around the world learning about climate change, environmental damage, and how fast fashion makes these problems worse. This rise in academic work shows that people from different fields, like environmental science, business management, and social sciences, are becoming more interested in the same things.

Acloser look at the most productive authors and sources shows how concentrated the field's scholarly contributions are. Journals like Sustainability (Switzerland) and the Journal of Cleaner Production not only have the most articles, but they are also the most relevant. This shows that people prefer platforms that focus on environmental and sustainability issues. Important writers like Niinimäki K., Shamsuzzaman M., and Nayak R. have become well-known and have written articles that have had a big impact on consumer behaviour, the environmental impact of fast fashion, and the design of sustainable products.

Thematic mapping shows that there are different groups of research activity. Motor themes like recycling, sustainable development, the circular economy, and the fashion industry are well-developed and important to the field. Basic ideas like supply chain management and manufacturing are still important but not fully developed, which means there is room for more research. Digital fashion, customisation, and artificial intelligence are some new ideas that could lead to more sustainable innovation in the future, but they aren't yet widely studied in academia. Moreover, Siminică et al. [43] have highlighted the influence of artificial intelligence in the field of digital transformation and customer service personalization. Ullal et al. also investigated the linkage between green energy and AI, considering the complex implications [44]. Co-word network analysis shows that the research structure is strong but changing. Core keywords like "sustainability", "textile industry", and "environmental impact" are strongly linked to each other. On the other hand, geographic indicators like "Bangladesh" show how important textile manufacturing issues are on a global and regional scale.

Even though the field is growing, the analysis shows that there are still some big gaps. There isn't much collaboration between fields, especially between environmental science and social issues like worker welfare or consumer awareness. Research is still mostly done in developed countries, with few studies coming from developing countries, where most textile manufacturing takes place. There aren't enough empirical and policy-focused studies either, which shows that we need more studies that look at real-world situations over time. The co-authorship network analysis shows that there are scholarly communities that are broken up but still productive. There are strong groups of authors who work together, especially South Asian and European authors, but there isn't much cross-cluster connectivity.

Encouraging more collaboration between different fields and regions could lead to more new ideas and a bigger impact from research on sustainable manufacturing.

CONCLUSION AND DIRECTIONS FOR FUTURE RESEARCH

This bibliometric study shows that there is a lot of new research being done on sustainable manufacturing in the fashion industry. This is because people are becoming more concerned about the environment and the need for responsible production methods. The study points out important contributors, influential journals, and major research topics like the circular economy, recycling, and sustainable development. It also points out new fields like digital fashion and artificial intelligence that are still growing. The research landscape is still broken up, with few studies done in developing countries and few studies done in developed countries. This is strange because most of the fast fashion manufacturing happens in developing countries.

Future research should work to close these gaps by encouraging studies that bring together environmental science, social sustainability, and supply chain management. We need more real-world case studies and long-term analyses to understand how sustainable practices affect people in the real world. Also, including areas that aren't well represented, especially in Asia and Africa, will give us a better idea of how global sustainability efforts are working. Lastly, studies that are based on policy and research that is done together by schools, businesses, and governments will be very important for turning ideas about sustainability into real plans of action in the fashion manufacturing industry.

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Research on the construction and application of a multi-regional waterproof rating system for hard shell jackets

DOI: 10.35530/IT.077.01.202598

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ABSTRACT – REZUMAT

Research on the construction and application of a multi-regional waterproof rating system for hard shell jackets

As an important piece of outdoor protective clothing, the waterproof performance of hard shell jackets is a crucial indicator for measuring their functionality. Traditional testing methods, which are mostly based on the fabric level, fail to fully consider the complexity of clothing structures. This study proposes an innovative "multi-regional waterproof scoring system". Through simulated rainfall experiments, hard shell jackets were divided into key areas such as the head, neck, shoulders, and chest, and weighted scores were given according to the severity of water infiltration and its impact on wearing comfort. Six commercially available hard shell jacket samples were selected for systematic testing under different rainfall intensities. The results show that zippers and stitching parts are key factors affecting waterproof performance. This rating system can objectively and comprehensively evaluate the protective ability of the entire garment, holding important application value for product research and development, consumer guidance, and the improvement of industry testing standards.

Keywords: *hard shell jackets, waterproof performance evaluation, multi-regional scoring system, rainfall simulation testing, structural design optimisation*

Cercetare privind construirea și aplicarea unui sistem multiregional de evaluare a impermeabilității pentru jachetele cu înveliș exterior

Fiind o piesă importantă de îmbrăcăminte de protecție pentru exterior, performanța de impermeabilitate a jachetelor cu înveliș exterior este un indicator crucial pentru măsurarea funcționalității acestora. Metodele tradiționale de testare, care se bazează în mare parte pe nivelul țesăturii, nu reușesc să ia în considerare pe deplin complexitatea structurilor de îmbrăcăminte. Acest studiu propune un „sistem inovator de evaluare a impermeabilității în mai multe regiuni". Prin experimente simulate de precipitații, jachetele impermeabile au fost împărțite în zone cheie, cum ar fi capul, gâtul, umerii și toracele, și au fost date scoruri ponderate în funcție de gravitatea infiltrării apei și de impactul acesteia asupra confortului la purtare. Au fost selectate șase eșantioane de jachetă impermeabilă disponibile în comerț pentru testare sistematică la diferite intensități ale precipitațiilor. Rezultatele arată că fermoarele și îmbinările sunt factori cheie care afectează performanța de impermeabilitate. Acest sistem de evaluare poate evalua în mod obiectiv și cuprinzător capacitatea de protecție a întregului articol de îmbrăcăminte, deținând o valoare importantă de aplicare pentru cercetarea și dezvoltarea produselor, îndrumarea consumatorilor și îmbunătățirea standardelor de testare din industrie.

Cuvinte-cheie: *jachete cu înveliș exterior, evaluarea performanței de impermeabilitate, sistem de notare multiregional, testare de simulare a precipitațiilor, optimizarea proiectării structurale*

INTRODUCTION

Hard shell jackets are essential for outdoor activities and harsh climates. Their core performance depends on fabrics that block liquid water yet allow water vapour to escape, ensuring dry and comfortable wear [1, 2]. These fabrics block liquid water while allowing water vapour to escape, ensuring comfort. The waterproof and breathable functions are typically realised through three types of technologies: membrane technology, coating treatment, and lamination processes [3, 4]. Studies have shown that nanofiber membranes prepared by electrospinning technology feature high porosity and specific surface area, which can significantly enhance water vapour transmission rates while maintaining good waterproof performance [5–7]. In addition, the application of surface hydrophobic treatment and hydrophobic finishing agents can significantly enhance the water repellency of fabrics [8, 9].

Three-layer structured laminated materials can enhance the mechanical strength of fabrics while maintaining waterproof performance [10, 11]. In recent years, studies have increasingly focused on smart and integrated functions. For example, temperature-responsive materials and graphene-based components enable adaptive breathability and wearable sensing. Researchers have applied temperature-responsive materials and two-dimensional nanomaterials, such as graphene, to fabrics to achieve environment-adaptive breathable regulation and wearable sensing functions [12–15]. These advances are driving outdoor clothing toward high performance with smart integration. At the same time, the concept of sustainable development has prompted the academic community to explore bio-based materials. For example, alginate is blended with aramid to prepare fabrics, which are used to enhance the flame retardancy and environmental friendliness of protective clothing [16]. The design of hard shell jackets integrated with solar cells has also emerged, balancing protective functions and emergency energy supply [17].

Waterproof performance is commonly assessed by spray tests (e.g., AATCC TM22, ISO 4920) and hydrostatic pressure tests (e.g., ISO 811), which respectively measure surface water repellency and resistance to water penetration [18–21]. However, because most standards evaluate fabrics rather than full garments, they struggle to capture performance under realistic wearing conditions. [22, 23]. Hard shell jackets have complex structures, and parts such as seams, zippers, and hoods are often weak areas in waterproofing. Traditional tests struggle to cover their overall protective capabilities [24]. Structural design elements, such as magnetic buttons, spliced sleeves, and sealed zippers, also have a significant impact on waterproof performance.

In recent years, researchers have gradually recognised the necessity of regional evaluation in reflecting the overall performance of garments. Different parts of hard shell jackets are exposed to rain at varying frequencies and pressures, imposing differentiated zonal requirements on their protective performance. Zonal graded testing can identify weak protective points, providing a scientific basis for functional optimisation and structural adjustment.

To address the deficiencies of current standards in evaluating the waterproof performance of garments at the clothing level, this paper proposes the construction of a "multi-regional waterproof scoring system for hard shell jackets". Through empirical research, the waterproof performance of each region is systematically evaluated, aiming to provide precise references for consumers and assist enterprises in product structural optimisation and quality improvement.

MATERIALS AND METHODS

Information on samples

This study selected 6 representative brand hard shell jacket samples from the market, covering different structural designs and material compositions. All samples were men's models (size L or XL) to ensure the consistency and representativeness of the experiment. These samples differ in waterproof fabrics, zipper types, stitching processes, etc., which helps evaluate their regional waterproof performance from multiple perspectives. The basic information of the hard shell jacket samples is shown in table 1.

In addition, each sample was photographed in kind to record its overall structure, providing an intuitive basis for subsequent regional analysis. The physical images of the hard shell jacket samples are shown in figure 1.

Design of the experiment

This study used a high-precision rainfall simulation system to conduct dynamic tests. The system provides adjustable flow, uniform distribution, and stable

Table 1

BASIC INFORMATION OF HARD SHELL JACKET SAMPLE

Sample no.	Brand	Product name	Style no.	Colour	Nominal fabric composition	Size
1	A	Men's Hard Shell Jacket	114301063	Black	Outer layer: 100% nylon Inner layer: 100% polyester (excluding film) Checkered pocket lining: 100% polyester	L
2	B	Hard Shell Jacket	NF0A86WG	Orange	Fabric: 100% nylon Excluding decorative parts/elastic fibres	L
3	C	Men's Hard Shell Jacket	A14CATR861	Purple	Outer layer: 100% polyester Inner layer: 100% polyester	L
4	D	Hard Shell Jacket	KG2411112	Yellow	100% nylon	L
5	E	Men's Woven Sports Top	152427626-1	Olive green	Outer layer: 100% polyester Inner layer: 100% polyester	L
6	E	Men's Lightweight Hard Shell Jacket	152430616-1	Olive green	Fabric - 100% nylon Fabric - Inner layer: 100% nylon Pocket lining - Outer layer: 100% nylon Pocket lining - Inner layer: 100% nylon	XL

Fig. 1. Physical images of hard shell jacket test samples (categorized by brand and product type): *a* – Brand A – Men's Hard Shell Jacket; *b* – Brand B – Hard Shell Jacket; *c* – Brand C – Men's Hard Shell Jacket; *d* – Brand D – Hard Shell Jacket; *e* – Brand E – Men's Woven Sports Top; *f* – Brand E – Men's Lightweight Hard Shell Jacket

spraying, realistically reproducing multi-level rainfall. Coupled with the zones in the next section, it exposes at-risk areas to realistic wetting patterns for reproducible whole-garment assessment.

Setting of rainfall intensity

According to the meteorological standard classification of rainfall intensity (light rain, moderate rain, heavy rain, torrential rain), this study set four levels of rainfall flow as simulation parameters, as follows:

- Light rain: 5 l/h
- Moderate rain: 15 l/h
- Heavy rain: 30 l/h
- Torrential rain: 60 l/h.

This study set each rainfall test to 30 min to fully expose performance at the corresponding intensity while limiting system error and external interference; the duration also aligns with typical outdoor rainfall.

Composition of the experimental system

The testing system consists of the following main components:

- Rainfall simulation system: A multi-nozzle uniform rainfall system for flow control;
- Garment support device: Equipped with a wearable dummy model (with a realistic wearing structure);
- Internal circulation system: Enables water recycling to save water.

This study dressed the dummy in a standard wearing state and adjusted all zippers, fasteners, and the hood according to the user guidelines; all tests used the same space and time window to control environmental variation. To facilitate replication, figure 2 lists the full setup, components, and the schematic diagram of the rainfall simulation system; the test duration settings are defined in the previous section, and an example of the rain test for samples is shown in figure 3.

Observation indicators

This study quantified waterproof performance under dynamic rainfall using a structured, multi-region indicator system designed to reflect how rain impinges on garments in use. The framework builds on traditional appearance-based evaluation and considers both function and wearer comfort.

Zonal partitioning and evaluation logic

According to the structural design of the garment and the exposure degree of key human activity areas, the entire hard shell jacket is divided into the following four core functional areas:

- Head Area: Corresponding to the hood and brim, it is the area most directly exposed to rainfall. The evaluation mainly focuses on the anti- infiltration capability of the hood and brim structure.
- Neck Area: One of the parts where the garment fits most closely to the skin. If the sealing performance is insufficient, rainwater can easily penetrate through the splicing gaps.

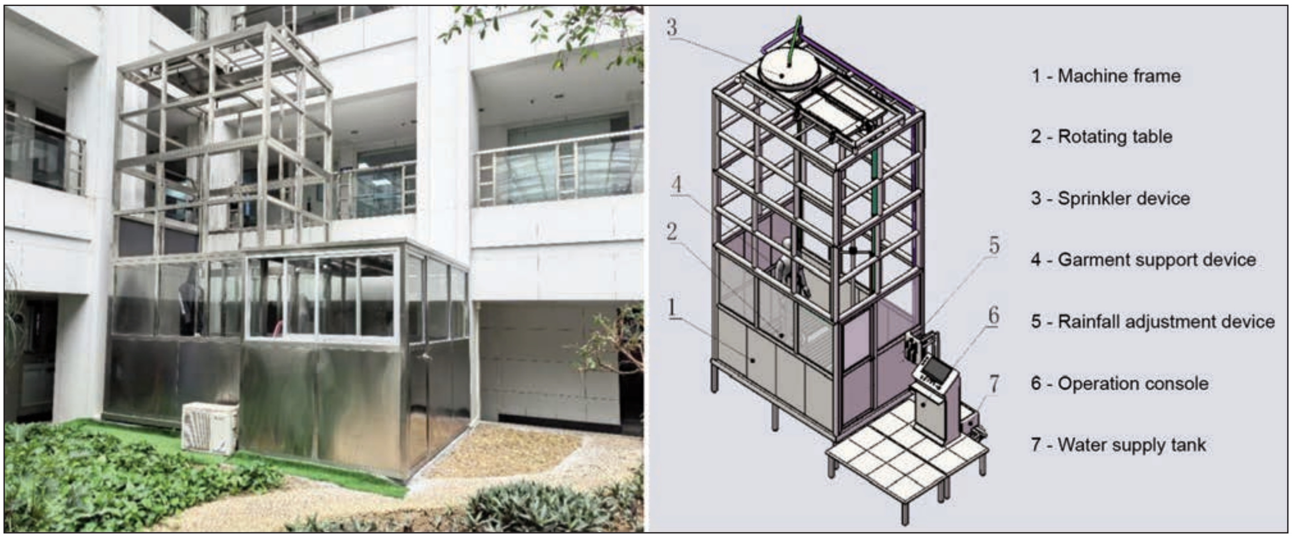

Fig. 2. Example of a rainfall simulation system

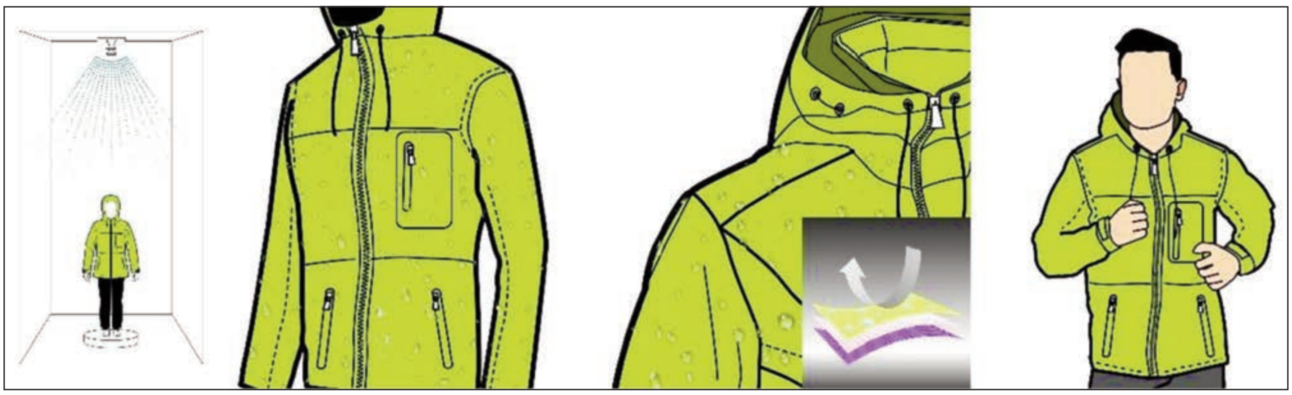

Fig. 3. Example of rain test for samples

- Shoulders Area: This area is subjected to greater force when wearing a backpack or exercising. The sealing integrity of stitching strips and fabric connections is particularly critical.
- Chest Area: Usually containing the main zipper structure, it is one of the areas with the highest waterproof risk. The key observations include the zipper protection piece and the sealing treatment of stitching seams.

These zones mirror typical outdoor exposure: direct impingement at the hood/brim, ingress along neck interfaces, load-affected seams at the shoulders, and runoff/zipper pathways across the chest.

Figure 4 shows the regional division. The evaluation focuses on infiltration in the lining and base layer, supplemented by external structural observations.

Observation methods and recording methods

To enhance the objectivity of interpretation and the intuitiveness of comparison, a grey highly hygroscopic base layer is used as the water infiltration display substrate during the test. Its colour difference is significant when wet, which helps identify the water infiltration trajectory and scope in each area, as shown in figure 5. In addition, after each round of testing, high-definition photography is immediately used to record before-and-after comparisons, supplemented by infrared imaging technology to correct judgment errors caused by local reflection or light changes.

Fig. 4. Key areas for key observation of hard-shell ackets: *1* – Head; *2* – Neck; *3* – Shoulders; *4* – Chest

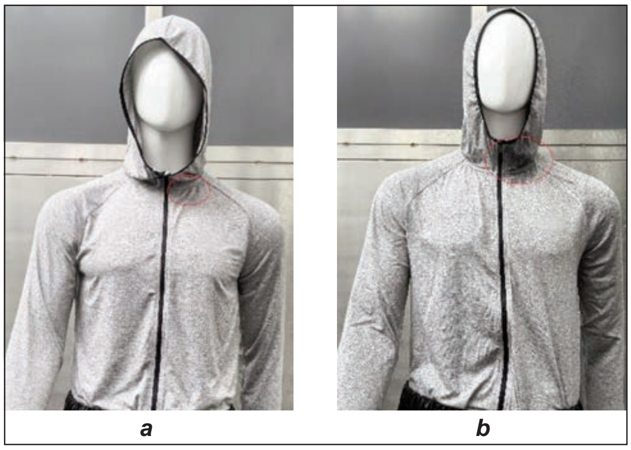

Fig. 5. Examples of the base underwear layer before and after water absorption and wetting: *a* – before; *b* – after

Water infiltration degree grading standard
In this study, the water infiltration conditions of each garment area were classified into the following four states, with corresponding quantitative scores assigned:

- Dry (Score 0): No obvious wet marks observed on the surface or interior.
- Moist (Score 1): Local fabric surface is wet but has not penetrated the inner layer, and no water droplets are formed.
- Water pooling (Score 2): Liquid water accumulates in structural parts of the garment, such as water pools in pockets.
- Soaked (Score 3): Both the inner and outer layers of the garment are wet, and the base underwear layer shows an obvious colour change.

Special Note: If the observation object is the base underwear layer, it is only divided into two levels: "Dry" and "Completely Soaked" (Scores 0 and 1), to reflect the sensitivity to the direct impact on wearing comfort.

Multi-regional waterproof scoring system

This study constructed a multi-index comprehensive scoring model based on zonal weighting. The calculation formula of the model is as follows:

$$S_{total} = \Sigma_{i=1}^{n} S_i \cdot W_i \qquad (1)$$

where W is the waterproof score (overall score for the garment); S_i – observation score of the i-th area; W_i – weight assigned to the i-th area; n – total number of garment areas considered.
The design of each weight is based on the following principles. Regional weights (W_r) are summarised in table 2 and reflect wearer protection and ingress risk. Table 2 provides an at-a-glance summary linking the zones, the corresponding scoring rules, and the assigned weights; lower scores indicate better waterproof performance. Level definitions are given in the previous section.

Data collection and error control

This study tested each sample three times at every rainfall intensity and used the average as the final score. Two trained observers cross-validated the ratings, and the protocol adopted a blind procedure to minimise subjective bias. All tests were conducted in the same experimental environment to avoid external interference.

Table 2

MULTI-REGION WATERPROOF SCORING SYSTEM FOR HARD SHELL JACKETS

Inspection area		Description and scoring	Weight
The pockets of the jacket		Levels per section *Water infiltration degree grading standard* (0–3)	1.0
Inner surface of jacket lining	Head	Binary per section *Water infiltration degree grading standard* (0/1)	2.0
	Neck		2.0
	Shoulders		2.0
	Chest		2.0
	Others		1.5
Base underwear layer	Head		3.0
	Neck		3.0
	Shoulders		3.0
	Chest		3.0
	Others		2.0

RESULTS AND DISCUSSION

This study analysed waterproof performance across four rainfall intensities using the multi-regional scoring system. Six commercial jackets were tested, and all data were recorded and statistically evaluated. Through comparisons of regional scoring results, overall score trends, typical water infiltration patterns, and material composition differences, the comprehensive impacts of various factors on the garment's waterproof performance were discussed.

Statistical analysis of regional scoring

Table 3 shows the zonal scores of six hard shell jackets quantified by the scoring system under four simulated rainfall conditions: light rain, moderate rain, heavy rain, and torrential rain. Overall, Sample 2 exhibited more frequent infiltration in light to moderate rain, especially moisture at the neck and the base-layer chest. This pattern suggests insufficient protection around the main zipper. Sample 4 showed no notable infiltration at any rainfall intensity, indicating consistently strong protection.
Figure 6 further statistically analysed the frequency of water infiltration in each key area. The chest and pocket areas showed the highest overall water infiltration frequency, indicating that these parts were common weak links in structural design and sealing treatment of current products.

Pearson correlation analysis between jacket samples and regional waterproof scores

To further examine the influence of garment structure and material differences on regional waterproof

Table 3

STATISTICAL TABLE OF SCORING RESULTS BY REGION FOR EACH SAMPLE							
Rainfall condition	**Region**	**Sample 1#**	**Sample 2#**	**Sample 3#**	**Sample 4#**	**Sample 5#**	**Sample 6#**
Light rain (5 l/h)	the pockets of the jacket	0	0	0	0	2	2
	inner surface of jacket lining	0	2	0	0	0	0
	base underwear layer	0	3	0	0	0	0
Moderate rain (15 l/h)	the pockets of the jacket	2	0	2	0	2	2
	inner surface of jacket lining	1.5	2	0	0	0	0
	base underwear layer	2	3	0	0	0	0
Heavy rain (30 l/h)	the pockets of the jacket	2	0	2	0	2	2
	inner surface of jacket lining	0	2	0	0	0	0
	base underwear layer	0	3	0	0	0	0
Torrential rain (60 l/h)	the pockets of the jacket	2	0	0	0	2	2
	inner surface of jacket lining	0	0	0	0	0	0
	base underwear layer	0	0	0	0	0	0

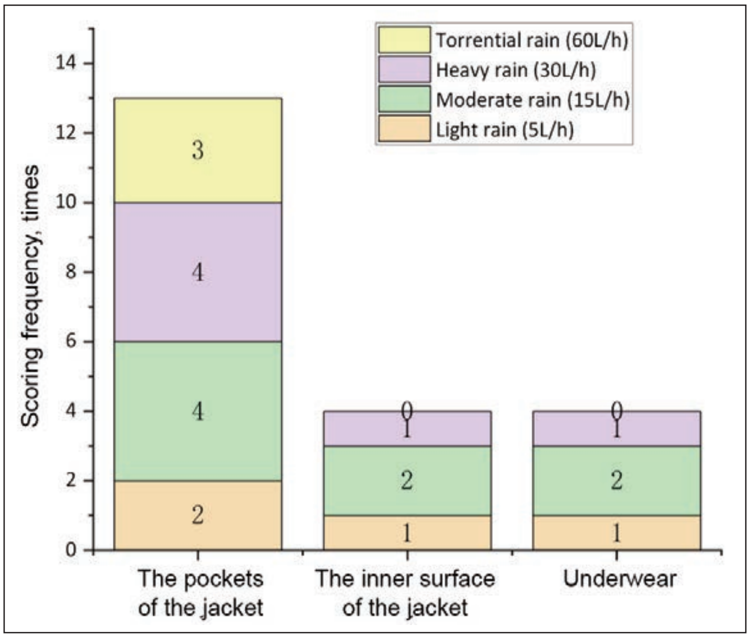

Fig. 6. Statistical chart of scoring frequency in each region

performance, Pearson correlation analysis was conducted to explore the relationships between clothing sample identifiers and scores across three key functional zones: pocket areas, inner surface of jacket lining, and base underwear layer. The results are presented in tables 4 to 6.

Table 4

PEARSON CORRELATION ANALYSIS OF CLOTHING SAMPLE AND POCKETS SCORE	
Variable	**Pockets Score**
Pearson correlation coefficient	0.367*
Significance (2-tailed)	0.078
N (Sample Size)	24

Note: * Correlation is not significant at the 0.05 level (2-tailed).

As shown in table 4, the correlation coefficient between sample number and pocket score was 0.367, with a p-value of 0.078. This indicates a moderate positive trend, but the result does not reach statistical significance ($p>0.05$). Therefore, it can be concluded that there is no statistically significant linear relationship between the specific clothing samples and their performance in pocket waterproofing. This may be attributed to the high variability in pocket design across samples, with factors such as flap structure, drainage design, and sealing treatment differing substantially, resulting in inconsistent outcomes.

In contrast, table 5 reveals a statistically significant negative correlation between clothing sample and inner surface of jacket lining score, with a Pearson coefficient of −0.434 and a p-value of 0.034 ($p<0.05$). This suggests that as the sample number increases (i.e., from sample 1 to 6), the inner surface of the jacket lining's waterproof performance improves (indicated by lower scores). Such a result implies that garments with more advanced or refined construction, such as taped seams, laminated linings, and integrated waterproof panels, are

Table 5

PEARSON CORRELATION ANALYSIS OF CLOTHING SAMPLE AND INNER SURFACE OF JACKET LINING SCORE	
Variable	**Inner surface of jacket lining score**
Pearson correlation coefficient	–0.434*
Significance (2-tailed)	0.034
N (Sample Size)	24

Note: * Correlation is significant at the 0.05 level (2-tailed).

more effective in preventing water infiltration into the internal layers.

Similarly, table 6 shows a significant negative correlation between sample number and base underwear layer score, with a coefficient of −0.442 and a p-value of 0.031. This finding indicates that garments with more robust structural waterproofing features are less likely to allow moisture penetration to the base layer, which directly impacts wearer comfort. The base underwear layer score, representing the final line of defence, serves as a sensitive indicator of total waterproof system failure; thus, lower values in later samples reflect superior design and material integration.

Table 6

PEARSON CORRELATION ANALYSIS OF CLOTHING SAMPLE AND BASE UNDERWEAR LAYER SCORE

Variable	Base underwear layer score
Pearson correlation coefficient	–0.442*
Significance (2-tailed)	0.031
N (Sample Size)	24

Note: * Correlation is significant at the 0.05 level (2-tailed).

While the correlation between pocket score and sample is not statistically significant, both the inner surface of the jacket lining and the base underwear layer exhibit significant negative correlations with sample identifiers. These results underscore the importance of garment-level structural waterproofing in determining actual protective performance. They also validate the effectiveness of the proposed multi-regional scoring system in sensitively identifying critical vulnerabilities in jacket designs under simulated rainfall conditions.

Overall waterproof score comparison

Figures 7 and 8 show the total scores of six hard shell jackets under different rainfall conditions and their radar chart distributions, respectively. A lower score indicates better waterproof performance.

Observations from the radar charts show that:

- Sample 4# has the lowest overall score, maintaining good protection under all rainfall intensities.
- Sample 2# has higher scores in multiple rainfall intensities, indicating obvious deficiencies in its overall waterproof performance.
- Samples 5# and 6# show average overall performance, but their pockets have Water pooling under all rainfall intensities, indicating defects in the waterproof design of the pockets that need improvement.

This result verified the sensitivity and scientificity of the zonal scoring system in distinguishing the protection capabilities of different structural schemes.

Analysis of typical waterproof failure modes

Guided by the zonal scores, we inspected low-scoring regions and observed the following typical failure patterns under simulated rainfall. Figure 9 shows typical waterproof failure cases recorded during the testing process, from which the following common failure modes are summarised:

- Zipper water infiltration: The main zipper area fails due to insufficient width of the protective piece or lack of sealing glue, causing rainwater to penetrate the chest along the zipper track.
- Poor seam sealing: The connecting seams between the shoulder and hood are not fully taped, allowing rainwater to enter the inner layer through gaps.
- Structural water pooling: Some pocket designs have flanged edges or lack drainage holes, making them prone to water accumulation and infiltration into the lining.
- Design and manufacturing implications are straightforward: widen or stiffen the storm flap and consider waterproof zippers to block track ingress; ensure continuous seam taping at hood–shoulder junctions with adequate seam allowance; add drainage or re-orient pocket openings to avoid water pooling.

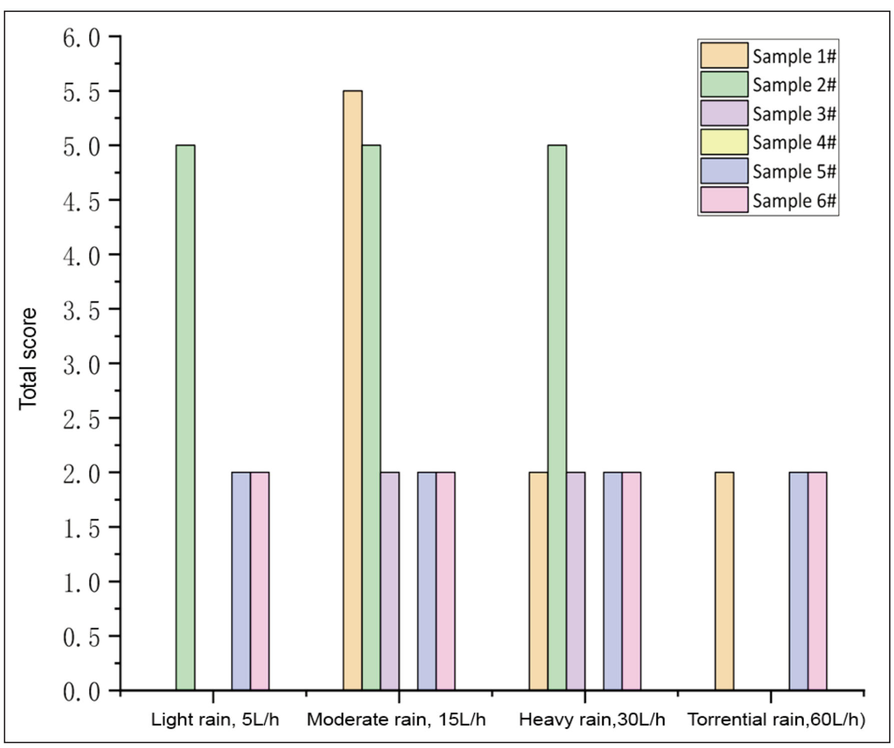

Fig. 7. The total waterproof scores of each sample

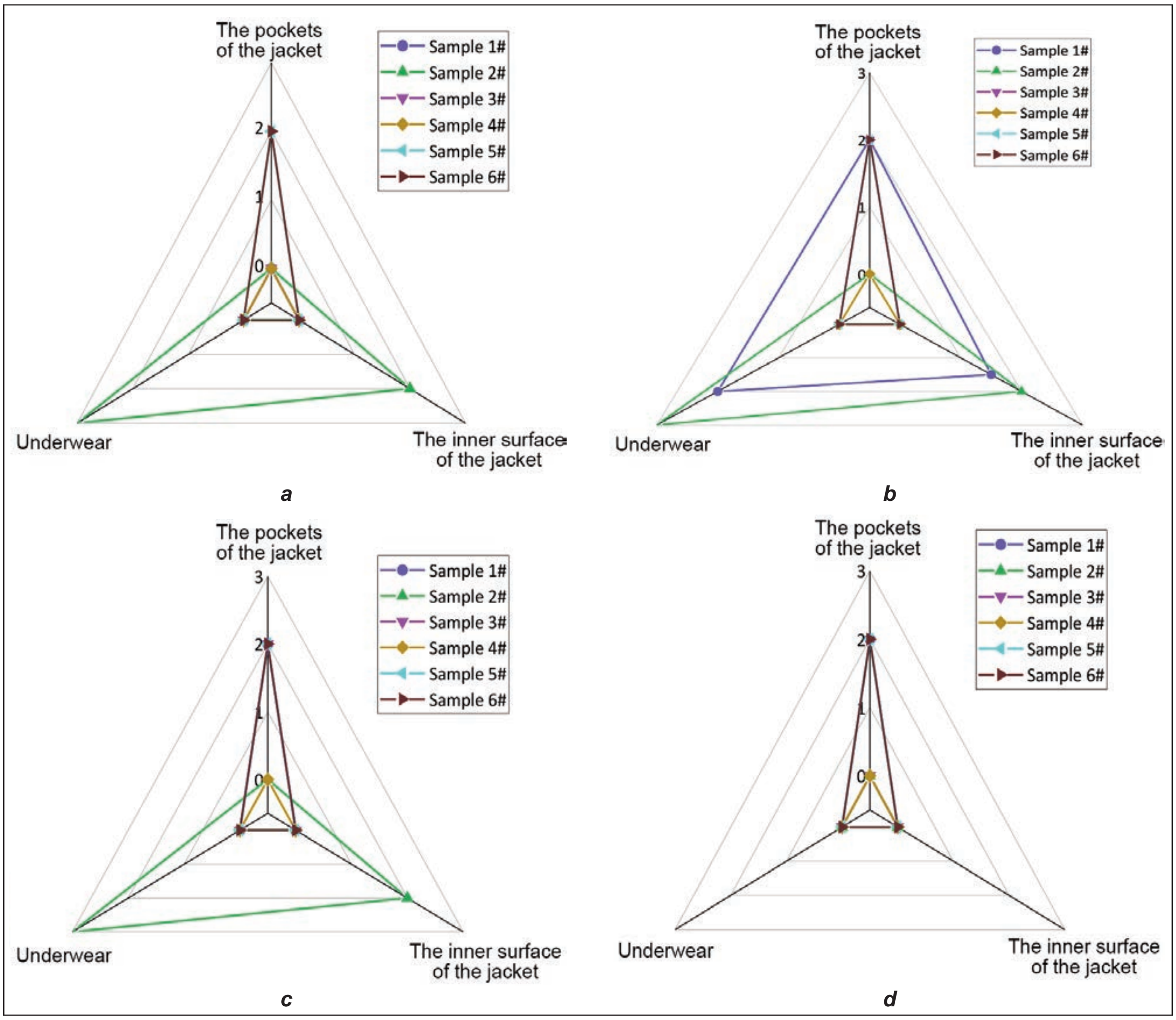

Fig. 8. Radar chart of total waterproof scores for each sample: *a* – light rain (5 l/h); *b* – moderate rain (15 l/h); *c* – heavy rain (30 l/h); *d* – torrential rain (60 l/h)

Fig. 9. Typical waterproof failure cases: zipper infiltration, incomplete seam sealing, and pocket water pooling

These phenomena are all reflected in the scoring results, indicating that the scoring system has practical value in identifying weak links.

Analysis of the relationship between fabric structure and waterproof performance

A review of the fabric information of the samples reveals that some samples with excellent scores, such as Sample 4#, mostly use three-layer composite structures or fabrics with DWR (durable water repellent) treatment on the surface, and their zippers and splicing parts are mostly equipped with hot-pressed adhesive strips or waterproof cover designs. In contrast, samples with poor scores often lack systematic sealing designs or use ordinary double-layer materials.

The combined analysis results of table 3 and the basic sample information show that fabric composition has a fundamental impact on overall waterproofness, but the packaging processes of structural details, such as taping, flanging, waterproof lip design, etc., are key factors determining actual performance.

Adaptability of the scoring system and standard extension value

The multi-regional waterproof scoring system established in this study can identify water infiltration risks in detailed structures under wearing conditions, effectively addressing the limitations of traditional fabric testing methods in overall garment evaluation. Compared with existing fabric-level testing methods such as ISO 811 and ISO 4920, this system better simulates real-world usage scenarios and applies to product R&D, quality assessment, and consumer guidance. Using the same exposure duration defined in the previous section, the method yields an overall grade together with zone scores. Table 2 summarises the weighting, and table 8 provides the final grade scale. This combined view supports targeted redesign and procurement decisions while remaining compatible with standard garment-level rain tests.

Regression Modelling of Sample Number and Regional Waterproof Scores

To further elucidate the influence of jacket design and material differences on regional waterproof performance, this study employed regression analysis to quantify the relationship between the clothing sample number and waterproof scores in three critical areas: pockets, inner surface of jacket lining, and base underwear layer. Linear and polynomial regression models were constructed based on scatter plot trends to assess the explanatory power of sample differences on regional performance variation.

Linear regression analysis

Figure 10 illustrates the linear regression trends between clothing sample number and scores in each region. The corresponding regression equations and R^2 values are as follows:

- Inner surface of jacket lining score:
  $y = 0.692 - 0.132 \times \text{sample}$
  $R^2 = 0.188$
- Pocket score:
  $y = 0.167 + 0.107 \times \text{sample}$
  $R^2 = 0.135$
- Base underwear layer score:
  $y = 0.950 - 0.182 \times \text{sample}$,
  $R^2 = 0.1195$

Here, *y* denotes the regional score, *sample* denotes the jacket ID (1–6), and R^2 denotes the coefficient of determination.

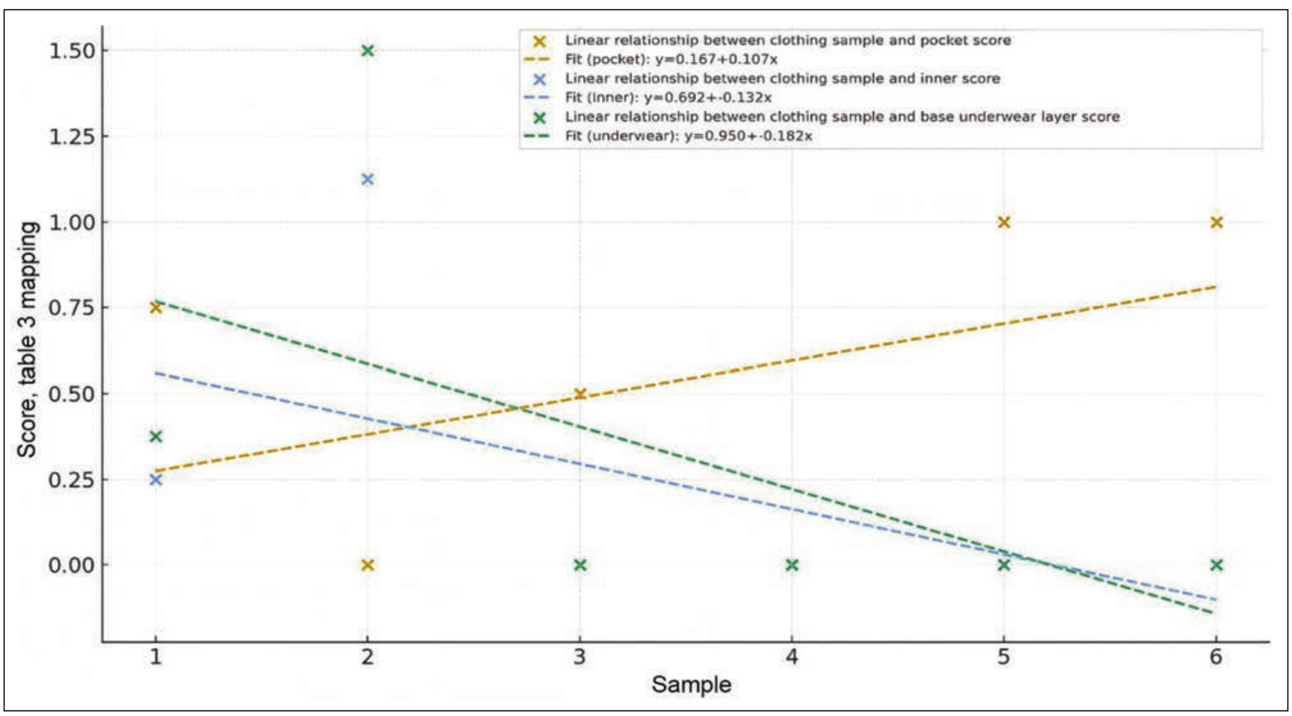

Fig. 10. Combined linear relationships between clothing sample and pocket/inner/base-underwear scores

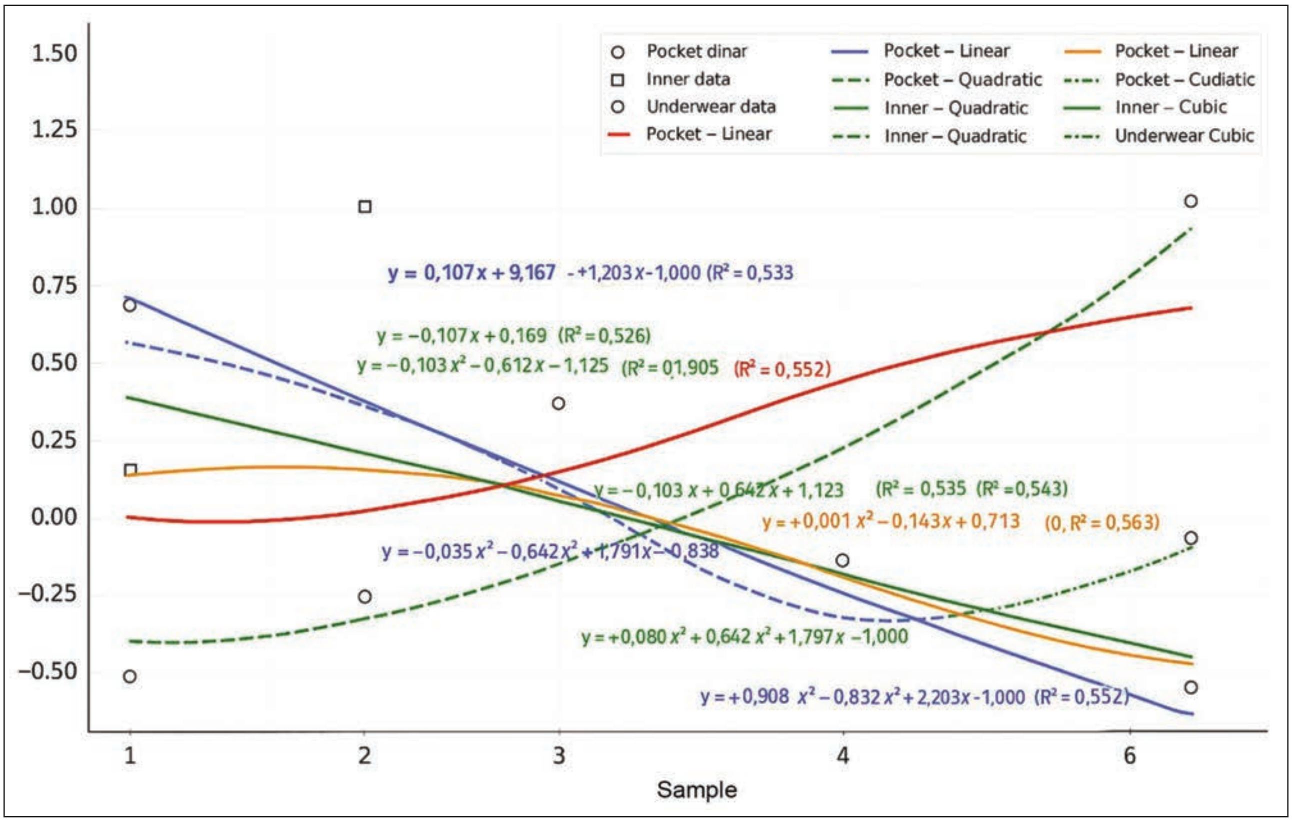

Fig. 11. Pocket, inner, and base-layer scores vs. sample: linear, quadratic, and cubic fits

These results indicate that, under a linear framework, the sample number explains only 11.9% to 18.8% of the variance in regional waterproof scores. The explanatory power of the linear model is therefore limited. This suggests that while structural and material differences across samples do exert some influence, the relationships are likely to be nonlinear or affected by other interactive variables such as seam complexity, zipper design, and surface treatments, which are not adequately captured by a simple linear approximation.

Polynomial regression analysis

To improve model fit and capture potential nonlinearities, polynomial regression models were constructed. Figure 11 presents the best-fitting polynomial trends for each regional score. The polynomial models yielded substantially improved coefficients of determination (R^2), indicating moderate explanatory power:

- Pocket score (Quadratic Fit):
  $R^2 = 0.452$

This suggests that the model explains 45.2% of the variance in pocket waterproof performance, revealing more complex, non-monotonic influences possibly related to specific pocket design elements.

- Inner surface of jacket lining score (Cubic Fit):
  $R^2 = 0.339$

The cubic model accounts for 33.9% of the variance in inner layer scores, indicating moderate explanatory power and reflecting the nuanced relationship between garment construction and internal protection.

- Base underwear layer score (Cubic Fit):
  $R^2 = 0.334$

The model explains 33.4% of the variation in base underwear layer score, reinforcing the relevance of higher-order modelling to capture cumulative effects of structural features.

Summary and interpretation

The improved R^2 values in polynomial models underscore the inadequacy of linear regression in capturing the complex interplay between structural design elements and waterproof performance. While the models remain moderate in explanatory strength, they provide useful insights into performance patterns and may serve as a reference for more refined predictive modelling in future research. These results also support the validity of the multi-regional scoring system, as it successfully differentiates samples based on actual protective performance under simulated rainfall.

CONSTRUCTION AND APPLICATION OF MULTI-REGIONAL SCORING SYSTEM

Building on a review of existing waterproof testing systems, we combine rainfall simulation with garment structural features to develop an adaptable, scalable, multi-regional scoring system for hard shell jackets. Taking structural zoning, weight assignment, and state quantification as the core methods, the model aims to achieve a comprehensive quantitative evaluation of the overall waterproof performance of the entire garment.

Structure and calculation formula of the scoring model

The overall waterproof scoring system is built on the multi-regional scoring system and assigns weights based on the actual impact of different rainfall intensities on the garment's waterproof function. The calculation formula of the model is as follows:

$$S_{total} = \sum_{i=1}^{n} S_i \cdot W_i \qquad (1)$$

where S_{total} is the overall waterproof score of the garment; S_i – waterproof score under the i-th rainfall intensity; W_i – weight coefficient corresponding to the i-th rainfall intensity; n – total number of rainfall intensities.

Intensity weights are summarised in table 7; definitions are given in previous section. The model can expand the regional dimension according to the application scenarios, and has good adaptability.

Table 7

WEIGHT SETTINGS FOR RAINFALL INTENSITIES

Rainfall Intensity	Weight	Description
Light rain	0.1	High frequency but low intensity
Moderate rain	0.2	Common scenario
Heavy rain	0.3	Risk escalation
Torrential rain	0.4	Extreme conditions

Classification criteria for scoring grades

To facilitate result interpretation and user decision-making support, this study further classifies the overall scores into three grades, as shown in table 8.

The grading system provides intuitive references for consumers, testing institutes, and enterprises, supporting cross-product comparisons and procurement decisions.

Table 8

CLASSIFICATION CRITERIA FOR SCORING GRADES

Overall score range	Waterproof performance grade	Description
0–1	Grade A	No water infiltration; excellent structural sealing and material protection
1–2	Grade B	Slight wetting in individual areas; can meet the usage requirements in moderate rainfall environments.
>2	Grade C	Multiple water infiltration or water accumulation; significant structural defects exist; recommended to avoid use in heavy rainfall environments.

Application example of the model in product testing

The scoring model was applied to analyse the results of this experimental test, as shown in table 9.

Table 9

CLASSIFICATION OF SCORING GRADES FOR THIS EXPERIMENTAL RESULT

Sample no.	Overall score	Waterproof performance grade
1#	2.5	Grade C
2#	3	Grade C
3#	1	Grade A
4#	0	Grade A
5#	2	Grade B
6#	2	Grade B

According to the scoring results in the table, Samples 1# and 2# received overall scores of 2.5 and 3, both classified as "Grade C". This indicates multiple water infiltration or accumulation issues in actual testing, significant structural defects, and unsuitability for heavy rainfall environments. It is recommended to systematically optimise the waterproof structural design. Samples 3# and 4#, with overall scores of 1 and 0, respectively, were rated "Grade A", meaning essentially no water infiltration and excellent structural sealing and material protection. In particular, Sample 4#'s zero-infiltration performance strongly verifies the outstanding reliability of its waterproof technology. Samples 5# and 6#, both with an overall score of 2, fall into the "Grade B" grade, indicating slight wetting in individual areas. While they can meet the usage requirements in moderate rainfall environments, there is still room for improvement. These results show that the scoring model accurately quantifies garment waterproof performance and pinpoints design deficiencies. The actionable grades guide design optimisation and process control, helping raise industry waterproofing standards (table 9 and figure 9). Readouts at the zone level, therefore, translate into targeted fixes, zipper flap/garage optimisation, complete seam sealing at critical joints, and pocket drainage or cover redesign, before re-testing to confirm gains in the affected scores.

Practical applicability and industry value

This model is practical to implement and delivers value at multiple levels. Because the protocol pairs a controllable rainfall simulator with anatomically grounded zones, its outcomes track outdoor wearing conditions, making the results actionable for design and procurement. Using the same exposure duration defined in the previous section, the method yields an overall grade together with zone scores. Table 2 summarises the weighting, and table 8 provides the final grade scale. This combined view supports targeted redesign and procurement decisions while remaining compatible with standard garment-level rain tests.

- Product R&D optimisation: Identifies weak protection links and supports structural optimisation and adjustment of material selection strategies.
- Consumer guidance and label design: In the future, a "regional protection label" can be developed

based on scoring results to enhance the accuracy of users' purchase decisions.
- Standard system extension: The model can serve as a supplementary dimension to the existing garment testing system, promoting the industry's transformation to a testing model of "functional zoning-wearing status-situation adaptation".
- Multi-category expansion: The model's methodology is universal and applicable to various protective garments such as softshell jackets, raincoats, and cycling suits.

CONCLUSION

The proposed multi-regional waterproof rating system yields a concise whole-garment grade while revealing actionable zone-level weaknesses. Applied to six commercial hardshell jackets, it cleanly separated performance into A to C grades and consistently pinpointed vulnerable structures such as main zippers, neck–shoulder seams, and pockets, findings supported by zonal scores and images. Garments with continuous seam sealing and well-integrated three-layer laminates delivered the strongest protection, including a zero-infiltration case, whereas inadequate zipper shielding or pocket drainage repeatedly underperformed and received lower grades.

These readouts translate directly into practice and enable faster design iteration, tighter quality control and supplier qualification, better informed procurement, and clearer guidance for consumers.

The study used six samples under controlled rainfall, which limits generality. Future work will broaden garment categories and sample size, incorporate dynamic movement and ageing or cleaning cycles, and cross-validate against field use and standardised tests to refine thresholds and strengthen external validity.

ACKNOWLEDGEMENTS

We would like to express our heartfelt gratitude to Mengsheng Zhang, Marketing Director of Wenzhou Darong Textile Instrument Co., Ltd., and his team for their invaluable support and professional expertise in the development and improvement of the rain simulation system. These efforts have significantly enhanced the accuracy and reliability of our research.

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Analysis of the carbon emission reduction mechanism in the textile industry under the dual control of carbon emissions and carbon trading prices

DOI: 10.35530/IT.077.01.202579

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ABSTRACT – REZUMAT

Analysis of the carbon emission reduction mechanism in the textile industry under the dual control of carbon emissions and carbon trading prices

Abstract: The textile industry, as a high-energy consumption and high-emission traditional sector, faces significant challenges in its emission reduction efforts. This paper, based on the dual control targets for carbon emissions, employs a panel regression model to empirically examine the impact of carbon trading prices in China's pilot carbon markets on carbon emissions and carbon emission intensity in the textile industry. The paper also explores the role of energy structure and energy efficiency in this process through a mediation effect model. The findings reveal that carbon trading prices have a significant negative impact on carbon emission intensity in the textile industry, with every 1% rise in carbon trading prices leading to a 0.005% drop in carbon emission intensity, while their effect on overall carbon emissions is comparatively weaker. Further analysis indicates that energy efficiency plays a fully mediating role in promoting carbon emission reductions, whereas adjustments to the energy structure have only a partial mediating effect. The study suggests that there should be substantial development of carbon trading markets, improvement of the price formation mechanism, and enhancement of energy efficiency through technological innovation and management optimisation, thereby facilitating the green and low-carbon transformation of the textile industry. This would provide policy recommendations and practical guidance for achieving the dual control targets for carbon emissions.

Keywords: *textile industry, carbon emission intensity, carbon trading prices, mediation effect*

Analiza mecanismului de reducere a emisiilor de carbon în industria textilă sub controlul dual al emisiilor de carbon și al prețurilor tranzacționării carbonului

Industria textilă, ca sector tradițional cu consum ridicat de energie și emisii ridicate, se confruntă cu provocări semnificative în eforturile sale de reducere a emisiilor. Această lucrare, bazată pe obiectivele duble de control al emisiilor de carbon, utilizează un model de regresie panel pentru a examina empiric impactul prețurilor tranzacționării carbonului pe piețele pilot de carbon din China asupra emisiilor de carbon și intensității emisiilor de carbon în industria textilă. Lucrarea explorează, de asemenea, rolul structurii energetice și al eficienței energetice în acest proces printr-un model de efect de mediere. Rezultatele arată că prețurile tranzacționării carbonului au un impact negativ semnificativ asupra intensității emisiilor de carbon în industria textilă, fiecare creștere de 1% a prețurilor tranzacționării carbonului ducând la o scădere de 0,005% a intensității emisiilor de carbon, în timp ce efectul lor asupra emisiilor totale de carbon este comparativ mai slab. O analiză mai aprofundată indică faptul că eficiența energetică joacă un rol de mediere deplină în promovarea reducerii emisiilor de carbon, în timp ce ajustările structurii energetice au doar un efect de mediere parțial. Studiul sugerează că ar trebui să existe o dezvoltare substanțială a piețelor de comercializare a carbonului, o îmbunătățire a mecanismului de formare a prețurilor și o sporire a eficienței energetice prin inovare tehnologică și optimizarea managementului, facilitând astfel transformarea ecologică și cu emisii reduse de carbon a industriei textile. Acest lucru ar oferi recomandări de politică și îndrumări practice pentru atingerea obiectivelor duble de control al emisiilor de carbon.

Cuvinte-cheie*: industria textilă, intensitatea emisiilor de carbon, prețuri de comercializare a carbonului, efect de mediere*

INTRODUCTION

Against the backdrop of deepening integration between global climate change and sustainable development, the Chinese government, in 2024, proposed a dual-control carbon emission system focused primarily on intensity control and supplemented by total volume control. This initiative aimed to accelerate the comprehensive transition of the economy and society towards green and low-carbon development [1, 2]. As a traditional pillar industry of the national economy and an important industry for people's livelihood, the textile industry employs over 20 million people and has an annual export value of more than 300 billion US dollars. Its production process involves multiple high-energy-consuming and high-emission links, such as fibre processing, dyeing and finishing, and is highly dependent on resources such as water, electricity, and steam. According to data from the *United Nations Environment*

Programme, the textile and apparel industry accounted for approximately 10% of global carbon emissions, making it the second-largest source of pollution after the petroleum industry.

Carbon trading markets, as market-based economic instruments, have emerged as vital policy tools used by governments to incentivise carbon reduction among market entities. They have offered new pathways for emission reduction within the textile industry [3]. Carbon trading prices, as a core element of these markets, played a critical role in guiding enterprises to optimise resource allocation and adjust production behaviours. Understanding how fluctuations in carbon trading prices influenced emission reduction decisions and actual outcomes among textile enterprises held significant implications not only for the industry's green transformation but also for the attainment of national dual-control carbon emission targets [4–6]. Analysing the effects of carbon trading prices on emission reduction within the textile industry addressed a pressing practical challenge and contributed both theoretical insights and practical guidance towards improving the carbon market mechanism and implementing the dual-control strategy effectively [7, 8].

In recent years, the issue of carbon emissions within the textile industry has garnered increasing scholarly attention. Liang et al. found that electricity, heat, and coal consumption were the primary sources of carbon emissions in the textile sector, with economic development level identified as the strongest positive driving factor [9]. Haseeb et al. highlighted that low energy efficiency within the industry was a major reason for excessive emissions [10]. Leal Filho et al. argued that enhancing energy and environmental performance was crucial to achieving green and low-carbon development in the textile sector and to improving pollution and emission reduction synergy [11]. Other studies also noted that the application of AI technology could help reduce material waste and improve energy efficiency (Akter & Masood). Peng et al. examined the integration of the textile and logistics industries and found that such convergence generally contributed to lower carbon emission intensity [12]. Wei et al. (2023) explored the effects of heterogeneous environmental regulations on carbon emissions in the textile sector, revealing that command-and-control regulations had an inverted U-shaped effect on carbon emission intensity, market-based incentives induced emissions reduction within a certain threshold, and public participation regulations presented a green paradox effect on total emissions [13].

With the rapid development of carbon trading markets, researchers increasingly investigated the emission reduction effects of carbon trading prices [14, 15]. Fleschutz et al. suggested that appropriate carbon pricing, combined with an active and large-scale carbon market, was essential for achieving energy savings and emissions reductions [16]. Hernandez et al., focusing on the Californian carbon market, found that its operation reduced industrial carbon and air pollutant emissions by 3–9% annually and narrowed industrial air pollution disparities by 6–10% per year [17]. Goldemberg (2020) noted that carbon prices reflected regional carbon abatement costs and quota supply-demand dynamics; therefore, it was reasonable for developing countries to exhibit lower carbon prices than developed nations [18]. Wu and Wang argued that there existed a threshold effect in carbon pricing, whereby only once prices surpassed a certain level would trading activities significantly drive carbon reduction [19].

The existing literature confirmed the general recognition of the emission reduction effect of carbon trading prices. However, limited research had specifically addressed their impact on the textile industry. As the world's largest producer, consumer, and exporter of textiles, China's textile sector faced severe challenges related to energy consumption, pollution, and emissions [20]. How to achieve green and low-carbon development in this industry has thus become a topic of extensive academic and industrial interest. Following the proposal of the dual-control carbon emission strategy, the focus had shifted to not only the total volume of emissions but also changes in emission intensity [21–23]. Unlike the "dual control of energy consumption", which focuses on controlling the total volume and intensity of energy consumption, the "dual control of carbon emissions" relaxes the regulation of energy consumption and emphasises a direct shift from energy consumption to carbon emissions control. Its core is to force the industry to undergo low-carbon transformation through total volume constraints, while guiding technological upgrading through intensity standards, forming a collaborative constraint mechanism of "total volume cap + intensity reduction". Cao and Zhang pointed out that achieving a shift from "dual-control of energy consumption" to "dual-control of carbon emissions" required the expansion of national carbon trading markets in both scale and impact. Based on this, this paper will take the textile industry as the research object to explore how carbon trading prices simultaneously affect the total volume and intensity of carbon emissions, in response to the new requirements of the dual control objectives for "collaborative control of total volume and intensity", providing theoretical and practical insights to support the industry's green development [24].

The marginal contributions of this paper were twofold: first, it examined carbon trading prices, as a core tool for carbon mitigation, as explanatory variables to analyse their impact on emission reduction in the textile sector, and further explored the underlying mechanisms through a mediation model; second, it addressed both carbon emissions and carbon emission intensity as dependent variables under the dual-control framework, thus offering a more comprehensive analysis of the reduction effects of carbon trading prices.

The remainder of this paper is organised as follows: 2^{nd} section presents the theoretical analysis, 3^{rd} section introduces the model specification, 4^{th} section conducts the empirical analysis, and the final section concludes with key findings and policy recommendations.

LITERATURE REVIEW AND THEORETICAL ANALYSIS

As carbon trading markets became increasingly mature, the influence of carbon trading prices on enterprises became more pronounced. High-emission firms were required to pay for their excess carbon emissions, while low- or zero-emission firms could generate economic returns by selling their surplus carbon allowances. Fluctuations in carbon trading prices guided enterprises to reallocate resources from high-carbon energy sectors to low-carbon alternatives [25]. Higher carbon trading prices incentivised firms to increase their investment in low-carbon technologies and clean energy, allocating more resources towards research and development. This process facilitated innovation and advancements in low-carbon technologies, thereby reducing emissions and contributing to carbon mitigation [26].

Green (2021) argued that carbon pricing policies had a significant suppressive effect on carbon emission intensity, namely, the higher the carbon price, the lower the emissions required to generate the same economic output [27]. Similarly, Huisingh et al. found that increases in carbon prices were associated with reductions in emission intensity, driven by technological improvements that promoted decarbonisation [28]. Based on this, the following hypothesis was proposed.

Hypothesis 1: Increases in carbon trading prices contributed to reductions in both carbon emissions and carbon emission intensity in the textile industry.

Fossil fuels, particularly coal, remained the primary source of carbon emissions in China [29]. Jiang et al. observed that the dual-control carbon strategy encouraged industries to proactively optimise their energy structures [30]. In response to changes in carbon trading prices, enterprises, driven by cost control and profit maximisation objectives, strategically adjusted their energy portfolios. They gradually reduced the share of high-carbon energy sources in their energy consumption structures while increasing reliance on relatively low-carbon alternatives [31].

In this process, carbon trading prices served as a key market-based regulatory mechanism, playing a crucial role in promoting the optimisation of energy structures. Rational and scientific adjustments in energy composition guided consumption patterns towards cleaner, more efficient, and lower-carbon trajectories. The energy structure, therefore, functioned as an intermediary, translating the price signals from carbon trading markets into tangible shifts in energy use, and became an important conduit through which carbon prices promoted emissions reduction [32].

On the other hand, in order to reduce the cost of carbon emissions, firms engaged in technological innovation and process improvements to enhance energy efficiency. This improvement in efficiency not only directly lowered emissions per unit of output but also strengthened firms' capacity to respond to fluctuations in carbon prices. Wang and Wang empirically demonstrated that improvements in energy efficiency were a key driver of decoupling carbon emissions from economic growth [33]. Under the carbon trading mechanism, firms reduced carbon emission intensity through more efficient energy use, without significantly compromising economic performance.

Based on the above analysis, the following hypothesis was proposed.

Hypothesis 2: Energy structure and energy efficiency acted as mediating variables in the relationship between carbon trading prices and emission reduction in the textile industry.

MODEL SPECIFICATION

This study focused on regions in China where carbon trading markets had been established. The dependent variables were the carbon emissions and carbon emission intensity of the textile industry within those regions. The core explanatory variable was the regional carbon trading price. A panel regression model was constructed as follows:

$$emi_{i,t} = a_0 + a_1 price_{i,t} + a_2 control_{i,t} + \varepsilon_{i,t} \quad (1)$$

$$int_{i,t} = b_0 + b_1 price_{i,t} + b_2 control_{i,t} + \varepsilon_{i,t} \quad (2)$$

In the above equation, *emi* is the carbon emission of the textile industry. *i* is different individuals, *t* is time, and a_j and b_j are the coefficients of each variable. *int* is the carbon emission intensity, which is defined as carbon emission/principal business income with reference to Bolton et al. [34]. *price* is the carbon trading price, which is measured by the average price of the yearly transaction, because both carbon emission and carbon emission intensity are annual data. *control* is the control variable. Based on the data availability and referring to the existing literature, the total assets and the annual number of employees in the textile industry are selected to represent the capital input and labour input, respectively, and are expressed as ASSET and LABOUR [35]. The total assets of an enterprise exert dual effects on carbon emissions through scale and technological effects: asset expansion may reduce carbon emission intensity due to economies of scale and technological upgrading, but it may also lead to an increase in total emissions due to increased production; the number of employees affects carbon efficiency through the scale and skill structure of the labour force. An increase in the proportion of high-skilled labour helps achieve higher efficiency and lower carbon emissions with fewer human inputs, while an inefficient expansion may exacerbate emissions.

To further explore the underlying mechanisms through which carbon trading prices influence energy transition, this study, based on theoretical analysis, introduced two new indicators, energy structure and energy efficiency, as mediating variables in the panel regression model. A mediation effect model was constructed to perform the regression estimation. The mediation effect model for carbon emissions was specified as follows:

$$M_{i,t} = c_0 + c_1 price_{i,t} + c_2 control_{i,t} + \varepsilon_{i,t} \quad (3)$$

$$emi_{i,t} = d_0 + d_1 price_{i,t} + d_2 M_{i,t} + d_3 control_{i,t} + \varepsilon_{i,t} \quad (4)$$

M is the mediating variable. In this paper, energy structure and energy efficiency are selected as mediating variables, which are denoted by estr and ee, respectively. Coal is the main source of carbon emissions in China, and changes in the proportion of coal consumption are more sensitive to the response of carbon trading price, which can be a better change in the energy structure. Therefore, referring to Guo et al., the energy consumption structure is defined as the proportion of coal in the total energy consumption [36]. Energy efficiency, on the other hand, is defined as the total amount of energy consumed per unit of GDP with reference to Hu [37]. In equation 3, c_1 represents the effect of price on the mediating variable; in equation 4, d_1 represents the effect of *price* on *emi* after the addition of the mediating variable, and d_2 represents the effect of the mediating variable *M* on *emi*. In equation 1 a_1 is significant is the premise for analysing the mediating effect, based on which, if c_1 and d_2 are significant, it represents the existence of a mediating effect. Where d_1 is not significant, it represents the existence of a complete mediation effect of variable *M*; otherwise, it is a partial mediation effect. The mediation effect model on carbon emission intensity is basically similar and will not be repeated here.

EMPIRICAL ANALYSIS

Data description

Since the initiation of China's pilot carbon emissions trading scheme, the government has established eight regional carbon markets in Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, Shenzhen, and Fujian. Among these, the markets in seven regions, excluding Fujian, were launched between June 2013 and June 2014, while the Fujian carbon market was launched in December 2016. Due to the lack of accurate statistical data on energy consumption structure in Fujian Province and the administrative status of Shenzhen as a prefecture-level city, both regions were excluded from the analysis. As a result, this study focused on the remaining six provinces and municipalities, covering the period from 2015 to 2021.

Carbon emissions data were obtained from the China Carbon Emission Accounts and Datasets (CEADs), while the remaining variables were sourced from the China Industrial Statistical Yearbook and the China Economic Census Yearbook, among others. A small number of missing values were supplemented using interpolation methods. Given the substantial variation across variables, except for carbon trading prices, all variables were log-transformed to reduce skewness. Descriptive statistics are presented in table 1.

Table 1

DESCRIPTIVE STATISTICS OF VARIABLES

Variable	Min	Max	Mean	Median	S.d.
emi	0.704	3.102	2.068	1.876	0.718
int	–1.404	0.381	–0.309	–0.296	0.463
price	2.253	49.95	25.85	24.55	14.76
estr	0.365	3.985	3.292	3.720	1.015
ee	–0.400	1.754	0.643	0.744	0.667
asset	2.802	7.229	5.330	5.054	1.356
labour	–2.040	3.340	0.962	0.672	1.791

The dependent variable *emi* ranged from 0.704 to 3.476, with a mean of 2.089, a median of 1.876, and a standard deviation of 0.753, indicating relatively low overall variability. The textile industry in Beijing exhibited the lowest level of carbon emissions, averaging approximately 10,000 tonnes per year, whereas Guangdong Province recorded the highest emissions, reaching 840,000 tonnes in 2021. Except for Chongqing, all other provinces and municipalities experienced varying degrees of decline in carbon emissions, suggesting that the low-carbon transition within the textile industry had yielded tangible results. In terms of carbon emission intensity, Hubei Province recorded the lowest intensity, while Shanghai exhibited the highest. Beijing had the highest average carbon trading price, reaching 64 yuan per tonne. In contrast, Guangdong, Tianjin, and Chongqing all reported average prices below 20 yuan per tonne, with Chongqing as low as 13 yuan per tonne.

Furthermore, the textile industries in Guangdong and Hubei were relatively large in scale, each generating over 200 billion yuan in annual main business revenue, with total assets exceeding 100 billion yuan and employing around 200,000 people. Conversely, Beijing had the smallest textile industry, with an annual main business revenue of approximately 2 billion yuan and only 1,300 employees in 2021.

Subsequently, Pearson correlation analysis was employed to examine the relationships among the variables. The results are presented in table 2. As shown, *price* was significantly negatively correlated with *emi*, indicating that higher carbon trading prices were associated with lower carbon emissions. Additionally, *price* was significantly negatively correlated with *estr* and positively correlated with *ee*, preliminarily indicating that carbon trading prices reduce the proportion of coal consumption and improve energy efficiency.

To avoid the issue of spurious regression, this study conducted unit root tests prior to model estimation to assess whether the core variables were stationary. The results are presented in table 3. The key variables, *emi*, *int*, and *price*, rejected the null hypothesis of a unit root at the 1% significance level, indicating

Table 2

CORRELATION ANALYSIS RESULTS							
emi	**emi**	**int**	**price**	**estr**	**ee**	**asset**	**labor**
	1						
int	0.298*	1					
price	–0.369**	0.0340	1				
estr	0.513***	–0.120	–0.755***	1			
ee	–0.660***	0.375**	0.519***	–0.601***	1		
asset	0.809***	–0.280*	–0.346**	0.545***	–0.921***	1	
labor	0.809***	–0.299*	–0.395***	0.576***	–0.889***	0.974***	1

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 3

UNIT ROOT TEST RESULTS			
Variable name	**emi**	**int**	**price**
p value	0.0001	0.0000	0.002

that these variables were stationary. Therefore, it was appropriate to proceed with the construction of the regression model.

Baseline regression analysis

In panel data regression analysis, three primary models were considered: the Random Effects (RE) model, the Pooled Ordinary Least Squares (POOL) model, and the Fixed Effects (FE) model. Table 4 presents the results of the model selection tests.

The F-test produced a statistic of 2.62 with a corresponding p-value of 0.0674. As this value exceeded the 0.05 significance threshold, the POOL model demonstrated a relative advantage over the FE model. Subsequently, the Breusch–Pagan (BP) test yielded a chi-square statistic of $\chi^2(1) = 85.55$ with a p-value of 0.000, indicating that the RE model outperformed the POOL model. Furthermore, the Hausman test produced a statistic of $\chi^2(3) = 1.73$ with a p-value of 0.63, which also exceeded the 0.05 significance level, suggesting that the RE model was preferable to the FE model.

Based on the results of these tests, this study ultimately adopted the Random Effects model as the baseline model for subsequent regression analysis.

Table 5 presents the results of the panel regression analysis. Columns (1) and (2) report the regression outcomes for carbon emissions. In column (1), only the core explanatory variable, carbon trading price, was included. Its coefficient was −0.0047 and was statistically significant at the 10% level, suggesting that higher carbon trading prices contributed to a reduction in carbon emissions in the textile industry. However, in column (2), after the inclusion of control variables, the coefficient of carbon trading price was no longer statistically significant, indicating that its effect on carbon emissions was not robust.

Columns (3) and (4) display the regression results for carbon emission intensity, with column (4) incorporating control variables. In both specifications, the coefficient for carbon trading price remained statistically significant at the 10% level, demonstrating that an increase in carbon trading prices can significantly reduce the carbon emission intensity of the textile industry, with every 1% rise in carbon trading prices leading to a 0.005% drop in carbon emission intensity. Taken together, the findings suggested that the impact of carbon trading prices was more pronounced in reducing carbon emission intensity than in reducing absolute carbon emissions. This may be because carbon emission intensity directly reflects the emission efficiency per unit of output. Enterprises

Table 4

PANEL MODEL SELECTION RESULTS		
Type of test	**Purpose of the test**	**Value of test**
F test	Comparative selection of FE and POOL models	F-statistic = 2.62, p = 0.0674
BP test	Comparative selection of RE and POOL models	$\chi^2(1) = 85.55$, p = 0.0000
Hausman test	Comparative selection of FE and RE models	$\chi^2(3) = 1.73$, p = 0.63

Table 5

BASELINE REGRESSION RESULTS				
Variables	**(1)**	**(2)**	**(3)**	**(4)**
	emi	**emi**	**int**	**int**
price	–0.0047*	–0.003	–0.0020*	–0.005*
	(–1.95)	(–1.14)	(–1.77)	(–1.90)
asset		–0.085		–0.249
		(–0.52)		(–1.51)
labour		0.138		–0.071
		(1.39)		(–0.70)
Constant	2.2218***	2.496***	–0.2463	1.250
	(6.96)	(2.84)	(–1.09)	(1.40)
Observations	42	42	42	42
Number of provinces	6	6	6	6

Note: z-statistics are reported in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively..

Table 6

RESULTS OF THE MEDIATION EFFECT MODEL					
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
	int	**estr**	**int**	**ee**	**int**
price	–0.0055*	–0.0223***	–0.0052*	0.0037***	–0.0009
	(–1.90)	(–4.84)	(–1.65)	(2.93)	(–0.26)
asset			0.0728		
			(0.64)		
labour					–1.4159***
					(–3.57)
Constant	–0.2486	0.2903	–0.3511*	0.0229	–0.0515
	(–1.51)	(1.24)	(–1.81)	(0.32)	(–0.30)
Observations	–0.0708	0.0156	–0.0883	–0.3668***	–0.6450***
Number of provinces	(–0.70)	(0.09)	(–0.87)	(–7.41)	(–3.41)

Note: z-statistics are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

can quickly respond to price signals by adopting low-cost measures such as replacing energy-saving equipment and optimising processes to reduce intensity. However, carbon emissions are the product of intensity and production scale. As a labour-intensive industry, the production scale of the textile industry is constrained by factors such as market demand and supply chain, and reducing production capacity incurs high costs. Therefore, enterprises are more inclined to maintain production, making total emissions less sensitive to carbon prices.

Mediation effect analysis

Based on the results of the baseline regression, carbon trading prices primarily reduced carbon emissions in the textile industry by lowering carbon emission intensity, with a comparatively weaker effect on absolute carbon emissions. To further examine the specific pathways through which carbon trading prices contributed to carbon reduction, this study employed a mediation model using energy structure and energy efficiency as mediating variables, as shown in table 6 [38].

In table 6, columns (2) and (3) present the mediation effects via energy structure, while columns (4) and (5) display the mediation effects via energy efficiency. For comparison, column (1) includes the regression results without any mediating variables.

In column (2), the coefficient of *price* was −0.0223 and statistically significant at the 1% level, indicating that carbon trading prices had a significant negative impact on the energy structure. Specifically, a one-unit increase in the carbon trading price was associated with a 2.23% reduction in the share of coal consumption. In column (3), the coefficient of *price* was −0.0052, slightly lower than in column (1), yet still significant at the 10% level. The coefficient of *estr* was positive, suggesting that a higher proportion of coal consumption corresponded to higher carbon emissions. However, this coefficient was not statistically significant, implying that the direct effect of carbon trading prices on carbon emission intensity was dominant, and that energy structure only partially mediated the relationship.

In column (4), the coefficient of *price* was 0.0037 and significant at the 1% level, indicating that higher carbon trading prices were associated with improved energy efficiency. In column (5), the coefficient of *price* declined to −0.0009 and lost its statistical significance, while the coefficient of *ee* was significantly negative. This result suggested that energy efficiency fully mediated the effect of carbon trading prices on reducing carbon emission intensity in the textile industry.

Moreover, examining columns (1), (3), and (5) collectively revealed that although the significance levels of asset and labour varied slightly, both variables were consistently negatively associated with int. That is, higher total assets and a larger workforce were linked to lower carbon emission intensity. Total assets represented capital investment, while the number of employees reflected labour input; greater input in either dimension typically resulted in reduced energy consumption, thereby lowering carbon emission intensity.

To further verify the robustness of the results, this study applied 10% level winsorisation to all variables and re-estimated the equations presented in table 6 [39–41]. This method effectively mitigated the potential influence of outliers on the regression outcomes [42–44]. The results remained consistent, confirming the robustness of the conclusions.

CONCLUSION AND POLICY RECOMMENDATIONS

This study investigated the impact of carbon trading prices on carbon emissions in China's textile industry, focusing on regions covered by the national carbon market pilots. Using a panel regression model, it was found that carbon trading prices had a significant negative effect on carbon emission intensity, while the effect on absolute carbon emissions was relatively modest. Further analysis, based on a mediation model, revealed that improvements in energy efficiency constituted the primary mechanism through which carbon trading prices reduced emissions. Adjustments in the energy structure played only a partial mediating role. Based on these findings, the following policy recommendations are proposed:

Vigorously develop the carbon trading market

First, expand the coverage of the carbon market, include enterprises along the industrial chain in quota management, formulate differentiated standards based on production processes and carbon emission intensity, set stricter emission reduction targets for high-energy-consuming enterprises, and force them to carry out technological transformation. Second, improve the price formation mechanism, introduce a "carbon price - emission reduction cost" linkage model, dynamically adjust the carbon price according to the industry's emission reduction costs, and enrich financial instruments such as carbon futures to enhance market liquidity. Third, strengthen policy support, provide tax incentives, financial subsidies, and other rewards to enterprises that exceed emission reduction targets, use the Internet of Things and blockchain technology to strengthen energy consumption monitoring, establish a data sharing platform, crack down on data fraud, and ensure a fair and effective market.

Improve energy efficiency

Focus on the dual upgrade of technology and management, promote energy-saving technologies such as waste heat recovery and intelligent control in printing and dyeing and chemical fibre processes, and deploy energy management systems to achieve dynamic control of energy consumption. Construct industry energy efficiency standards, set energy efficiency benchmarks for product categories, and guide enterprises in strategic energy conservation. Build a technology sharing platform, organise technical exchanges and demonstration observations, implement contract energy management models, lower the threshold for enterprise technological transformation, and accelerate the implementation of energy-saving technologies.

Adjust the energy structure and reduce coal consumption

Advance energy transformation through a two-pronged approach. On one hand, encourage enterprises to apply distributed photovoltaic, biomass energy, and other renewable energy sources, and promote the elimination of coal-fired boilers or their replacement with clean energy. On the other hand, implement total coal consumption control, promote clean combustion technologies and support environmental protection facilities for enterprises that retain coal-fired equipment. Through financial subsidies, quota rewards, and price transmission mechanisms, reduce the cost of using clean energy for enterprises, enhance its economic substitutability for coal, and achieve a clean energy structure.

This paper only covers the textile industry in regions where China's pilot carbon markets are located, excluding enterprises in non-pilot regions, which may limit the generalizability of conclusions. Moreover, it does not distinguish the heterogeneous impacts among different sub-sectors (such as clothing and home textiles). The mediating effect analysis only focuses on energy efficiency and energy structure, without covering other potential paths such as the application of carbon capture technology and industrial structure adjustment. In the future, the sample can be expanded to the national textile industry to conduct a comparative analysis of emission reduction differences between pilot and non-pilot regions as well as among different sub-sectors, so as to reveal the regional and industrial heterogeneous impacts of carbon trading policies. Meanwhile, more mediating variables (such as carbon capture technology and industrial concentration) can be included to construct a more comprehensive framework of emission reduction path mechanisms.

ACKNOWLEDGMENTS

This work was supported by Youth Project of Humanities and Social Sciences Research, Ministry of Education: "Research on the Impact of Carbon Price Fluctuations on Heterogeneous Enterprises under Dual Carbon Control Constraints and Policy Implications" (Grant No. 24YJC790211).

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Beyond the single thread: how organisational, technological, and environmental factors jointly shape green patent persistence in textile firms

DOI: 10.35530/IT.077.01.202577

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ABSTRACT – REZUMAT

Beyond the single thread: how organisational, technological, and environmental factors jointly shape green patent persistence in textile firms

As one of the most resource-intensive and polluting manufacturing industries, the textile sector's sustained green patenting activities are garnering increasing attention. This study investigates 48 Chinese A-share listed textile enterprises, employing a combined Necessity Condition Analysis (NCA) and fuzzy-set Qualitative Comparative Analysis (fsQCA) approach. We systematically explore how five antecedent conditions, firm size, executive educational background, digital transformation, media attention, and government subsidies, collectively influence the sustained green patent application performance of textile enterprises through various configurations. The results show that no single factor qualifies as a necessary condition; rather, sustained green patenting emerges from asymmetric combinations of factors. Media attention and government subsidies appear as common core elements across configurations associated with high levels of sustained green patenting. We identify two high-performance pathways: an "environment-dominated–organisational collaboration" pathway and a "technology–environment-driven" pathway. Conversely, we uncover four pathways associated with low sustained green patenting: "environmental deficiency", "technological inadequacy", "organisational weakness", and "single-factor presence". Overall, the study elucidates the complex causal configurations shaping sustained green patenting in textile firms and offers implications for the industry's sustainable development.

Keywords: *textile industry, sustained green patent applications, socio-ecological systems theory, fsQCA*

Dincolo de o singură perspectivă: modul în care factorii organizaționali, tehnologici și de mediu modelează împreună persistența brevetelor ecologice în firmele textile

Fiind una dintre industriile manufacturiere cu cel mai mare consum de resurse și cele mai poluante, activitățile de brevetare ecologică susținută ale sectorului textil atrag din ce în ce mai multă atenție. Acest studiu analizează 48 de întreprinderi textile din China listate la bursă, utilizând o abordare combinată de analiză a condițiilor de necesitate (NCA) și analiză comparativă calitativă fuzzy (fsQCA). Explorăm în mod sistematic modul în care cinci condiții antecedente, dimensiunea întreprinderii, nivelul de studii al conducerii, transformarea digitală, atenția mass-media și subvențiile guvernamentale, influențează în mod colectiv performanța susținută a întreprinderilor textile în materie de cereri de brevete ecologice prin diverse configurații. Rezultatele arată că niciun factor nu poate fi considerat o condiție necesară; mai degrabă, brevetarea ecologică susținută rezultă din combinații asimetrice de factori. Atenția mass-media și subvențiile guvernamentale apar ca elemente comune de bază în toate configurațiile asociate cu niveluri ridicate de brevetare ecologică susținută. Identificăm două căi de performanță ridicată: o cale „de colaborare organizațională – dominată de mediu" și o cale „determinată de tehnologie-mediu". În schimb, descoperim patru căi asociate cu un nivel scăzut de brevetare ecologică susținută: „deficiență de mediu", „inadecvare tehnologică", „slăbiciune organizațională" și „prezența unui singur factor". În ansamblu, studiul elucidează configurațiile cauzale complexe care modelează brevetarea ecologică susținută în întreprinderile textile și oferă implicații pentru dezvoltarea durabilă a industriei.

Cuvinte-cheie*: industria textilă, cereri susținute de brevete ecologice, teoria sistemelor socio-ecologice, fsQCA*

INTRODUCTION

The textile industry is a cornerstone of the global economy, not only creating vast employment opportunities but also making significant contributions to the economic growth of many countries. However, with the rise of fast fashion and the proliferation of overproduction and consumption, the industry has increasingly exposed serious issues of resource waste and environmental pollution [1]. In the production phase, textile manufacturing is highly dependent on energy and water resources, and the emission of various harmful substances poses a threat to both the ecological environment and the health of local communities. Furthermore, the industry faces social sustainability challenges, such as low wages, insufficient human rights protection, and poor working conditions for workers [2–4].

According to relevant statistics, approximately 92 million tons of textile waste are generated each year, yet only about 20% is collected for recycling or reuse. The proportion of recycled materials used for new production is a mere 0.3%. In addition, some studies predict that by 2050, global textile consumption will triple and could account for more than a quarter of total global carbon dioxide (CO_2) emissions. Given this mounting pressure for sustainable development, textile firms must proactively adjust their traditional business models and accelerate the transition towards a greener and more sustainable approach to ensure long-term viability [5].

To address these challenges, green innovation has emerged as a critical pathway for textile companies to achieve environmental transformation. As a typical manufacturing sector with high resource consumption and concentrated pollution, the textile industry faces increasingly stringent environmental regulations and fierce market competition. To genuinely improve their environmental performance, firms must continuously engage in relevant innovation activities [6]. Unlike one-off or phased green initiatives, continuous green innovation emphasises a long-term commitment of resources to progressively optimise environmental technologies and production processes. This sustained effort not only helps firms effectively reduce their environmental footprint and meet regulatory and societal expectations but, more importantly, it significantly enhances their long-term competitiveness. By consistently investing in green innovation, firms can achieve continuous cost reductions, improve resource efficiency, and foster product differentiation, thereby securing a favourable position in a competitive market [7]. Therefore, an in-depth exploration of the drivers of continuous green innovation in textile firms and their underlying mechanisms holds significant theoretical and practical value.

To help firms achieve continuous green innovation, existing research has explored its influencing factors from multiple perspectives [8, 9]. Internally, some scholars argue that larger firms with more abundant resources and capabilities are better positioned for continuous green innovation [10, 11]. However, other studies have found that due to complex organisational structures and high coordination costs, medium-to-large enterprises may exhibit path dependence and slow reactions when pursuing green innovation [12]. Externally, evidence shows that firms located in regions with strict environmental regulations generally achieve a higher level of green innovation [13]. Yet, where formal institutional constraints are weak, informal mechanisms like media supervision can serve as an effective supplement, indirectly encouraging firms to improve green innovation by increasing information transparency and public pressure [14].

It is noteworthy that existing studies on the drivers of continuous green innovation have largely adopted a single-factor approach, leading to inconsistent conclusions. This inconsistency may stem from a traditional research paradigm that fails to fully capture the complex interactions among influencing factors [15]. Currently, most mainstream research on continuous green innovation relies on linear regression models, which tend to analyse the "net effect" of variables. This makes it difficult to capture their complementarity, substitutability, and asymmetry [15]. Such a narrow perspective not only hinders a comprehensive understanding of the complex mechanisms at play but also limits the provision of systematic and effective guidance for business practice [16].

Social ecological systems theory posits that individuals and their social environment form a social ecosystem where various subsystems are interconnected and interact with one another. As a key component of this ecosystem, a firm's actions and outcomes are also interrelated with various systemic elements [17]. Furthermore, from a practical standpoint, advancing continuous green innovation is a complex systemic endeavour influenced by both a firm's internal characteristics and external institutional and social factors [18]. Therefore, it is essential to study continuous green innovation within the broader social ecosystem to understand how different environmental elements can synergistically align to drive textile firms towards this goal.

Qualitative Comparative Analysis (QCA) is an effective method for addressing causal complexity and offers significant advantages for this purpose. QCA emphasises the interaction among antecedent conditions rather than their isolated existence, focusing on the holistic effect of condition combinations. This approach can provide a deeper understanding of the causal mechanisms of continuous green innovation. Moreover, QCA can identify multiple configurations of sufficient conditions leading to the same outcome and test for causal asymmetry between high and low outcomes. This capability allows for a clear depiction of the diverse pathways textile firms can take to achieve continuous green innovation and the underlying logic of each path.

China provides a unique and representative research context. As the world's largest producer and consumer of textiles, its industry is vast and its supply chain is highly comprehensive, spanning from raw material sourcing, spinning and weaving, and garment manufacturing to final sales. This provides a rich pool of industry practice and data. According to 2025 statistics, China generates approximately 20 million tons of textile waste annually, ranking first globally. This massive waste output creates a more urgent need for the Chinese textile industry to transform, particularly in improving resource efficiency, comprehensive waste management, and green innovation practices.

Furthermore, the Chinese textile industry has faced increasingly strict environmental policies and industrial restructuring measures in recent years. In September 2020, the Chinese government officially announced its "carbon peaking and carbon neutrality" goals at the 75th United Nations General Assembly, with targets to peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060 [19, 20]. Following this announcement, the textile industry, as a high-carbon emitter, has quickly become a key focus for policy regulation and green transformation. For instance, the Implementation Plan for Clean Production Transformation in Key Industries, enacted in 2023, further requires textile firms to fully adopt clean production technologies in high-energy consumption stages like printing, dyeing, and chemical fibre production.

Based on this analysis, we aim to address three key research questions: (1) Is there any single factor that is a necessary condition for continuous green patent applications in textile firms? (2) Which combinations of factors lead to high or low levels of continuous green patent applications in textile firms? (3) Which potential factors should policymakers pay attention to? Through our exploration of these questions, we seek to uncover the complex causal relationships behind continuous green patent applications in textile firms and provide substantive guidance and suggestions for understanding the drivers of green innovation from a configurational perspective.

This study contributes to the extant literature in two main ways. First, our research departs from the traditional statistical paradigm of analysing the net effect of single variables [10, 21–23]. While previous studies mainly relied on traditional models to analyse the isolated influence of individual factors, they lacked an exploration of how different factors combine and substitute for one another to drive continuous green innovation. Drawing on a set-theoretic perspective [24], we adopt a configurational approach to view continuous green patent applications as the result of multiple interacting factors. This reveals how different combinations of conditions jointly drive a firm's green innovation performance through synergistic or substitutive mechanisms. The introduction of this perspective effectively addresses the shortcomings of existing research in explaining the nonlinear relationships among variables. Second, by comparing the configurational pathways for high and low levels of continuous green innovation in textile firms, we confirm the presence of causal asymmetry. That is, the combinations of conditions that lead to high-level innovation cannot simply be inverted to explain the causes of low-level innovation. This finding provides new empirical evidence for refining the theoretical framework of continuous green innovation.

THEORETICAL FOUNDATION AND MODEL CONSTRUCTION

Theoretical foundation

Social-ecological systems theory provides a framework for systematically analysing the interactions between individuals and their environments, emphasising that individual behaviour is influenced by multilevel environmental factors collectively. This theory segments ecosystems into three layers: the micro-level, focused on the individual; the meso-level, involving small groups directly linked to the individual, like families and organisations; and the macro-level, encompassing broader social constructs such as culture, institutions, and policy frameworks. Through dynamic interactions at these hierarchical levels, social-ecological systems shape individual behaviours and decisions [17].

Recently, researchers have begun applying social-ecological systems theory to organisational studies, suggesting that enterprises are also immersed within multi-level environmental systems, influenced by factors from various levels. An enterprise's capabilities and behaviours (micro-level), industry and regional pressures (meso-level), along with market competition dynamics and regulatory policies (macro-level), can all impact corporate innovation [25, 26].

Therefore, when analysing corporate green innovation, it is vital to situate it within the broader social-ecological system, identifying the collaborative effects among environmental factors at various levels. This theory offers an ideal analytical framework and structural foundation for understanding diverse mechanisms that drive organisational innovation.

Model construction

As previously discussed, a firm's continuous green innovation is not influenced by isolated system elements but rather through a synergistic mechanism, resulting in a nonlinear, interactive, and equifinal relationship among factors. This complexity makes it difficult for traditional linear regression models to fully capture the combined effects of multiple variables. In contrast, fuzzy-set qualitative comparative analysis (fsQCA) is uniquely suited for this task. It can identify multiple configurational paths to a single outcome and simultaneously characterise the complementarity and substitutability among condition variables, making it ideal for analysing the multi-level drivers of corporate green innovation within a social ecological system framework.

From the micro-level, the size of an enterprise is a crucial internal structural characteristic influencing its green innovation capabilities. The textile industry is typically resource-intensive and highly polluting, where green innovation requires substantial capital investment and long-term technological accumulation. According to Schumpeter's hypothesis, in contexts where capital markets are imperfect [27, 28], larger organizations are more likely to gain external financing, providing them with superior financial capacity and risk tolerance. This enables continuous investment in the development of green dyeing technologies, upgrading of environmental equipment, and the establishment of energy-saving and emission-reduction systems, subsequently enhancing their sustained green innovation levels [10, 11]. Additionally, large textile companies often have mature management systems, standardised production processes, and strict adherence to environmental compliance, allowing them to effectively implement green production techniques and enhance the efficiency of organisational execution in green innovation. However, research also points out that medium and large enterprises may face organisational inertia during green innovation. Complex internal structures with multiple layers can slow down

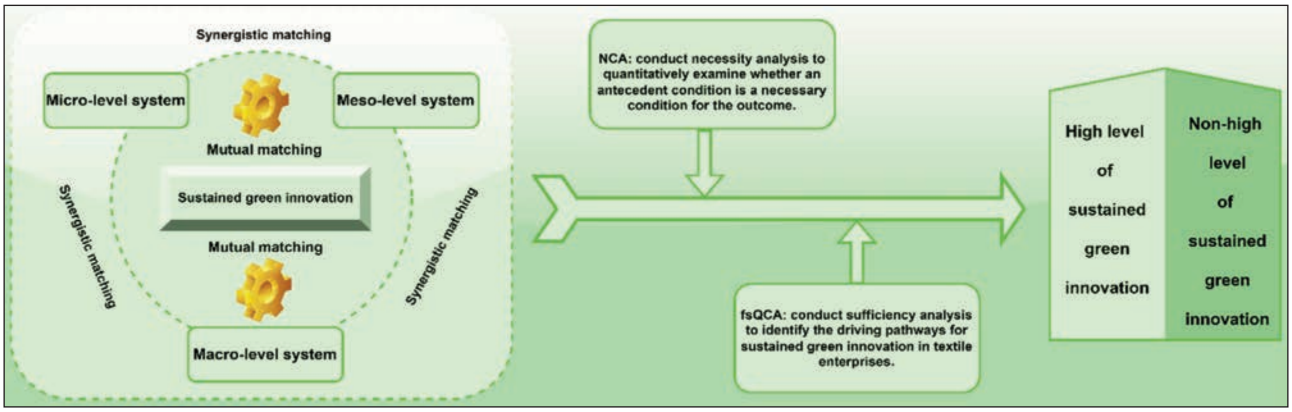

Fig. 1. Theoretical framework

decision-making related to green technologies and resource allocation, while increasing communication and coordination costs might reduce project execution efficiency, thereby impairing the agility and adaptability of green innovation [12].

From the meso-level perspective, digital transformation and executive academic backgrounds are increasingly crucial in promoting sustained green innovation. As enterprises seek to improve green processes, smart manufacturing, and clean production, they need digital technologies to enhance resource allocation efficiency and environmental management capabilities. Digital technologies provide transparency and visualisation that help reduce internal operational and coordination costs and significantly lower external transaction costs, such as those related to search, negotiation, and supervision in green supply chain management [29]. For instance, using IoT, big data, and smart sensors, textile enterprises can monitor energy use and emissions in dyeing processes in real time, improving control and responsiveness in green production [30]. Moreover, Upper Echelons Theory indicates that executives play a pivotal role in strategic planning and resource allocation decisions, with their educational backgrounds and cognitive levels directly affecting the organisation's innovation focus and environmental strategy choices. In the textile sector, managers with higher education backgrounds are more likely to possess systemic thinking and foresight, enabling them to understand green development trends, introduce advanced green management concepts and digital tools, and drive exploration and advancements in green dyeing technology, wastewater recycling, and green certification systems to enhance sustainable green innovation capacity.

From the macro-level perspective, sustained green innovation in enterprises is influenced by external environmental factors, including supervisory pressure and policy frameworks. New Institutional Economics suggests that in environments where government enforcement is inadequate or regulatory systems are underdeveloped, media oversight can serve as an effective alternative institutional constraint [14]. In the textile industry, media often exposes issues like excessive wastewater discharge and non-compliance in chemical dye usage, prompting enterprises to maintain legal compliance and social reputation by adopting green materials and creating eco-friendly products [31, 32]. However, some studies highlight that under strong social supervision pressure, some textile firms may prefer short-term reactive measures, such as temporarily acquiring pollution control equipment or upgrading emission monitoring systems, rather than investing in longer-term, high-risk green technology research and development [33]. Additionally, policy support, particularly government subsidies, is becoming a vital external resource in driving green transformation in textile enterprises. According to signalling theory, green subsidies not only alleviate initial financial pressures but also release positive signals about the enterprise's commitment to green governance, attracting further financial resources and commercial cooperation opportunities [34]. This ensures that enterprises have sufficient funds for green innovation and sustainable production.

In conclusion, integrating social-ecological systems theory, we identify five antecedent conditions from the micro, meso, and macro contexts: enterprise size, digital transformation, executive academic backgrounds, media pressure, and government subsidies. These conditions are used to construct a configurational analysis framework for sustained green patent applications in textile companies. The detailed research framework is shown in figure 1.

RESEARCH DESIGN

Research methods

Necessary Condition Analysis (NCA)

NCA is a tool used to identify and quantify whether a variable is a necessary condition for a particular outcome. Unlike fuzzy set qualitative comparative analysis (QCA), which assesses conditions based on set relations, NCA specifies the minimum level a variable must reach to achieve a specific outcome [35]. This method highlights how conditions constrain results by calculating effect sizes and identifying bottleneck points. In practice, the "NCA" package in R-Studio provides ceiling regression (CR) and ceiling envelope (CE) methods for continuous and discrete variables, respectively. Determining necessary conditions using NCA requires an effect size (d) greater than 0.1 and significance verified through a Monte Carlo simulation permutation test ($p < 0.05$).

Fuzzy Set Qualitative Comparative Analysis (fsQCA)

QCA is a set-theoretic and Boolean-based method that treats cases as members of different condition sets. By measuring each case's "membership score" within these sets, it reveals the complex causal relationships between condition combinations and the outcome. Unlike traditional binary logic, fsQCA allows for variable membership to range from 0 to 1, capturing the gradual and nuanced nature of real-world conditions. This method is widely used in management and social sciences to identify "necessary" and "sufficient" conditions, which help uncover multi-causal pathways and causal asymmetry [30].

We chose fsQCA for the following reasons. First, a firm's continuous green innovation is influenced by a complex interplay of factors, leading to nonlinear relationships, multiple causal paths, and causal asymmetry [36, 37]. Traditional linear models, which focus on the independent net effect of variables, are ill-equipped to capture these complexities. fsQCA, by analysing the necessity and sufficiency of condition combinations, can reveal how multiple, distinct configurations lead to the same outcome, thus fully capturing the interactions, complementarity, and substitutability among variables. Second, fsQCA allows conditions to have varying degrees of membership, which provides a more granular reflection of the strength and relative importance of different factors. This makes it particularly suitable for studying complex, multi-dimensional phenomena. Finally, fsQCA is well-suited for small-to-medium sample sizes. Our sample of 48 cases is an ideal size for using this method to conduct an in-depth configurational analysis, rather than relying on traditional large-sample linear inference.

Variable selection and data sources

Following the China Securities Regulatory Commission's 2012 industry classification standards, we selected textile companies listed on Shanghai and Shenzhen A-shares in 2024 as our research subjects. During sample selection, ST and *ST companies and those missing key data were excluded, resulting in a sample of 48 listed textile companies. Annual reports were sourced from official websites of the Shenzhen Stock Exchange and Shanghai Stock Exchange, media attention data came from the CNRDS database, and financial data was retrieved from the CSMAR database. Given the lag effect in sustained green innovation, antecedent conditions were lagged by one period.

Variable measurement and calibration

Outcome variable

Our outcome variable is the continuous green patent application of firms. As a preliminary step, we first need to measure green innovation itself. Patents are a widely used and reliable proxy for innovation output, as they represent specific, quantifiable achievements that possess originality, uniqueness, and market competitiveness. They are easily evaluated and compared due to their relatively uniform global standards, and they directly reflect a firm's innovation performance and development trends.

To identify green patents, we screened the patent application information of our sample firms from the website of the China National Intellectual Property Administration, using the "IPC Green List" developed by the World Intellectual Property Organisation. We then use the number of green patent applications as our measure of green innovation.

Consistent with previous research [6], we measure the level of continuous green innovation by comparing green patent applications across consecutive periods to reflect the sustainability of a firm's innovation efforts. The specific formula is as follows:

$$OIP_t = \frac{Patent_t + Patent_{t-1}}{Patent_{t-1} + Patent_{t-2}} \times (Patent_t + Patent_{t-1}) \quad (1)$$

here, OIP_t represents the continuity of a firm's innovation output in year t, while $Patent_{t-2}$, $Patent_{t-1}$, and $Patent_{i,t}$ denote the number of green patent applications for firm i in years $t-2$, $t-1$, and t, respectively.

Micro system

Enterprise Size: Enterprise size can be measured in various ways, such as employee count, assets total, profits, and revenue. We followed mainstream studies employing the natural logarithm of total assets for this measurement [38, 39].

Meso system

Digital Transformation and Executive Educational Backgrounds: For digital transformation, following Wu et al. [40], we employ text analysis to measure corporate digital transformation. First, the core of digital transformation behaviour is defined as the "application of foundational technologies" and the "implementation of technological practices". The application of foundational technologies encompasses four typical digital transformation technologies: artificial intelligence (A), blockchain (B), cloud computing (C), and big data (D). The implementation of technological practices (E) is categorised based on their practical application. Figure 2 presents the keyword map. Second, utilising a dataset compiled by extracting text from the annual reports of the sample firms using Python, keywords from figure 2 are searched, matched, and counted for frequency. These frequencies are then aggregated by key technological category to form a final summed word frequency, thus constructing the digital transformation indicator system for firms. Finally, we apply a logarithmic transformation to the total word frequency to derive the overall indicator measuring a firm's digital transformation. On the other hand, we measure executive education level using the ratio of the total education level scores of listed company executives to the number of executives. In the CSMAR database, executive educational backgrounds are classified as follows: 1 = Technical/Vocational Secondary School and below, 2 = Associate Degree (Junior College), 3 = Bachelor's Degree, 4 = Master's Degree, 5 = Doctoral Degree, 6 = Other.

Macro system

Media Attention and Government Subsidies: Media attention is quantified by annual media coverage, including online and print reports. Government subsidies are measured by direct fiscal support, adjusted by adding one and taking the logarithm.

We used quantiles for calibrating data according to mainstream studies [36, 41], setting full membership thresholds, crossover points, and full non-membership thresholds at the 95%, 50%, and 5% quantiles of the case data.

EMPIRICAL ANALYSIS

Analysis of necessary conditions

Before conducting QCA, we test whether individual factors constitute necessary conditions for high levels of continuous green patent applications. We import the calibrated fuzzy-set data into R-Studio to perform necessity tests for each antecedent condition. The NCA results indicate that the necessity of executive educational background and government subsidies is statistically insignificant (P-value > 0.05), meaning neither condition is individually necessary for the outcome. Although firm size, digital transformation, and media attention are statistically significant (P-value < 0.05), their effect sizes (d) are all below 0.1, and thus none constitutes a necessary condition for the outcome.

Furthermore, we examine the necessity bottleneck levels for each condition. Table 1 reveals that achieving a 100% level of continuous green innovation requires a firm size level of 9.6%, a digital transformation level of 1%, an executive education level of 1%, a media attention level of 5.3%, and a government subsidy level of 7.9%.

To further confirm the robustness of these findings, we conducted a necessity analysis using fsQCA 3.0 software. Generally, a necessary condition must have a consistency score of at least 0.9 [41]. The consistency scores for each antecedent condition

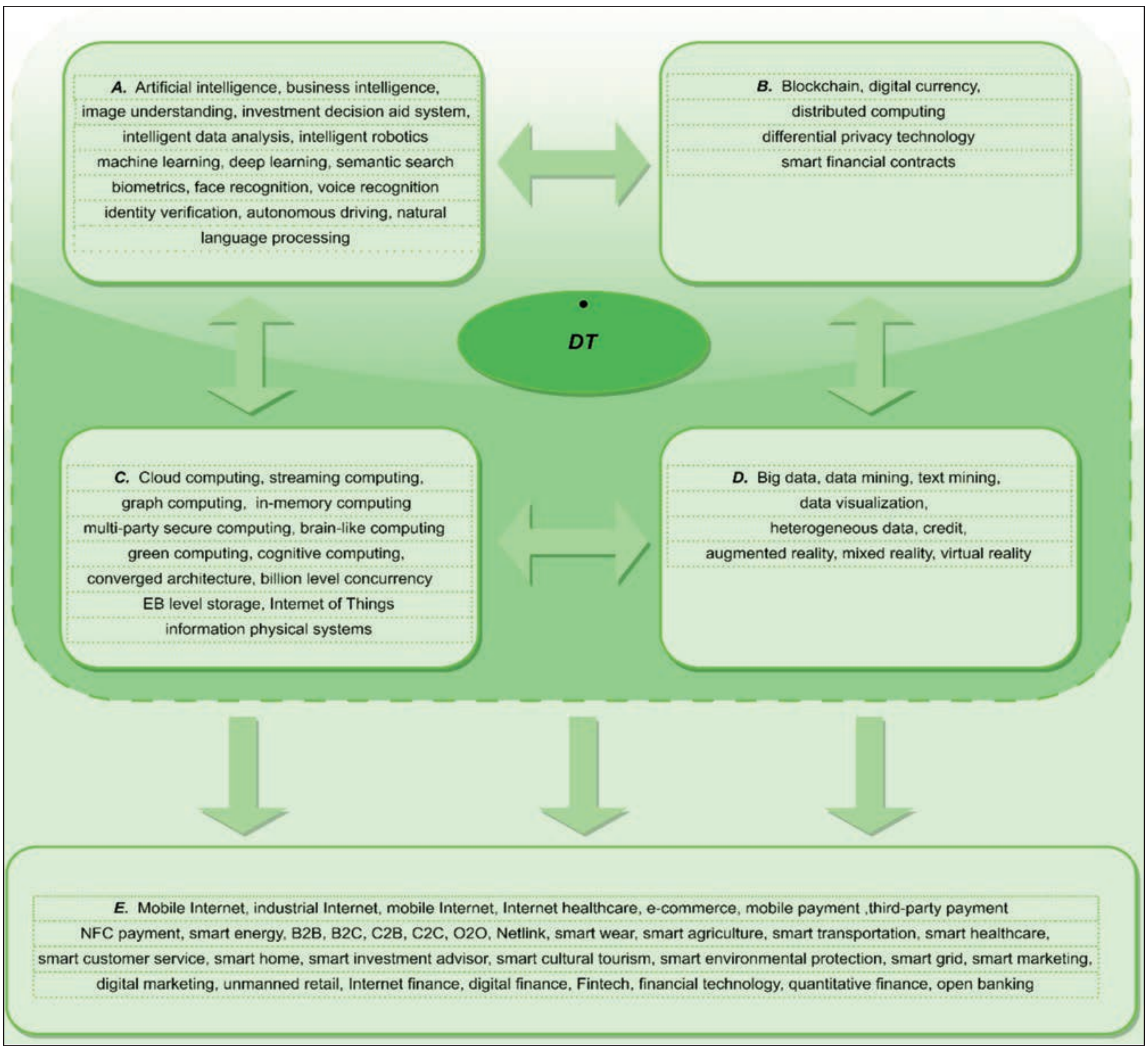

Fig. 2. Characteristic keyword map

Table 1

ANALYSIS RESULTS OF BOTTLENECK LEVEL IN NCA METHOD (%)					
Sustained green innovation	**Firm size**	**Digital transformation**	**Executive educational attainment**	**Media attention**	**Government subsidies**
0	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN
30	NN	NN	NN	NN	NN
40	NN	NN	NN	NN	NN
50	NN	NN	NN	NN	NN
60	NN	NN	NN	NN	NN
70	4.4	NN	NN	NN	NN
80	6.1	NN	NN	NN	1.5
90	7.9	NN	NN	3.9	4.2
100	9.6	1	1	5.3	7.9

Note: The table uses a cap regression analysis CR; NN indicates not necessary.

and its complement fell below this 0.9 threshold. This robustly confirms that no single factor is, by itself, a necessary condition for improving a textile firm's continuous green patent applications.

This finding carries significant economic implications. It suggests that continuous green innovation in the textile industry is not driven by a single factor in isolation but is instead a product of inherent synergy. In other words, firms require an organic combination of multiple conditions to effectively foster the sustained development of green innovation. This result implies that managers should focus on the systematic coordination of various influencing factors rather than strengthening a single aspect in isolation. Given these findings, it is essential to proceed with a sufficiency analysis to explore how different combinations of conditions jointly drive continuous green patent applications in textile firms.

Sufficiency analysis

Unlike necessary condition analysis, causal configuration analysis examines the sufficiency of different combinations of antecedent conditions for the outcome from a set-theoretic perspective. The analysis requires setting frequency and consistency thresholds. The frequency threshold specifies the minimum number of cases per configuration, excluding cases below this value. Following established practices, we set the raw consistency threshold, the proportional reduction in inconsistency (PRI) threshold, and the case frequency threshold to 0.8, 0.7, and 1, respectively. The fsQCA procedure produces three solution types: the complex solution, the intermediate solution, and the parsimonious solution. We primarily report the intermediate solution, using the parsimonious solution to distinguish core conditions within the configurations [36]. Given causal asymmetry, we also report configurations associated with the absence of high continuous green innovation.

Table 2 shows that the four solution configurations for high levels of continuous green patent applications achieve an overall solution consistency of 0.817, exceeding the minimum threshold of 0.75 [41], with a solution coverage of 0.585. This indicates that these configurations collectively explain approximately 58.5% of the cases, demonstrating improved levels of continuous green patent applications among textile firms. Furthermore, comparing the consistency and raw coverage scores of individual configuration paths (figure 3), L2b exhibits the highest values on both metrics. This suggests that configuration L2b demonstrates the strongest explanatory power for high levels of continuous green patent applications, indicating greater robustness and representativeness.

Table 3 shows that the solution for low levels of continuous green patent applications achieves an overall consistency of 0.813, exceeding the minimum threshold of 0.75, with a solution coverage of 0.602. This accounts for approximately 60.2% of cases exhibiting low levels of continuous green innovation in textile firms. Furthermore, comparison of consistency and raw coverage scores across configuration paths (figure 4) reveals that S4a demonstrates the highest values on both metrics. This indicates that the concurrent absence of executive educational background and government subsidies, when digital transformation is the sole driver, most frequently associates with low levels of continuous green patent applications.

Summary of results

We employ intermediate and parsimonious solutions to identify core and peripheral conditions, categorising them into two archetypes: Environment-Led & Organisation-Coordinated and Technology-Environment-Driven.

1. *Environment-Led and Organisation-Coordinated (L1a+L1b)*

Configuration L1a exhibits a consistency of 0.838 and raw coverage of 0.340, accounting for approximately 34% of sample cases. Configuration L1b shows a consistency of 0.876 and raw coverage of 0.266, explaining approximately 27% of sample cases. In L1a, firm size, media attention, and government subsidies constitute core conditions, while

Table 2

CONFIGURATION ANALYSIS FOR HIGH LEVELS OF CONTINUOUS GREEN PATENT APPLICATIONS				
Causal conditions	**Environment-Dominant-Organizational coordination**		**Technology-Environment driven**	
	L1a	**L1b**	**L2a**	**L2b**
Firm size	▣	▣		★
Digital transformation	★		▣	▣
Executive educational attainment	★	▣	★	★
Media attention	▣	▣	▣	▣
Government subsidies	▣	▣	▣	▣
Consistency	0.838	0.876	0.868	0.895
Raw coverage	0.340	0.266	0.328	0.394
Unique coverage	0.117	0.024	0.008	0.073
Solution consistency	0.817			
Solution coverage	0.585			

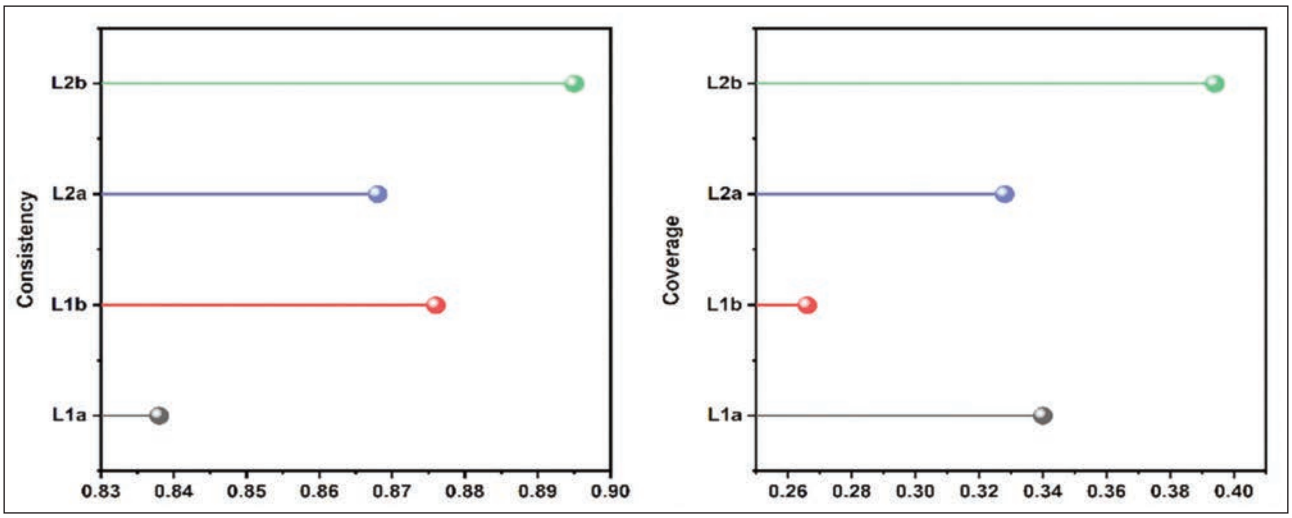

Fig. 3. Consistency and coverage

Table 3

CONFIGURATION ANALYSIS FOR LOW LEVELS OF CONTINUOUS GREEN PATENT APPLICATIONS								
Causal conditions	**Environment-Absent**		**Techonology-Deficient**			**Organizationally Weak**	**Single-Factor Presence**	
	S1a	**S1b**	**S2a**	**S2b**	**S2c**	**S3a**	**S4a**	**S4b**
Firm size	✱		✱	✱	✱	⊡		⊡
Digital transformation		✱	⊡	⊡	⊡		▣	
Executive educational attainment	★	✱		★	⊡	⊡	⊡	
Media attention	⊡	⊡	✱	✱	★	★	✱	▣
Government subsidies	⊡	⊡	★	✱	✱		⊡	⊡
Consistency	0.836	0.897	0.910	0.886	0.834	0.910	0.912	0.855
Raw coverage	0.484	0.243	0.216	0.368	0.334	0.216	0.486	0.244
Unique coverage	0.107	0.015	0.008	0.015	0.012	0.008	0.005	0.014
Solution consistency	0.813							
Solution coverage	0.602							

Note: ▣ denotes the presence of a core condition; ⊡ denotes the absence of a core condition; ★ denotes the presence of a peripheral (contributing) condition; ✱ denotes the absence of a peripheral (contributing) condition; "blank" indicates that the condition's presence or absence is irrelevant for the configuration.

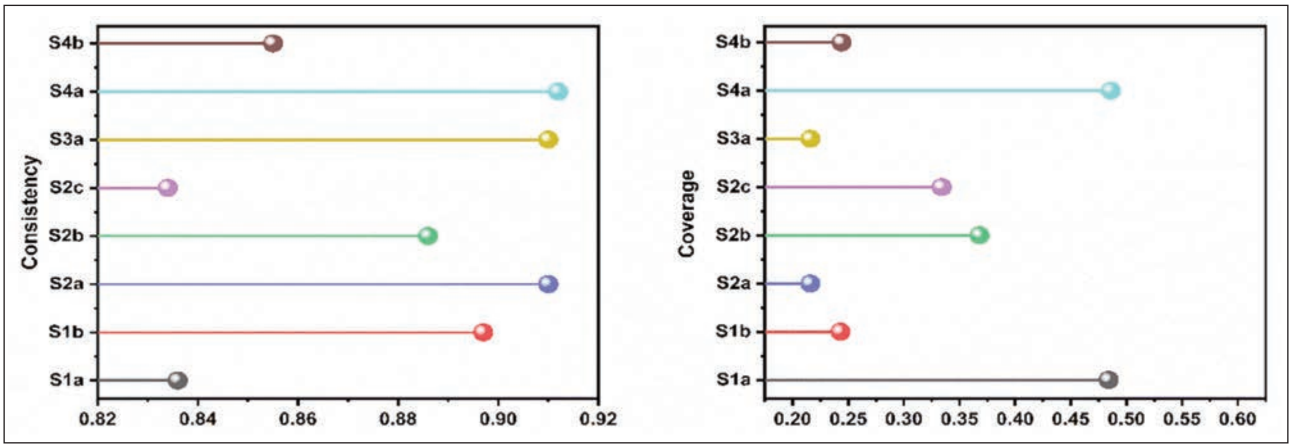

Fig. 4. Consistency and coverage

digital transformation and executives' educational attainment play supplementary roles. This indicates that in the textile industry, firms of substantial scale more readily secure government subsidies and media attention. The continuous infusion of these external resources facilitates green innovation activities. In such cases, while the firm's digital infrastructure and managerial education level are not decisive, they provide effective support in resource utilisation and innovation implementation. In L1b, firm size, executives' educational attainment, media attention, and government subsidies form core conditions, suggesting that large textile enterprises with management teams possessing advanced degrees better identify and respond to external policy and public opinion pressures, thereby enhancing responsiveness to green transformation. This configuration reinforces the synergistic effect between internal organisational capabilities and external drivers. Collectively, the L1a and L1b pathways emphasise macro-level drivers, such as government funding and public oversight, while relying on internal organisational foundations like economies of scale or executive competence. Thus, we designate this archetype as Environment-Led and Organisation-Coordinated.

2. *Technology-Environment-Driven (L2a+L2b)*

Configuration L2a demonstrates a consistency of 0.868 and raw coverage of 0.328, accounting for approximately 33% of sample cases. Configuration L2b yields a consistency of 0.895 and raw coverage of 0.394, explaining approximately 39% of sample cases. In L2a, digital transformation, media attention, and government subsidies constitute core conditions, with executives' educational attainment playing a supplementary role. This indicates that in advancing green innovation within the textile industry, digital transformation serves as the key driver for optimising resource allocation and upgrading process control, while sustained media attention and government subsidies provide powerful external incentives. Although executive teams with advanced degrees lack decisive influence, they enable more effective policy integration and enhance green strategy implementation efficiency. In L2b, digital transformation, media attention, and government subsidies similarly form core conditions, with firm size and executives' educational attainment also contributing significantly. This suggests that achieving green innovation in the textile industry requires not only digital capabilities and external support but also adequate resource foundations and managerial competencies, facilitating synergistic improvements in technology absorption, policy alignment, and resource integration during green innovation. Overall, both L2a and L2b pathways underscore the co-driving effects of technological factors and the macro-environment. Therefore, we designate this archetype as Technology-Environment-Driven.

3. We also identified eight configurations leading to low sustained green patent applications in textile enterprises. Based on their distinctive features, we categorise these as: Environment-Absent, Technology-Deficient, Organisation-Weak, and Single-Factor Presence pathways. In configurations S1a, S1b, S2a, S2b, S2c, and S3a, core conditions are consistently absent, demonstrating that enhanced sustained green patent levels in textile firms only occur when coordination exists among micro-, meso-, and macro-level factors. In S4a and S4b, only digital transformation and media attention act independently as core conditions, indicating that achieving sustained green patent applications in this industry emerges not from isolated drivers but from multifactor synergies.

Comparative analysis of configurations generating high versus low sustained green patent applications reveals significant causal asymmetry (figure 5). Specifically, the condition sets enabling high-level outcomes are not merely negations of those producing low-level outcomes. Notably, across all four high-outcome pathways (L1a, L1b, L2a, L2b), media attention and government subsidies consistently appear as core conditions, highlighting their universal applicability in driving high sustained green patent applications.

Robustness analysis

In fsQCA, robustness testing can be performed through multiple approaches, such as adjusting the frequency threshold and consistency threshold to

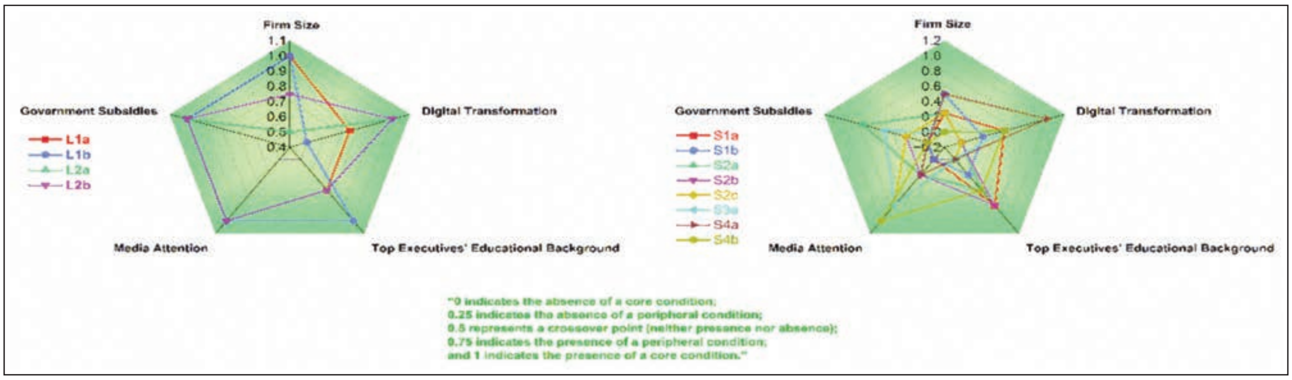

Fig. 5. Configuration radar chart

examine configuration stability under alternative specifications. For this study, we modified the frequency threshold from its original value to 2 while maintaining other parameters, releasing additional borderline cases and enabling observation of configuration changes. Table 4 shows that core pathways (L1a, L1b, and L2b) persist and closely match original results. These outcomes represent a subset of the high-level configurations in table 2, demonstrating robust stability of key configurations across parameter settings. Table 5 further indicates that pathways generating low-level sustained green patent applications remain essentially unchanged structurally. Collectively, post-adjustment comparative analysis confirms the strong robustness of our identified critical configurations, with research conclusions maintaining high explanatory power and credibility under alternative specifications.

Table 4

HIGH-LEVEL SUSTAINED GREEN PATENT APPLICATIONS (ROBUSTNESS TEST)			
Causal Conditions	**L1a**	**L1b**	**L2b**
Firm size	▣	▣	
Digital transformation	★		▣
Executive educational attainment		▣	★
Media attention	▣	▣	▣
Government subsidies	▣	▣	▣
Consistency	0.838	0.868	0.869
Raw coverage	0.340	0.328	0.356
Unique coverage	0.129	0.049	0.090
Solution consistency	0.824		
Solution coverage	0.563		

Note: ▣ denotes the presence of a core condition; ⊡ denotes the absence of a core condition; ★ denotes the presence of a peripheral (contributing) condition; ∗ denotes the absence of a peripheral (contributing) condition; "blank" indicates that the condition's presence or absence is irrelevant for the configuration.

CONCLUSION

We selected 48 Chinese A-share listed textile enterprises as our sample. Drawing upon social-ecological system theory, we employed NCA necessity analysis and fsQCA to investigate the mechanisms and pathways influencing enterprises' sustained green patent applications. Our main conclusions are as follows:

(1) Digital transformation, enterprise scale, executive educational background, government subsidies, and media attention are important factors affecting the level of sustained green patent applications in textile

Table 5

LOW-LEVEL SUSTAINED GREEN PATENT APPLICATIONS (ROBUSTNESS TEST)								
Causal conditions	**S1a**	**S1b**	**S2a**	**S2b**	**S2c**	**S3a**	**S4a**	**S4b**
Firm size	∗	∗	∗	∗	∗	⊡	∗	∗
Digital transformation		∗	⊡	⊡	⊡	∗	▣	∗
Executive educational attainment		∗		∗	⊡	⊡	⊡	∗
Media attention	⊡	⊡		∗		★	∗	▣
Government subsidies	⊡	⊡	★		∗			⊡
Consistency	0.836	0.908	0.929	0.886	0.834	0.910	0.912	0.855
Raw coverage	0.384	0.205	0.335	0.368	0.334	0.216	0.435	0.244
Unique coverage	0.110	0.010	0.018	0.015	0.012	0.008	0.005	0.014
Solution consistency	0.875							
Solution coverage	0.575							

Note: ▣ denotes the presence of a core condition; ⊡ denotes the absence of a core condition; ★ denotes the presence of a peripheral (contributing) condition; ∗ denotes the absence of a peripheral (contributing) condition; "blank" indicates that the condition's presence or absence is irrelevant for the configuration.

enterprises, and contribute in distinct ways across different configurations. However, NCA results indicate that none of these five factors individually constitutes a necessary condition for enhancing green patent performance. Instead, firms' green patent capability is more dependent on the synergistic configuration and complementary mechanisms of multiple factors.

(2) We identified four configurations that lead to a high level of sustained green patent applications in textile enterprises. These can be categorised into two main pathways: the environment-dominated–organisational collaboration pathway and the technology-environment-driven pathway.

(3) Across all high-level green patent application configurations, media attention and government subsidies consistently appear as core conditions. This demonstrates the universality and criticality of these two macro-environmental factors in promoting green innovation in textile enterprises, highlighting their importance for achieving high-level green patent output.

(4) The conditional configurations affecting green patent applications in textile enterprises exhibit clear causal asymmetry. That is, the combination of factors leading to high-level green patent applications is not equivalent to the inverse configuration of conditions resulting in low-level applications.

This study offers significant theoretical and practical implications. Firstly, it expands the research perspective on sustained green patent applications. While existing literature primarily focuses on the linear effects of single factors [10, 21, 22], our study, grounded in configuration theory, identifies the synergistic mechanisms through which multiple factors drive sustained green patent applications. This actively responds to recent calls for research on the coupling of ecological elements [24, 42]. Secondly, we confirm the asymmetric nature of causality: the combinations of conditions leading to high-level innovation cannot simply be inverted to explain low-level innovation. This finding enriches the theoretical understanding within the green innovation domain.

Based on our findings, we propose the following policy implications to effectively enhance continuous green innovation in textile firms:

- First, from the perspective of textile firm managers, achieving high-level continuous green innovation requires a holistic approach. Managers must consider the intricate interplay among micro, meso, and macro-level factors rather than focusing on a single dimension. By adopting a configurational mindset, they can make informed decisions that promote sustained green innovation. For instance, along the environment-led and organisational synergy path, managers should strengthen communication with government bodies and media outlets, actively seek subsidies and public support, and leverage their firm's size to establish cross-departmental coordination. This will enhance their responsiveness to external changes and avoid the risk of low innovation levels, a finding consistent with our conclusion that no single factor is a necessary condition for green innovation.
- Second, government departments should pay greater attention to the incentive role of environmental subsidies in promoting green technology innovation within the textile industry and improve the precision and alignment of policy design. For firms on the environment-led and organisational synergy path, the focus should be on refining the mechanisms for precise subsidy allocation and oversight to ensure funds are used for optimising green production processes and building organisational capabilities. For firms on the technology-environment driven path, increased financial and tax support should be directed toward R&D and digital transformation projects. This targeted support can more effectively stimulate green innovation and facilitate the sustainable development of the textile industry by matching policy design with the specific characteristics of each pathway.

Our use of the fsQCA method to identify sufficient condition combinations is intended to complement, not replace, traditional regression analysis that uncovers the net effects of single variables. This approach provides a richer perspective on complex causal relationships. Despite our contributions, this study has several limitations. First, our reliance on cross-sectional data for static analysis limits our ability to capture temporal dynamics. Future research could apply time-series or dynamic QCA methods to explore the long-term effects of antecedent variables on continuous green innovation. Second, while we selected a comprehensive set of empirically tested variables from existing literature across micro, meso, and macro levels, we may have omitted some key factors due to data availability and sample characteristics. The complexity of firms' motivations for continuous green innovation may not be fully captured. Future studies could expand the variable dimensions to include factors like corporate culture or governance structures.

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Economic policy uncertainty and micro-level green development: an empirical study of Chinese textile firms

DOI: 10.35530/IT.077.01.202595

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ABSTRACT – REZUMAT

Economic policy uncertainty and micro-level green development: an empirical study of Chinese textile firms

As the world's second-largest polluter, the Environmental, Social, and Governance (ESG) transformation of the textile industry is crucial for global sustainable development. China, as a major global textile producer, has textile enterprises whose ESG performance directly impacts global climate governance objectives. However, economic policy uncertainty (EPU) poses a significant challenge to the ESG investment decisions of textile firms. ESG investments within the textile sector are characterised by substantial upfront capital, prolonged payback periods, and elevated risks, rendering them highly dependent on a stable policy environment. Policy uncertainty can significantly impede enterprises' green transition. This study investigates the impact of EPU on the ESG performance of Chinese A-share textile companies from 2009 to 2024. Our findings indicate that heightened EPU significantly diminishes the ESG performance of textile enterprises. This negative effect is particularly pronounced in financially distressed firms, those with lower information transparency, and state-owned enterprises. Mechanism analysis reveals that EPU primarily hampers ESG investment in textile firms by exacerbating bank credit contraction and prompting firms to increase cash holdings, which collectively reduce their working capital circulation capacity. This paper extends the literature on ESG determinants from a macro policy perspective, offering novel theoretical insights and empirical evidence for understanding the green transformation of traditional manufacturing industries.

Keywords: *textile industry, economic policy uncertainty, corporate ESG performance, corporate cash holdings, bank credit*

Incertitudinea politicii economice și dezvoltarea ecologică la nivel micro: un studiu empiric asupra firmelor textile din China

Fiind al doilea cel mai mare poluator din lume, transformarea industriei textile din punct de vedere al factorilor de mediu, sociali și de guvernanță (ESG) este crucială pentru dezvoltarea durabilă la nivel global. China, în calitate de important producător mondial de produse textile, are întreprinderi textile ale căror performanțe ESG au un impact direct asupra obiectivelor globale de guvernanță climatică. Cu toate acestea, incertitudinea politicii economice (EPU) reprezintă o provocare semnificativă pentru deciziile de investiții ESG ale firmelor textile. Investițiile ESG în sectorul textil se caracterizează prin capital inițial substanțial, perioade de recuperare prelungite și riscuri ridicate, ceea ce le face să depindă în mare măsură de un mediu politic stabil. Incertitudinea politică poate împiedica în mod semnificativ tranziția ecologică a întreprinderilor. Acest studiu investighează impactul EPU asupra performanței ESG a companiilor textile chineze cu acțiuni de tip A din 2009 până în 2024. Concluziile noastre indică faptul că EPU crescută diminuează în mod semnificativ performanța ESG a întreprinderilor textile. Acest efect negativ este deosebit de pronunțat în cazul firmelor aflate în dificultate financiară, al celor cu o transparență informațională redusă și al întreprinderilor de stat. Analiza mecanismului relevă faptul că EPU împiedică în primul rând investițiile ESG în firmele textile, exacerbând contracția creditelor bancare și determinând firmele să-și mărească deținerile de numerar, ceea ce reduce în mod colectiv capacitatea lor de circulație a capitalului circulant. Acest articol extinde literatura de specialitate privind factorii determinanți ESG dintr-o perspectivă macroeconomică, oferind perspective teoretice noi și dovezi empirice pentru înțelegerea transformării ecologice a industriilor manufacturiere tradiționale.

Cuvinte-cheie*: industria textilă, incertitudine în politica economică, performanța ESG a companiilor, deținerile de numerar ale companiilor, credit bancar*

INTRODUCTION

Recently, corporate sustainability and high-quality growth have become central themes in global economic governance. ESG performance has rapidly evolved from a voluntary, "nice-to-have" attribute to a fundamental requirement for operating in capital markets and navigating complex supply chains [1]. For resource-intensive manufacturing sectors, ESG investments are not only crucial for long-term carbon reduction and pollution control targets but also directly influence financing costs, supply chain resilience, and access to international markets [2]. In industries like textiles, characterised by intricate supply chains and high water and energy consumption, pollution control and energy-saving facilities often require substantial, long-term, and irreversible capital commitments. Consequently, understanding the conditions under which firms sustain their ESG investments is a matter of significant policy importance and practical urgency [3]. The growing stringency of cross-border green standards and trade rules, coupled with China's accelerated "carbon peak and carbon neutrality" agenda, has made the strategic integration of ESG into capital budgeting and performance evaluation a necessary corporate evolution [4].

While the existing literature on the drivers of corporate ESG has yielded substantial insights, it has primarily focused on internal, firm-level characteristics, such as board structure and independence [5], executive traits and incentives [6], and institutional investor oversight. In contrast, the role of the macro policy environment and its uncertainty, a fundamental external force shaping corporate decisions, remains largely underexplored. Theoretically, the net effect of economic policy uncertainty (EPU) on corporate ESG decisions is ambiguous, as it triggers two competing mechanisms. On one hand, EPU may inhibit a firm's ESG performance. Drawing on real options theory [7], when the future direction of policies (e.g., environmental taxes, subsidy standards) is unclear, the option value of waiting to make irreversible ESG investments increases significantly. In this context, rational managers may postpone or scale back such investments to avoid potential sunk costs [8]. Simultaneously, asymmetric information theory suggests that policy uncertainty amplifies the volatility of a firm's future cash flows, widening the information gap with external financiers like banks. This can lead banks to tighten credit and raise risk premiums [9], thereby severely restricting a firm's financial capacity for large-scale ESG investments. On the other hand, EPU may, under certain conditions, incentivise greater ESG investment. According to risk management theory, robust ESG performance can be viewed as a form of "reputational insurance" [10]. During periods of policy turmoil, firms that proactively engage in social responsibility can build greater social trust and stakeholder support. This "social capital" can effectively mitigate negative shocks and enhance a firm's operational resilience [11]. Therefore, forward-thinking managers may strategically leverage ESG investments to hedge against risks stemming from policy uncertainty and build a unique competitive advantage. This tension, between the "investment inhibition" driven by real options and financing constraints, and the "strategic incentive" stemming from risk management and reputation building, constitutes the central research question of this paper. Disentangling the interplay between these two forces is crucial for understanding corporate sustainability strategies in an uncertain environment.

The Chinese context provides an ideal setting for investigating this question. First, as the world's leading textile manufacturing hub, China's vast industrial scale and intricate supply chains ensure that ESG practices have significant environmental and social impacts. Second, Chinese firms face the dual pressures of international green trade barriers and the domestic "dual carbon" strategy, making their ESG decisions far more sensitive to macroeconomic policy guidance than those in mature economies [12]. Finally, China's unique, bank-dominated, and policy-influenced financial system [13] makes the transmission of economic policy uncertainty to corporate financing channels particularly direct and pronounced. These unique industry and institutional features allow us to clearly observe how policy uncertainty impacts corporate ESG behaviour through both financing constraints and risk management channels, thereby offering unique and valuable empirical evidence from the world's largest emerging economy to the international literature.

This study uses a balanced panel dataset of A-share listed textile and related manufacturing companies in China from 2009 to 2024. We integrate financial and governance data from authoritative sources and use the SNSI ESG rating as our dependent variable. We employ a widely-used measure of economic policy uncertainty and address temporal consistency by aggregating it to the quarterly level. In our empirical analysis, we first estimate the average effect of EPU on corporate ESG within a firm- and time-fixed effects framework, while controlling for a wide range of covariates, including profitability, size, leverage, growth, and industry performance. We further cluster standard errors at the firm and time dimensions to ensure robust inference. Second, for our mechanism analysis, we introduce two mediating variables, bank loans and excess cash, to test the financing constraint and risk management channels, respectively, using a combined mediation analysis and stepwise regression approach. Third, we conduct heterogeneity analyses based on ownership type, information transparency, and financial health to identify how these effects differ across firms with varying governance and constraint environments. Finally, we use an instrumental variables approach with an exogenous policy uncertainty proxy and dynamic panel estimation to address potential endogeneity and persistence issues. We also perform a series of systematic robustness checks, including using alternative EPU measures, trend filtering, outlier treatment, and alternative sample specifications.

This paper makes several key contributions: First, a Theoretical Contribution. We contribute to the theoretical literature by moving beyond the existing focus on internal firm characteristics to construct a systematic framework that links macroeconomic policy uncertainty to micro-firm ESG decisions. While traditional ESG research has often overlooked the macro policy environment as a critical external driver, we draw on insights from information economics and behavioural finance to analyse how policy uncertainty alters a firm's risk perceptions, investment expectations, and resource allocation, ultimately influencing its ESG practices. This theoretical innovation not only enriches the study of ESG antecedents but also provides a new analytical framework for understanding the complex interplay among "policy, firm, and environment", offering significant theoretical value.

Second, an Industry-Specific Empirical Contribution. Our choice of the textile industry as a research focus is both representative and policy-relevant. As a typical "high-pollution, high-energy-consumption, and labour-intensive" traditional manufacturing sector, the textile industry faces uniquely complex and profound challenges in its ESG transition. Compared to high-tech or service industries, ESG investments in the textile sector are characterised by large capital outlays, long cycles, and high technical risks, making them more dependent on a stable policy environment. Furthermore, the textile industry is a cornerstone of China's manufacturing economy and a key sector for achieving the national "dual carbon" goal. By focusing on this specific industry, our paper provides important empirical evidence on the ESG transformation of traditional manufacturing and offers a valuable methodological reference for research on other resource-intensive, policy-sensitive industries.

Third, a Methodological Contribution to Mechanism Identification. This paper makes an important innovation in mechanism analysis by being the first to identify and verify the dual transmission channels, financing constraints and risk aversion, through which economic policy uncertainty affects the ESG performance of textile firms. We find that policy uncertainty influences corporate ESG decisions through two pathways: first, through the external financing channel, where it exacerbates information asymmetry between banks and firms, prompting financial institutions to adopt more cautious lending policies. This leads to financing difficulties and rising costs for firms, forcing them to scale back ESG investments. Second, through the internal risk management channel, where policy uncertainty incentivises firms to increase cash holdings to manage potential risks, thereby reducing capital available for ESG practices. The identification of this dual mechanism not only deepens our understanding of how policy uncertainty impacts corporate behaviour but also provides a scientific basis for policymakers to design more effective ESG promotion policies.

Fourth, the Discovery of Policy Heterogeneity Effects. We further uncover significant heterogeneity in the effects of policy uncertainty on different types of textile firms. Our findings reveal that the negative impact of policy uncertainty is more pronounced for financially distressed firms, firms with low information transparency, and state-owned enterprises. This discovery enriches our understanding of firm heterogeneity and provides crucial insights for designing targeted ESG policies. For financially distressed firms, EPU further worsens their financing environment, making it harder to secure the capital needed for an ESG transition. For firms with low information transparency, EPU exacerbates information asymmetry with external investors, increasing the opportunity cost of ESG investments. For state-owned enterprises, EPU may cause them to overemphasise policy signals in their ESG decisions, to the detriment of market demands. The identification of these heterogeneous effects offers a new perspective for explaining the differences in ESG behaviour among firms with different ownership types and developmental stages.

LITERATURE REVIEW

Economic Policy Uncertainty (EPU)

Economic policy uncertainty (EPU) has a demonstrable impact at both the macroeconomic and microeconomic levels. At the macro level, EPU can lead to a decrease in aggregate output and price levels, causing a negative demand shock [14], and can influence the exchange rate and capital market volatility [9]. Recent research also indicates that such macroeconomic shocks can amplify financial market risks through cross-border capital flows [15].

At the microeconomic level, uncertainty can affect firms' investment decisions and efficiency, exacerbate external financing constraints, and inhibit corporate innovation and R&D [16, 17]. Additionally, uncertainty may prompt firms to increase their holdings of financial assets and other non-productive expenditures. It may also increase the reliance on short-term debt for long-term investments [18] and mitigate managerial overconfidence [19]. Furthermore, existing studies show that changes in economic policy affect firms' recycling and emission reduction behaviours [20]. Some scholars argue that corporate social responsibility can serve as a strategic tool for competitive advantage during times of EPU [21]. This perspective suggests that firms may increase their social responsibility efforts and allocate more resources to technological innovation when faced with economic policy uncertainty. However, whether firms genuinely fulfil these commitments remains a subject of debate.

Environmental, Social, and Governance (ESG)

By definition, ESG is a comprehensive framework that integrates the three key pillars of corporate behaviour: environmental, social, and governance [22]. Operationally, ESG practices increase a firm's environmental performance pressure, broaden the scope of corporate governance, and guide firms to engage with stakeholders in co-creating value.

Academic research on ESG drivers suggests that firms are motivated to adopt ESG practices by both external regulatory pressure and internal managerial characteristics [23]. With respect to external pressure, Filatotchev and Nakajima [24] argue that firms face complex institutional pressures and demands from multiple stakeholders, which direct managerial attention toward ESG performance. Regarding internal managerial characteristics, the primary factors influencing a firm's ESG practices are the choices, motivations, and values of the managers involved in the decision-making process. Ahn [6], for instance, found that a broader CEO attention span is associated with better sustainability performance. Similarly, Crifo et al. [5] showed that a higher proportion of internal directors can also effectively improve a firm's ESG performance. Building on these findings, companies are increasingly incorporating ESG into their evaluation systems and linking it to executive compensation to enhance internal incentives for ESG engagement.

In the study of ESG's economic benefits, the short-term literature has emphasised the positive impact of ESG performance and disclosure on corporate financial performance, as well as the returns on ESG-related investment portfolios. However, the findings in this area have been mixed. Some studies confirm a positive relationship between ESG practices and corporate financial performance, contending that firms actively engaged in sustainable and socially responsible practices have superior financial outcomes. Conversely, Duque-Grisales and Aguilera-Caracuel [25] found a statistically significant negative relationship between ESG scores and financial performance. From a long-term perspective, studies have examined how ESG investments and disclosures affect the future environment, reflecting stakeholders' expectations for corporate responsibility, transparency, and information provision. So, the disclosure of non-financial information related to ESG performance can elicit a positive market response. This suggests that environmental and social responsibility has become a key driver of product innovation and can create long-term value for a firm.

THEORETICAL ANALYSIS AND RESEARCH HYPOTHESES

In terms of its content, the ESG framework provides a comprehensive evaluation of a firm's environmental, social, and governance factors. It not only helps to build a positive corporate reputation but also aligns with the new development paradigm, offering a systematic and quantifiable approach to promote sustainable and green development [26]. As a foundation for socially responsible investment, the environmental dimension's metrics, such as carbon emissions, serve as an effective tool for measuring a firm's practical contribution to achieving "dual carbon" strategic goals [27,28]. While China's green economy is still in its nascent stages at the microeconomic level, ESG indicators can be a valuable complement to existing measures of an economic entity's low-carbon performance. However, as microeconomic actors, a firm's daily operations are primarily driven by the decisions of its senior managers. These managers typically prioritize stabilizing cash flow and increasing operating income. Since the long-term environmental benefits of ESG often outweigh its immediate financial returns, managers may selectively reduce or forgo ESG investments [25].

When economic policy changes, rising uncertainty can increase banks' lending risk. To mitigate this risk, banks often tighten lending standards, which can lead to a credit crunch and a distorted allocation of credit resources [29]. Consequently, the criteria for assessing corporate loan risk become more stringent, and the cost of corporate borrowing rises. Due to the volatility of economic policy, banks find it difficult to evaluate a firm's prospects. The frequent updates to lending policies exacerbate the burden of information processing for banks, reducing firms' access to external financing and prompting them to curb investment [30]. This, in turn, lowers a firm's willingness to invest in ESG, leading them to reduce or even abandon such commitments. Furthermore, some investors perceive a firm's ESG practices as an attempt by managers to enhance their personal status and reputation, viewing it as an irresponsible behaviour that can introduce uncertainty into a firm's operations and profitability, thereby increasing investment risk. This perception can further reduce the likelihood of banks providing credit.

From the perspective of ESG returns, they are long-term, intangible, and difficult to monetise. This complicates managers' decisions regarding ESG adoption. ESG practices are a form of long-term value investment that requires substantial upfront resources. The returns are often indirect and do not generate a stable cash flow immediately. Since ESG investments divert a firm's operational resources, and a firm's available resources are finite [31], short-term financial indicators may weaken, and credit risk may increase [32]. Similarly, existing research shows that external shocks, such as physical climate risks, can significantly weaken the sustainability of corporate investments [33]. When a government engages in macroeconomic regulation, economic policies can exhibit frequent changes, which makes the external information environment more uncertain and complex. The rise in EPU increases the degree of information uncertainty in capital markets, making future market demand more difficult to predict and amplifying the volatility of corporate cash flows. This strengthens a firm's precautionary savings motive [26], prompting external investors to become more cautious. As a result, managers are more inclined to increase liquid asset holdings and focus on working capital management to mitigate the adverse impacts of the external environment on core business operations [34]. This diversion of discretionary funds reduces the resources available for other less urgent activities, including ESG investments.

In summary, under the influence of economic policy uncertainty, two primary mechanisms are at play. First, banks tighten lending standards, which reduces a firm's ability to obtain external financing and the capital available for ESG initiatives. Second, firms face increased internal cash flow pressure, which effectively means they lack the discretionary resources for effective ESG practices. That is, to reduce the risk of cash flow uncertainty and prioritise short-term returns, managers consider ESG investments, which do not generate immediate financial benefits, as non-essential long-term expenditures and therefore reduce their commitment to them. Consequently, corporate managers are more inclined to invest in projects with high short-term returns to mitigate operational risks stemming from financing constraints, rather than pursuing ESG practices. This ultimately undermines the ability of ESG to promote green development at the microeconomic level.

Based on this, this paper proposes the following hypotheses:

H1: Ceteris paribus, economic policy uncertainty has a negative impact on corporate ESG performance.

H2: When economic policy uncertainty increases, enterprises obtain fewer loans from banks, thereby reducing their ESG investment.

H3: When economic policy uncertainty increases, enterprises increase their precautionary cash holdings, which reduces the funds available for discretionary investment and thereby diminishes their ESG investment.

RESEARCH DESIGN

Data sources and sample selection

This study utilises Chinese A-share textile companies from 2009 to 2024 as its initial sample. We then subjected this sample to a rigorous screening process, which included: (1) excluding observations from 'ST' and '*ST' companies (firms under special treatment due to financial distress or regulatory non-compliance), and (2) removing observations with missing data. After this screening, we obtained a final sample of 2,724 company-quarter observations. To mitigate the influence of extreme values on our results, we Winsorized all continuous variables at the 1st and 99th percentiles.

Firm-level financial and governance data were sourced from the CSMAR database, while macro-level GDP and CPI data were obtained from the National Bureau of Statistics of China website. All statistical analyses were performed using Stata 17.

Definition of variables

Economic Policy Uncertainty (EPU)

Our primary measure of economic policy uncertainty is the China Economic Policy Uncertainty Index, as developed by Baker et al. [35]. The raw data were downloaded directly from the official website: www.policyuncertainty.com. As reported by the South China Morning Post, this index is constructed based on the percentage of news articles containing the keywords "China", "economy", "uncertainty", and "policy" relative to the total number of articles published in that month. Baker et al. [35] contend that the South China Morning Post, being the most influential and widely circulated English newspaper in Hong Kong, serves as a representative platform for news report retrieval. Furthermore, existing research has widely validated the applicability of this index in measuring China's economic policy uncertainty.

Corporate ESG performance

The primary dependent variable in this study, corporate ESG performance, is measured using data from the SNSI (Sino-Securities Index) ESG rating system, a widely used and highly regarded data source in China's A-share market. The SNSI framework is designed to provide a comprehensive and reliable basis for measuring firms' sustainable development practices by incorporating local characteristics of Chinese companies while benchmarking against international ESG evaluation standards.

The underlying structure of the SNSI system is granular and built upon a top-down, three-level framework. Its highest level consists of the three core pillars of ESG: Environment, Social, and Governance. These pillars are further divided into 14 specific sustainable development themes, such as environmental management, green production, employee rights, supply chain management, shareholder protection, and board operation. These themes are ultimately measured by 26 key indicators and over 130 foundational data points, which serve as the most basic units of the rating. Examples of these data points include greenhouse gas emissions per unit of revenue and the proportion of independent directors. The data is sourced from firms' annual reports, ESG reports, government websites, and mainstream news media.

In terms of scoring, the SNSI system first standardises and scores the foundational data points. It then aggregates these scores hierarchically using industry weighting to generate individual scores for each of the three pillars, as well as a final composite ESG score. In our baseline regression, we use this standardised composite score as our primary measure of corporate ESG performance. As a continuous variable, it provides a more granular measure that can capture marginal changes in a firm's ESG performance. For robustness checks, we also employ the nine-point ordinal scale (AAA to C) that SNSI uses to grade corporate ESG performance, thereby confirming the reliability of our findings.

Control variables

Consistent with prior studies, such as Liu et al. [36] and Ma et al. [37], we include a set of firm- and macro-level variables to control for their potential influence on ESG performance: Company Size (*Size*); Leverage Ratio (*Lev*); Return on Assets (*Roa*); Cash Flow Level (*Cfo*); Fixed Asset Ratio (*Fang*); Largest Shareholder Ownership Ratio (*First*): Measured as the ratio of shares held by the largest shareholder to total shares outstanding; Tobin's Q (*TobinQ*); Independent Director Ratio (*Ind*); Dual Role (*Dual*); Managerial Shareholding Ratio (*MS*); Executives with Legal Background (*MLaw*).

Model design

To test Hypothesis H1, we constructed the following econometric model:

$$ESG_{it} = \alpha_0 + \alpha_1 EPU_t + \alpha \sum Controls_{it} + \theta_i + \varepsilon_{it} \quad (1)$$

where ESG_{it} represents the corporate ESG performance score for firm i in quarter t, with higher scores indicating better ESG performance and a greater commitment to sustainable development and long-term value creation. EPU_t denotes the economic policy uncertainty index for quarter t. This annual measure is constructed by arithmetically averaging the monthly EPU data for each year. $Controls_{it}$ is a set of firm- and macro-level control variables. The model also includes firm fixed effects (θ_i) to control for time-invariant, unobservable firm characteristics, and ε_{it} is the random error term. Consistent with the literature, such as Yang et al. [38] and Xiong et al. [39], we employ firm-clustered robust standard errors to account for potential heteroscedasticity and serial correlation within firms.

To account for the potential lagged effect of EPU on firms, all control variables are lagged by one period. Consistent with Hypothesis H1, which posits that increased economic policy uncertainty will lead to reduced ESG investment and, consequently, diminished corporate ESG performance, we expect the coefficient α_1 to be negative (table 1).

EMPIRICAL RESULTS

Descriptive statistics

Table 2 presents the descriptive statistics for our main variables. The Economic Policy Uncertainty

Table 1

VARIABLE DEFINITIONS		
Variable name	**Variable symbol**	**Variable definition**
Corporate ESG performance	ESG	ESG score level for A-share listed textile companies from the SNSI ESG evaluation system (2009–2024). The original score is divided by 100 for normalisation.
Economic policy uncertainty	EPU	Annual index of China's economic policy uncertainty, calculated as the arithmetic average of monthly data from Baker et al. [35], and then divided by 100 for normalisation.
Firm size	Size	Natural logarithm of total assets.
Return on assets	ROA	Ratio of net profit to total assets.
Growth	Growth	Year-on-year growth rate of enterprise operating income.
Leverage ratio	LEV	Ratio of total liabilities to total assets.
Cash flow from operating activities	Cfo	Ratio of net cash flow from operating activities to total assets.
Fixed asset ratio	Tang	Ratio of fixed assets to total assets.
Tobin's Q	TobinQ	Ratio of the company's market value to the company's replacement cost.
Largest shareholder's ownership percentage	Top1	Shareholding ratio of the company's largest shareholder.
Industry competition	HHI	Herfindahl-Hirschman Index, calculated as the sum of the squares of the market shares (based on operating income) of all firms in the industry.
Economic cycle	GDPGrowth	Year-on-year growth of the current domestic GDP.
M2 growth rate	M2Growth	Growth rate of broad money supply.
Social fixed asset investment scale	FD	Ratio of economy-wide total fixed asset investment to GDP in the current period.

Table 2

DESCRIPTIVE STATISTICS FOR CORE VARIABLES						
Variable	**N**	**Mean**	**SD**	**P25**	**Median**	**P75**
ESG	2724	0.729	0.0510	0.700	0.732	0.763
EPU	2724	3.906	2.534	1.547	3.012	5.749
Size	2724	22.01	1.268	21.09	21.83	22.70
ROA	2724	0.0110	0.0170	0.00300	0.0100	0.0190
growth	2724	0.140	0.591	–0.137	0.0500	0.265
LEV	2724	0.403	0.202	0.238	0.403	0.547
Cfo	2724	0.0120	0.0380	–0.00800	0.0110	0.0310
Tang	2724	0.179	0.148	0.0640	0.147	0.253
TobinQ	2724	2.122	1.298	1.327	1.712	2.409
Top1	2724	0.00300	0.00100	0.00200	0.00300	0.00400
HHI	2724	0.0510	0.0750	0.0120	0.0160	0.0610
GDPGrowth	2724	0.0330	0.111	0.0370	0.0880	0.107
M2Growth	2724	0.189	1.436	–0.394	-0.0970	0.435
FD	2724	0.197	0.0850	0.136	0.177	0.229

(EPU) index has a mean of 3.906 and a standard deviation of 2.534, with its 25th and 75th percentiles at 1.547 and 5.749, respectively. This indicates a relatively significant fluctuation in China's economic policy uncertainty during the sample period. The mean of the Corporate ESG Performance (ESG) score is 0.729, with a standard deviation of 0.0510. Its 25th percentile is 0.700, and the 75th percentile is 0.763, suggesting that, on average, the ESG performance of A-share textile listed companies in China is relatively high.

Benchmark regression

We begin by testing Hypothesis H1. Table 3 presents the regression results. Columns (1), (2), and (3) in table 3 all incorporate both quarter-fixed effects and firm-fixed effects. Specifically, Column (1) includes only the independent variable, economic policy uncertainty. Column (2) adds firm-level control variables, while Column (3) incorporates both firm-level and macro-level control variables alongside the independent variable.

The regression results consistently show that the coefficient for EPU is significantly negative at the 1% level, indicating a robust negative correlation between economic policy uncertainty and corporate ESG performance. This means that as economic policy uncertainty increases, a firm's ESG performance tends to decrease, which validates our Hypothesis H1. From an economic perspective, taking Column (3) as an example, a one-unit increase in economic policy uncertainty is associated with a 0.002-unit decrease in a listed company's ESG performance.

Regarding the control variables in our sample, the coefficient for Size is significantly positive, suggesting that larger companies tend to exhibit higher levels of ESG performance. ROA has a significant positive coefficient, implying that firms with better financial performance are more likely to actively invest in environmental, social, and governance initiatives. The coefficient for LEV is significantly negative, indicating that firms with higher financial risk tend to have lower ESG performance. Top1 (largest shareholder's ownership percentage) shows a significant positive coefficient, suggesting that a higher ownership stake by the largest shareholder is associated with greater engagement in ESG aspects. GDPGrowth is significantly positively correlated with ESG, implying that during periods of stronger economic cycles, firms tend to show higher ESG performance and are more inclined to invest in environmental, social, and governance areas. Growth has a significant negative coefficient, which is interesting and might warrant further discussion in the discussion section. TobinQ also shows a significant negative coefficient. It's important to note that control variables that do not show a statistically significant relationship with the dependent variable (e.g., Cfo, Tang, HHI, FD, M2Growth in certain models) do not necessarily imply an absence of a relationship with corporate ESG performance. Our interpretations of these control variables are confined to our specific research sample and design. Furthermore, some control variables might be subject to endogeneity, meaning their values could be influenced by other variables in the model.

Table 3

BENCHMARK REGRESSION

Variable	(1) ESG	(2) ESG	(3) ESG
EPU	–0.001***	–0.001***	–0.002***
	(0.000)	(0.000)	(0.000)
Size		0.009***	0.009***
		(0.002)	(0.002)
ROA		0.229***	0.224***
		(0.031)	(0.030)
growth		–0.001***	–0.001***
		(0.000)	(0.000)
LEV		–0.049***	–0.049***
		(0.008)	(0.008)
Cfo		–0.010	–0.009
		(0.007)	(0.007)
Tang		–0.006	–0.005
		(0.011)	(0.011)
TobinQ		–0.003***	–0.003***
		(0.001)	(0.001)
Top1		3.034**	3.044**
		(1.439)	(1.443)
HHI			–0.004
			(0.019)
GDPGrowth			0.027***
			(0.005)
M2Growth			0.001***
			(0.000)
FD			0.001
			(0.006)
_cons	0.733***	0.555***	0.544***
	(0.001)	(0.043)	(0.045)
Quarter-Fixed Effects	Yes	Yes	Yes
Firm-Fixed Effects	Yes	Yes	Yes
N	2724	2724	2724
r2_a	0.541	0.560	0.561

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

Robustness tests

Alternative measures of the independent variable

In our primary regression analysis, we used the arithmetic mean of the China Economic Policy Uncertainty (EPU) index, as reported by the South China Morning Post, as our independent variable. To ensure the robustness of our findings, we additionally tested using the weighted average and the quarter-end month value of the China EPU index from the same source. The regression results are presented in table 4, where Column (1) uses the EPU weighted average as the independent variable, Column (2) employs the EPU quarter-end month value, and Column (3) utilises an EPU dummy variable (EPU_DUM). For the EPU dummy variable, we applied HP filtering to the quarterly mean of the China EPU index. If the resulting cyclical component was greater than 0, indicating a period of rising economic policy uncertainty, the variable EPU_DUM was assigned a value of 1. The robustness test regression results consistently indicate that the independent variable coefficients are significantly negative at the 1% level across all models. This means that economic policy uncertainty is significantly negatively correlated with corporate ESG performance; specifically, higher economic policy uncertainty leads to lower corporate ESG performance. This again validates Hypothesis H1 of our study.

Table 4

ROBUSTNESS TEST USING ALTERNATIVE BAKER ET AL. EPU MEASURES

Variable	(1)	(2)	(3)
	ESG	ESG	ESG
EPU (Weighted Average)	–0.002***		
	(0.000)		
EPU (Quarter-End Value)		–0.001***	
		(0.000)	
EPU_DUM			–0.005***
			(0.001)
Controls	YES	YES	YES
_cons	0.544***	0.547***	0.607***
	(0.045)	(0.044)	(0.042)
Quarter-Fixed Effects	Yes	Yes	Yes
Firm-Fixed Effects	Yes	Yes	Yes
N	2724	2724	2724
r2_a	0.561	0.562	0.561

Although most existing research on China's economic policy uncertainty uses the index constructed by Baker et al. [35], it may have certain limitations. The China Economic Policy Uncertainty Index relies solely on the South China Morning Post from Hong Kong. As an English-language newspaper, its reporting might not fully align with that of Chinese-language newspapers, potentially leading to measurement bias. Furthermore, relying on a single newspaper as a data source can make the index susceptible to reporting biases and may hinder the development of more detailed measurement indicators. In contrast, the economic policy uncertainty index compiled by Davis et al. [40] uses People's Daily and Guangming Daily, two mainstream mainland Chinese newspapers, as its data sources. This index constructs EPU by selecting keywords from economic, policy, and uncertainty themes and statistically counting their frequency, thus offering a more objective, comprehensive, and accurate reflection of changes in China's economic policy uncertainty. Therefore, to further test the robustness of our results, we additionally used the Davis et al. [40] index to measure China's economic policy uncertainty. The results are shown in table 5, where Column (1) uses the EPU2 arithmetic average as the independent variable, Column (2) uses the EPU2 weighted average, and Column (3) employs the EPU2 quarter-end month value. The regression results indicate that the coefficient for EPU2 remains significantly negative at the 5% level, confirming that our research conclusions hold.

Table 5

ROBUSTNESS TEST USING ALTERNATIVE DAVIS ET AL. EPU MEASURES

Variable	(1)	(2)	(3)
	ESG	ESG	ESG
EPU2 (Arithmetic Average)	–0.001**		
	(0.001)		
EPU2 (Weighted Average)		–0.002***	
		(0.001)	
EPU2 (Quarter-End Value)			–0.002***
			(0.000)
Controls	YES	YES	YES
_cons	0.586***	0.583***	0.581***
	(0.044)	(0.044)	(0.043)
Quarter-Fixed Effects	Yes	Yes	Yes
Firm-Fixed Effects	Yes	Yes	Yes
N	2724	2724	2724
r2_a	0.559	0.559	0.560

Alternative measures of the dependent variable

Our primary measure of corporate ESG performance is derived from the rating results of the Huazheng ESG evaluation system. We calculated the ESG scores for A-share listed companies in the textile industry from 2009 to 2024. These scores were initially continuous. For robustness, we then converted them into a nine-point ordinal scale, assigning higher scores to better ESG performance. Table 6 presents the regression results using these alternative dependent variable measures: Column (1) uses the original continuous Huazheng ESG evaluation score as the dependent variable, while Column (2) uses the nine-point ordinal ESG score and employs an ordered logit model to account for its ordinal nature. The results consistently show that the EPU coefficient is significantly negative at the 1% level in both models. This reinforces our primary conclusion that economic policy uncertainty has a robust negative impact on corporate ESG performance, meaning higher uncertainty is associated with lower ESG performance, further validating our core findings.

Table 6

ROBUSTNESS TESTS USING ALTERNATIVE ESG PERFORMANCE MEASURES		
Variable	**(1)**	**(2)**
	ESG	**ESG**
EPU	–0.029***	–0.075***
	(0.007)	(0.020)
Controls	YES	YES
_cons	0.228	
	(0.912)	
Quarter-Fixed Effects	Yes	Yes
Firm-Fixed Effects	Yes	Yes
N	2724	2724
r2_a	0.525	

Instrumental variables

Although economic policy uncertainty is relatively exogenous for individual micro-enterprises, the performance of these enterprises can partially inform macroeconomic policy adjustments. Given that listed companies can, to some extent, reflect the current state of China's economic development, there might be a potential for reverse causality. Specifically, in the context of this study, a reverse causal relationship might exist between economic policy uncertainty and corporate ESG performance. To address this potential endogeneity issue, we employed the US Economic Policy Uncertainty index and the Global Economic Policy Uncertainty index as instrumental variables [41], conducting a two-stage least squares (2SLS) estimation. Both US and global economic policy uncertainties are closely related to China's economic policy uncertainty; for example, China's interest rates and exchange rates are quickly influenced by changes in US or global monetary policy. The regression results are presented in Columns (1) and (2) of table 7. In both columns, the coefficient of EPU remains significantly negative at the 1% level, indicating that our research conclusion is robust.

Dynamic panel

Considering the continuous nature of firms' investment and financing decisions, prior period values of the dependent variable may influence current period values. To account for this effect, we included the one-period lagged dependent variable in our model and conducted a dynamic panel GMM estimation. As shown in Column (3) of table 7, the lagged corporate ESG performance has a significant positive impact on current corporate ESG performance. However, this does not alter the fundamental conclusion regarding EPU's impact on corporate ESG performance.

Mechanism tests

Our prior analysis revealed that when economic policy uncertainty increases, firms tend to exhibit lower ESG performance. To further investigate the mechanisms through which economic policy uncertainty affects corporate ESG performance, we conducted a mediation analysis using bank loans and excess cash holdings as mediating variables.

Table 7

INSTRUMENTAL VARIABLE AND DYNAMIC PANEL REGRESSION TESTS			
Variable	**(1)**	**(2)**	**(3)**
	ESG	**ESG**	**ESG**
EPU	–0.001**	–0.001***	–0.001***
	(0.000)	(0.000)	(0.000)
ESG			0.945***
			(0.056)
Size	0.008***	0.009***	–0.019
	(0.002)	(0.002)	(0.013)
ROA	0.231***	0.228***	–1.128**
	(0.031)	(0.031)	(0.491)
growth	–0.001***	–0.001***	0.002
	(0.000)	(0.000)	(0.003)
LEV	–0.049***	–0.049***	0.027
	(0.008)	(0.008)	(0.031)
Cfo	–0.011	–0.010	–0.182
	(0.007)	(0.007)	(0.178)
Tang	–0.006	–0.006	–0.065
	(0.011)	(0.011)	(0.045)
TobinQ	–0.002***	–0.003***	0.001
	(0.001)	(0.001)	(0.003)
Top1	3.261**	3.179**	–4.281
	(1.449)	(1.445)	(10.578)
HHI	–0.002	–0.003	–0.080
	(0.019)	(0.019)	(0.072)
GDPGrowth	0.025***	0.026***	0.032***
	(0.005)	(0.005)	(0.010)
M2Growth	0.001***	0.001***	0.000
	(0.000)	(0.000)	(0.000)
FD	–0.003	–0.001	0.001
	(0.006)	(0.006)	(0.020)
Quarter-Fixed Effects	Yes	Yes	Yes
Firm-Fixed Effects	Yes	Yes	Yes
N	2724	2724	2615
r2_a	0.049	0.049	

Consistent with existing literature, we employed a sequential approach for our mediation analysis. The specific test models are as follows:

$$ESG_{it} = \alpha_0 + \alpha_1 EPU_t + \alpha \Sigma Controls_{it} + \theta_i + \varepsilon_{it} \quad (2)$$

$$\text{Mediator} = \beta_0 + \beta_1 EPU_t + \beta \Sigma Controls_{it} + \theta_i + \varepsilon_{it} \quad (3)$$

$$ESG_{it} = \gamma_0 + \gamma_1 EPU_t + \gamma \text{Mediator} + \gamma' \Sigma Controls_{it} + \theta_i + \varepsilon_{it} \quad (4)$$

First, we estimate the total effect of economic policy uncertainty (EPU) on corporate ESG performance. Second, we examine the effect of economic policy uncertainty on the Mediator. Finally, we include the Mediator in the regression to assess whether the direct effect of economic policy uncertainty on corporate ESG performance is weakened. The mediating variables are bank loans (Loan) and excess cash holdings (XCash).

Bank loans

Bank credit is the most common and primary financing channel for Chinese enterprises [18]. Therefore, intensified economic policy uncertainty directly affects the banking system's credit risk. Frequent changes in domestic economic policies negatively impact firms' cash flows, while an unfavourable economic environment makes it more challenging for firms to accurately estimate the net present value of new investment projects, thereby exacerbating financing difficulties. Consequently, banks' credit assessments of firms become more challenging [42]. Furthermore, studies indicate that banks' bankruptcy risk directly increases when facing high uncertainty. To mitigate these elevated risks, banks often impose higher borrowing interest rates and adopt stricter credit policies, a phenomenon commonly known as "credit rationing" or "loan aversion" [43]. This leads to increased borrowing costs for firms, tightened financing constraints, and reduced access to external funding. Faced with difficulties in securing loans and rising costs, firms may then prioritise short-term economic interests, subsequently reducing their willingness to invest in ESG initiatives. Bank loans (Loan) are defined as the sum of the annual change in short-term loans, long-term loans, and non-current liabilities due within one year, scaled by total assets.

Columns (1) and (2) of table 8 present the regression results with bank loans (Loan) as the mediating variable. In Column (1), EPU is significantly negatively associated with Loan at the 1% level, indicating that an increase in economic policy uncertainty constrains corporate bank loans. Furthermore, after incorporating the Loan variable into Column (2), the regression coefficient of EPU remains significantly negative, and the coefficient of Loan is positive and statistically significant, confirming a significant mediating effect.

Excess cash holdings

Second, regarding the impact on internal cash holdings, when economic policy uncertainty intensifies, external information becomes more complex and convoluted. This makes it difficult for management to accurately forecast future operating cash flows and market demand, leading firms to adopt more cautious strategies and reduce their investment intentions, which can, in turn, affect future profitability.

Concurrently, the precautionary savings theory suggests that holding cash helps firms cope with operational risks [34]. Thus, when risks increase, firms, driven by precautionary motives, may forgo current investment opportunities and opt to increase their cash holdings to cushion against future cash flow uncertainty. By setting aside more cash as a precautionary reserve for adverse impacts, the utilisation of firms' existing cash becomes restricted, and their idle available funds diminish. Given that ESG investments typically require substantial long-term capital, firms facing economic policy uncertainty often choose to allocate more resources to maintaining cash holdings, thereby reducing their discretionary idle funds and consequently impacting their investment in ESG [44].

For excess cash holdings (XCash), given that firms may hold a certain amount of cash for operational and growth needs, we use excess cash as a proxy for firms' precautionary cash motives, following the method proposed by Frésard and Salva [45]. We made appropriate adjustments to their original model due to information disclosure characteristics under Chinese accounting standards. Specifically, R&D expense data is often unavailable in China, with many firms not disclosing it in their annual reports, leading to significant missing data. Therefore, consistent with most prior literature, we did not include R&D as a control variable in our model. We constructed the following model (5) to estimate firms' predicted cash holdings; the residual term from this regression represents the firm's excess cash holding, denoted as Ex_cash.

$$Ln\ (Cash\ it) = \alpha + \beta_1 Size_{it} + \beta_2 CF_{it} + \beta_3 NETWC_{it} + \\ + \beta_4 Growth_{it} + \beta_5 CAPEX_{it} + \beta_6 Lev_{it} + \beta_7 Dividend_{it} + \\ + \Sigma Year + \varepsilon_{it} \quad (5)$$

Here, the dependent variable Cash represents corporate cash holdings, specifically defined as the ratio of cash and cash equivalents to total assets (denoted as Cash1). In a robustness check, we also used the ratio of cash and cash equivalents to net assets (denoted as Cash2). The control variables include Firm Size (Size); Cash Flow (CF); Net Working Capital (NETWC); Growth, defined as the company's sales revenue growth rate; Capital Expenditure (CAPEX); Financial Leverage (Lev); and a Dividend dummy variable, which takes a value of 1 if dividends were paid in the current year and 0 otherwise. We also controlled for annual fixed effects.

The regression results using excess cash holdings (XCash) as the mediating variable are shown in Columns (3) and (4) of table 9. In Column (3), EPU is significantly negatively associated with XCash at the 1% level, demonstrating that rising economic policy uncertainty leads to a reduction in firms' excess cash holdings. Moreover, after including the XCash variable in Column (4), the regression coefficient of EPU remains significantly negative at the 1% level. Its coefficient (–0.002) is smaller (more negative) than the EPU regression coefficient (–0.001) in Column (1) of table 8, and the coefficient of XCash is significantly positive at the 1% level.

In summary, both bank loans and excess cash holdings serve as significant mediating channels through which economic policy uncertainty negatively impacts corporate ESG performance. Specifically, increased economic policy uncertainty simultaneously constrains corporate bank loans and reduces excess cash holdings, which in turn leads to a decline in corporate ESG performance.

Table 8

MECHANISM TEST				
Variable	**(1)**	**(2)**	**(3)**	**(4)**
	Loan	**ESG**	**XCash**	**ESG**
EPU	–0.001***	–0.001***	–0.001***	–0.002***
	(0.000)	(0.000)	(0.000)	
Loan		0.037***		
		(0.008)		
XCash				0.009***
				(0.003)
Controls	YES	YES	YES	YES
_cons	–0.020	0.545***	0.083	0.540***
	(0.045)	(0.056)	(0.045)	
Quarter-Fixed Effects	Yes	Yes	Yes	Yes
Firm-Fixed Effects	Yes	Yes	Yes	Yes
N	2724	2724	2689	2689
r2_a	0.094	0.562	0.149	0.562

Heterogeneity analysis

Nature of ownership

Different ownership structures cause firms to bear varying responsibilities and risks, thus leading economic policy uncertainty to have distinct impacts on different types of firms. As key representatives of national interests, state-owned enterprises (SOEs) often have investment and financing behaviours closely tied to national policies or local economic development needs. Consequently, when economic policy uncertainty rises, SOEs cannot adjust as quickly as non-state-owned enterprises (non-SOEs) [46], leading to a more pronounced impact on their ESG performance. In contrast, non-SOEs prioritize marketization and autonomous decision-making, offering greater flexibility. This makes them more adept at responding to changes in economic policy, resulting in a lesser impact on their ESG performance. Furthermore, a firm's ownership type significantly influences its access to external financing. SOEs tend to have a more singular source of loans, primarily relying on bank credit, whereas non-SOEs can access funds through more convenient channels like bond issuance and stock offerings [47]. This also grants non-SOEs greater autonomy in managing ESG-related risks.

To examine the moderating role of ownership type on the relationship between economic policy uncertainty and corporate social responsibility performance, we divided the full sample into an SOE group and a non-SOE group based on their ownership nature. SOEs were coded as 1, and non-SOEs as 0.

The regression results are presented in table 9. Specifically, Column (1) displays the regression results for the ownership type groups. The coefficient of EPU is significantly positive at the 1% level, indicating that SOEs, relative to non-SOEs, are more stable in an environment of economic policy uncertainty. Their reduction in ESG investment is significantly smaller than that of non-SOEs.

Information transparency

As the information environment gradually improves, firms are increasingly attracting greater scrutiny and oversight. This intensifies their motivation to invest in ESG aspects to achieve better market performance. Research indicates that high information transparency can enhance market oversight of firms, leading to increased market attention and assessment. Conversely, firms with lower information transparency are more challenging to monitor effectively, which raises the incidence of misconduct, and managers can more easily conceal their illicit activities [48]. Furthermore, due to more pronounced information asymmetry for firms with lower transparency [49], the market's reaction to such behaviours tends to be more muted, consequently leading to less severe reputational losses for these firms. Therefore, when economic uncertainty intensifies, firms with lower information transparency are often more inclined to reduce ESG investments in pursuit of short-term gains.

To examine the moderating effect of information transparency on the relationship between economic policy uncertainty and corporate ESG performance, we extended Model (1) by introducing the accrued earnings management variable and constructing the following Model (6):

$$ESG_{it} = \alpha_0 + \alpha_1 EPU_t + \alpha_2 DA + \alpha_3 DA \times EPU_t + \alpha \sum Controls_{it} + \theta_i + \varepsilon_{it} \qquad (6)$$

This study employs accrued earnings management (DA) as a proxy for information transparency, calculated using the modified Jones [50] model. The calculation process is as follows:

$$\frac{TA_{i,t}}{A_{i,t-1}} = \beta_0 \frac{1}{A_{i,t-1}} + \beta_1 \frac{\Delta REV_{i,t}}{A_{i,t-1}} + \beta_2 \frac{PPE_{i,t}}{A_{i,t-1}} + \varepsilon_{i,t} \qquad \text{(I)}$$

$$NDA_{i,t} = \beta_0 \frac{1}{A_{i,t-1}} + \beta_1 \frac{\Delta REV_{i,t} - \Delta REC_{i,t}}{A_{i,t-1}} + \beta_2 \frac{PPE_{i,t}}{A_{i,t-1}} \qquad \text{(II)}$$

$$DA_{i,t} = \frac{TA_{i,t}}{A_{i,t-1}} - NDA_{i,t} \qquad \text{(III)}$$

where *TA* represents Total Accruals, calculated as Operating Profit minus Net Cash Flow from Operating Activities; *NDA* denotes Non-Discretionary Accruals; *DA* signifies Discretionary Accruals. A larger absolute value of *DA* indicates greater earnings management discretion and, consequently, lower accounting information quality; ΔREV_t is the change in Operating Revenue in period *t*; ΔREC_t is the change in Accounts Receivable in period *t*; PPE_t represents Net Fixed Assets in period *t*; A_{t-1} refers to total assets at the end of year *t*−1, used to scale variables and control for firm size effects.

The calculation involves a three-step procedure: First, a cross-sectional regression (often referred to as sub-model I in the *DA* calculation) is performed annually and by industry to obtain the estimated coefficients. Second, these estimated coefficients are then used to compute Non-Discretionary Accruals (*NDA*) (sub-model II). Finally, Discretionary Accruals (*DA*) are derived as the residual by subtracting *NDA* from Total Accruals (sub-model III).

Column (2) of table 9 presents the regression results for the moderating effect of information transparency on the relationship between economic policy uncertainty and corporate ESG performance. The results indicate that the interaction term between economic policy uncertainty and accrued earnings management (*EPU* × *DA*) is significantly negative. This suggests that the negative impact of economic policy uncertainty on corporate ESG performance is more pronounced in firms with lower information transparency (i.e., higher discretionary accruals).

Conversely, when firms exhibit higher information transparency (lower discretionary accruals), the detrimental effect of rising economic policy uncertainty on their ESG performance is mitigated, as they are likely more motivated to actively invest in environmental, social, and governance initiatives to manage potential risks.

Financial distress

ESG performance often demonstrates a positive relationship with a firm's financial health [51]. As uncertainty rises, firms tend to postpone investment, and managers build up cash reserves to mitigate unknown risks [52]. However, reduced investment inevitably hurts financial performance, making it harder for financially distressed firms to invest in ESG initiatives. At the same time, this investment inhibition also decreases a firm's willingness to seek external financing. Furthermore, rising economic policy uncertainty forces banks to adopt tighter credit policies [53] and complicates their credit assessments. This leaves financially distressed firms facing higher debt financing costs and stricter financing constraints [54]. When financially distressed firms are confronted with the combined pressures of economic policy uncertainty, high operating risks, and significant financing constraints, they find it more difficult to allocate resources toward corporate social responsibility, which directly undermines their ESG performance.

To examine the moderating effect of financial distress on the relationship between economic policy uncertainty and corporate ESG performance, we extended Model (1) by introducing a financial distress variable and constructing the following Model (7):

$$ESG_{it} = \alpha_0 + \alpha_1 EPU_t + \alpha_2 Zscore + \alpha_3 Zscore \times EPU_t + \alpha \sum Controls_{it} + \theta_i + \varepsilon_{it} \quad (7)$$

Here, *Zscore* is our proxy for corporate financial distress, measured using Altman's (1968) Z-score to gauge the likelihood of a firm entering financial distress. For ease of coefficient interpretation, we reverse-coded the Z-score by taking its inverse. With this adjustment, a higher Z-score indicates a higher probability of financial distress. This approach maintains the original model's predictive validity while making the direction of the regression coefficient more intuitive.

Column (3) of table 10 presents the regression results for the moderating effect of financial distress. We find that the interaction term between economic policy uncertainty and our Z-score has a significant negative coefficient. This indicates that the negative impact of EPU on ESG performance is more pronounced for financially distressed firms. In other words, when a firm faces a higher degree of financial distress, it has a reduced incentive to prioritise ESG investments.

Table 9

HETEROGENEITY ANALYSIS

Variable	(1) ESG	(2) ESG	(3) ESG
EPU×SOE	0.003***		
	(0.001)		
EPU×DA		–0.011**	
		(0.006)	
DA		–0.020	
		(0.013)	
EPU×Zscore			–0.034***
			(0.012)
Zscore			–0.097**
			(0.048)
EPU	–0.002***	–0.002***	–0.001***
	(0.000)	(0.000)	(0.000)
SOE	0.009		
	(0.005)		
Controls	YES	YES	YES
_cons	0.552***	0.551***	0.534***
	(0.045)	(0.047)	(0.045)
Quarter-Fixed Effects	Yes	Yes	Yes
Firm-Fixed Effects	Yes	Yes	Yes
N	2724	2716	2703
r2_a	0.565	0.563	0.562

CONCLUSION AND DISCUSSION

This study provides systematic empirical evidence on how economic policy uncertainty (EPU) impacts the ESG performance of listed textile companies in China, using a dataset spanning from 2009 to 2024. Our baseline regression results show that an increase in EPU significantly undermines a firm's ESG performance. This finding remains robust across a variety of checks, including using alternative variable measures, instrumental variable methods, and dynamic panel models. Our mechanism analysis further reveals two key transmission channels: financing constraints and risk aversion. First, EPU exacerbates a credit crunch by raising loan thresholds and financing costs, which limit a firm's capacity to undertake ESG investments. Second, EPU prompts firms to increase precautionary cash holdings, diverting discretionary funds that could have been used for long-term ESG projects. Our heterogeneity analysis shows that this negative effect is more pronounced for financially distressed firms, those with low information transparency, and state-owned enterprises. Furthermore, the decline in ESG performance due to EPU can lead to a decrease in a firm's financing capabilities and total factor productivity, creating a feedback loop that hinders the green transition of the textile industry.

This research makes several important contributions to the existing literature. First, we expand the scope of ESG antecedent studies by shifting the focus from internal firm characteristics to the broader macro policy environment. We establish a theoretical framework that explains how EPU influences a firm's ESG decisions and provide empirical evidence for the dual channels of financing constraints and risk management. Second, by focusing on the textile industry, a classic example of a "high-pollution, high-energy-consumption, high-water-consumption" sector, our study addresses the practical challenges of traditional manufacturing under China's "dual carbon" goal, enriching the literature that has previously focused on high-tech and service industries. Third, our methodological contribution lies in simultaneously identifying and verifying these dual mechanisms, which deepens our understanding of how macroeconomic uncertainty shapes corporate sustainability. Our findings expand the analytical framework of the policy-firm-environment interaction and align with recent calls to incorporate macro-level factors into micro-sustainability analysis.

Our findings offer several important policy implications for various stakeholders. For government policymakers, maintaining a stable and predictable policy environment is crucial for promoting corporate ESG investment, especially in capital-intensive industries with long payback periods, like the textile sector. ESG-related regulations should prioritise policy continuity and avoid frequent or sudden changes that could undermine a firm's long-term sustainability commitments. Financial institutions, in turn, should enhance green credit mechanisms and reduce financing frictions during periods of high EPU to ensure a steady flow of ESG-oriented capital. For corporate managers, it is essential to improve information transparency and build robust risk management systems to buffer the adverse effects of EPU on sustainable investments. Additionally, differentiated support measures are needed to address the heterogeneity of policy effects. For instance, targeted green financing policies could be implemented for financially constrained firms, stricter ESG disclosure requirements could be established for firms with low information transparency, and a balanced performance evaluation system that considers both market demands and policy guidance could be created for state-owned enterprises.

Despite our comprehensive empirical analysis, a few limitations remain. First, while we control for a variety of firm- and macro-level variables, our estimates may still be subject to omitted variable bias from factors such as industry-specific environmental regulations or global demand shocks. Second, our study primarily relies on the SNSI/Huazheng ESG rating system, and its scoring criteria may differ from other domestic or international ESG evaluation systems. Third, because our sample is limited to Chinese textile firms, the direct generalizability of our findings to other industries or countries is limited. Finally, although we performed robustness checks using alternative EPU indices, potential biases stemming from media sources may still exist.

Based on these limitations, we propose several avenues for future research. First, scholars could conduct cross-country comparative studies to test whether the mechanisms identified in our study are also valid in different institutional environments and financial systems. Second, future research could introduce diverse ESG data sources (such as Refinitiv, MSCI, or firm-level survey data) to improve measurement validity and enable multi-dimensional cross-validation. Third, the research scope could be extended to other high-impact industries (like steel or chemical manufacturing) to compare the EPU-ESG relationship across different sectors. Finally, future studies could combine scenario analysis with policy simulation to predict how changes in the policy environment might reshape firms' ESG strategies in the context of a climate transition.

ACKNOWLEDGEMENT

This work was supported by the 2024 Heilongjiang Provincial Department of Education "Excellent Young Teachers Basic Research Support Program" (Project No. YQJH2024174).

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The impact of ESG performance on green technological innovation in textile enterprises under the dual-carbon strategy

DOI: 10.35530/IT.077.01.202575

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ABSTRACT – REZUMAT

The impact of ESG performance on green technological innovation in textile enterprises under the dual-carbon strategy

Under the evolving paradigm shaped by China's "dual-carbon" goals, green technological innovation has emerged as a central driver for achieving sustainable development, particularly in the textile industry, a sector characterised by high resource consumption and significant environmental impact. Environmental, Social, and Governance (ESG) performance, widely recognised as a critical metric for assessing corporate sustainability, has received increasing attention for its influence on green innovation. This study investigated the relationship between ESG performance and green technological innovation using panel data from textile companies listed on the A-share markets in Shanghai and Shenzhen between 2015 and 2023. As a labour-intensive industry with intensive energy use and pollutant emissions, the textile sector faces unique pressures to transition toward low-carbon operations, making green technological innovation (e.g., clean production, circular economy technologies) pivotal for its sustainable development. Employing a fixed-effects model, the study revealed that strong ESG performance significantly promoted green innovation within textile firms, with the effect displaying notable heterogeneity across ownership types. Further analysis indicated that ESG performance facilitated green innovation by attracting heightened attention from analysts, thereby alleviating information asymmetry and enhancing external oversight. These findings contribute to the literature on ESG and corporate green innovation, offering theoretical and practical guidance for textile firms seeking to enhance green technological capabilities through improved ESG strategies in the context of China's dual-carbon policy agenda.

Keywords: *dual-carbon targets, ESG performance, green technological innovation, textile enterprises*

Impactul performanței ESG asupra inovării tehnologice ecologice în întreprinderile textile în cadrul strategiei duale privind carbonul

În contextul paradigmei în continuă evoluție, modelată de obiectivele „duale" ale Chinei în materie de emisii de carbon, inovarea tehnologică ecologică a devenit un motor central pentru realizarea dezvoltării durabile, în special în industria textilă, un sector caracterizat prin consumul ridicat de resurse și impactul semnificativ asupra mediului. Performanța în materie de mediu, socială și de guvernanță (ESG), recunoscută pe scară largă ca un indicator esențial pentru evaluarea durabilității corporative, a beneficiat de o atenție sporită datorită influenței sale asupra inovării ecologice. Acest studiu a investigat relația dintre performanța ESG și inovarea tehnologică ecologică utilizând date panel de la companii textile listate pe piețele de acțiuni A din Shanghai și Shenzhen între 2015 și 2023. Fiind o industrie cu utilizare intensivă a forței de muncă, cu un consum intensiv de energie și emisii poluante, sectorul textil se confruntă cu presiuni unice pentru a trece la operațiuni cu emisii reduse de carbon, ceea ce face ca inovarea tehnologică ecologică (de exemplu, producția curată, tehnologiile economiei circulare) să fie esențială pentru dezvoltarea sa durabilă. Utilizând un model cu efecte fixe, studiul a relevat că performanța ESG ridicată a promovat în mod semnificativ inovarea ecologică în cadrul firmelor textile, efectul prezentând o eterogenitate notabilă între tipurile de proprietate. Analize suplimentare au indicat că performanța ESG a facilitat inovarea ecologică prin atragerea unei atenții sporite din partea analiștilor, atenuând astfel asimetria informațională și îmbunătățind supravegherea externă. Aceste concluzii contribuie la literatura de specialitate privind ESG și inovarea ecologică corporativă, oferind îndrumări teoretice și practice pentru firmele textile care doresc să își îmbunătățească capacitățile tehnologice ecologice prin strategii ESG îmbunătățite în contextul agendei politice duale a Chinei privind emisiile de carbon.

Cuvinte-cheie: *obiective duble privind emisiile de carbon, performanța ESG, inovarea tehnologică ecologică, întreprinderi textile*

INTRODUCTION

Research background

Amidst the increasingly severe challenge of global climate change, contemporary society has faced unprecedented environmental crises [1]. Rising global temperatures, frequent extreme weather events, and ongoing sea-level rise have collectively constrained the prospects for sustainable socio-economic development [2]. In reply to these worldwide challenges, China clearly pledged to reach the peak of carbon emissions by 2030 and attain carbon neutrality by 2060. These ambitious targets aimed to reduce greenhouse gas emissions significantly, thereby promoting global climate stability and sustainable growth.

Driven by the dual-carbon goals, government reports have called for the manufacturing sector to pursue high-end, intelligent, and green development pathways [3]. As primary actors in economic activity, enterprises have increasingly borne responsibility not only for their own performance but also for their broader environmental impacts [4]. Consequently, corporate ESG performance has garnered extensive societal attention. ESG functions as a holistic indicator of a company's sustainability in three aspects: environmental conservation, social responsibility, and corporate management [5]. Excellent ESG performance enhances a firm's reputation and brand value while attracting investors and consumers, thereby generating greater commercial value and competitive advantage [6].

Nevertheless, within the context of the dual-carbon transition, reliance on traditional business models and conventional technological innovation has become insufficient to meet sustainability demands [7]. Green technological innovation has thus become a strategic imperative for firms to upgrade and transition towards sustainable operations [8].

Encompassing clean production technologies, energy-efficient systems, and circular economy solutions, green innovation aims to reduce both energy consumption and pollutant emissions, achieving environmental and economic gains simultaneously [9]. Despite its potential, green innovation faces significant barriers such as technological limitations, high capital requirements, and policy dependency. These challenges necessitate stronger ESG performance to help enterprises secure essential resources and external support [10].

Therefore, this study intended to investigate the impact of ESG performance on green technological innovation in the textile industry under China's dual-carbon framework. By analysing the distinct effects of different ESG dimensions, the study sought to uncover underlying mechanisms and heterogeneity in innovation outcomes. The findings intend to provide targeted strategic insights for enterprises and contribute to the development of ESG-driven innovation theory within the context of sustainable industrial transformation.

Research goals and significance

This research intends to thoroughly investigate the influence mechanisms of corporate ESG performance on green technological innovation under the backdrop of China's dual-carbon strategy.

Specifically, by constructing a scientific ESG performance evaluation index system, this research sought to measure corporate practices in the fields of environmental, social, and governance aspects. By employing empirical research approaches, the research investigated the intrinsic connections between ESG performance and both input and output of green technological innovation, identifying key factors and moderating variables that influence this relationship. The discoveries provide theoretical bases and practical directions for enterprises to formulate ESG-based green technological innovation strategies.

From a theoretical viewpoint, this research enriches and extends academic research in the fields of corporate social responsibility (CSR), sustainable development, and management of innovation. In the field of CSR, conventional research has mainly concentrated on the influence of individual CSR aspects on corporate performance. In contrast, this study incorporates multidimensional ESG factors into the analytical framework, providing a comprehensive examination of their effect on green technological innovation, thereby deepening theoretical understanding of the synergetic development of CSR practices and corporate innovation strategies. Within the field of sustainable development, the study reveals how companies, while pursuing economic objectives, can drive green technological innovation through ESG responsibilities, providing a micro-level theoretical support for achieving sustainable development goals and further refining the scope and connotation of sustainable development theory. In innovation management, this research breaks the limitations of previous studies, which predominantly focused on traditional factors such as technology and market conditions. By introducing ESG as a fresh perspective, the research broadens the scope of innovation management theory, facilitating the advancement of a more thorough and organised framework for corporate innovation management.

From a practical perspective, this research provides crucial decision-making insights for enterprises, investors, and government agencies. For companies, it assists managers in identifying the beneficial influence of ESG performance on green technological innovation, encouraging the integration of ESG principles into corporate strategic planning and daily operations. This approach facilitates increased investment in green technological innovation, enhancing the firm's sustainable development capacity and core competitiveness. By improving ESG performance, companies can appeal to consumers who are environmentally aware and socially accountable, thus expanding market share and establishing a favourable brand image. For investors, the study provides new evaluation standards and reference points for investment decisions. Investors can focus on companies with strong ESG performance to select investments with better growth prospects and sustainability, thus reducing investment risks and achieving long-term stable returns. For government agencies, this research provides empirical evidence that can inform the development of policies, helping authorities refine relevant laws and regulations. It also supports the enhancement of ESG practices and green technological innovation, promoting industrial structural upgrades and fostering green, sustainable economic development. For instance, the government may utilise fiscal incentives like tax cuts and subsidies to urge companies to enhance ESG performance and boost investment in green technological innovation. thereby creating a favourable policy and market environment for green innovation.

Research contributions

Theoretical significance

This research specifically focuses on the textile industry, a traditional manufacturing sector characterised by a long industrial chain, high pollution, high energy consumption, and unique ESG challenges (such as printing and dyeing wastewater and labour rights in the supply chain). By analysing the correlation between textile enterprises' ESG practices and green technological innovation (e.g., cleaner production and recycled fibre technologies), it reveals the driving mechanism of ESG performance on green innovation in this industry systematically for the first time. This study innovatively verifies the mediating role of "analyst attention": ESG performance indirectly promotes corporate green technological innovation by attracting analyst coverage (reducing information asymmetry and strengthening external supervision). The discovery of this mechanism enriches the "signal transmission" and "external governance" theories in the realm of ESG and innovation; it offers a fresh viewpoint for comprehending the indirect driving route of ESG on innovation.

Practical significance

Based on the outcomes of heterogeneity analysis, distinct ESG optimisation paths are put forward for state-owned enterprises (possessing policy and resource advantages), non-state-owned enterprises (primarily market-driven), and enterprises of different sizes (large enterprises with stronger resource conversion capabilities). Meanwhile, combined with the technical characteristics of textile sub-sectors (cotton textiles, chemical fibres, garment manufacturing), specific directions for the cooperation between ESG and green innovation are provided (e.g., chemical fibre enterprises should strengthen the layout of patents for recycling technologies). It offers the government a combined proposal of "ESG disclosure standards + industry incentive policies" (such as enhancing the transparency of ESG information in textile enterprises) and provides investors with a three-dimensional evaluation framework of "ESG scores + analyst coverage + green patents", helping to accurately identify enterprises with green transformation potential and promoting the textile industry toward low-carbon and sustainable development.

LITERATURE REVIEW

ESG performance research

Shaikh argued that ESG represents an investment ideology and corporate assessment criterion centred on a company's environmental, social, and governance performance instead of its financial performance [11]. It stresses the organic combination of economic and social benefits and acts as a vital mechanism for attaining high-quality economic growth and sustainable corporate progress. In current literature, academic studies on ESG performance have mainly focused on corporate value, financial performance, financing costs, and risk management. ESG performance can not only reduce information asymmetry inside and outside a company but also boost its long-term value [12, 13]. Zhou et al. discovered that ESG performance significantly enhanced both the book value and market value of enterprises [14]. Clementino and Perkins discovered that firms with superior ESG performance are able to convey more favourable signals to external stakeholders, improving corporate value and reducing financial and compliance risks [15]. Yu et al., analysing data from the A-share manufacturing sector, discovered a notable positive correlation between ESG disclosure and corporate value, with ESG disclosure only promoting corporate value after policy implementation [16]. Aydoğmuş et al. noted that strong ESG performance could significantly improve corporate value [17]. Zhang and You argued that the value-increasing effect of ESG performance was more prominent for non-state-owned enterprises in institutional settings with greater information transmission efficiency [18].

ESG disclosure enhances corporate transparency and reduces information asymmetry, while also shaping a firm's social obligation image and strengthening relationships with stakeholders, thereby increasing its credibility [19]. Therefore, A company's performance is significantly and positively influenced by its ESG performance [20]. Nirino et al. determined that companies boasting higher ESG ratings hold a competitive edge, having a positive effect on financial performance [21]. Crifo et al. put forward that ESG performance, related to corporate social responsibility and sustainable development, has emerged as a crucial driver of corporate performance [22]. It exerts a positive impact on economic performance and long-term competitiveness via brand image improvement, operational optimisation, risk mitigation, and capital attraction.

Positive ESG performance helps companies reduce their debt financing costs [23]. From the perspectives of market risk and financing costs, existing research has confirmed that ESG performance reduces both total and systematic risks [24] and that improved ESG performance can lower financing costs, thereby enhancing corporate value [25]. Furthermore, Studies have investigated the influence of ESG performance on market risks after an initial public offering (IPO). Research shows that ESG performance and disclosure assist companies in building reputational capital with investors post-listing, thus enhancing the firm's ability to withstand risk [26].

Relevant research on green technological innovation

Green innovation centres around and primarily consists of green technological innovation. Green technology denotes technologies, processes, or products that cut down environmental pollution and the consumption of raw materials and energy [27]. Lv et al. contended that the outcomes of green technological innovation can effectively relieve the financial constraints of enterprises [28]. Yuan and Zhang indicated that the enforcement of environmental regulations in China had a notable inhibitory impact on green technological innovation, whereas digital transformation could positively moderate the influence of environmental regulations on green technological innovation by lowering production costs [29]. Hao et al. stated that the digital economy could boost green technological innovation in advanced manufacturing sectors, with resource optimisation and industrial upgrading acting as vital intermediary channels [30]. Digital finance can spur green technological innovation by alleviating financing constraints, driving industrial improvements, and stimulating market demand [31]. Moreover, digital transformation can not only enhance the quantity of a firm's green technological innovation but also substantially improve the quality of these innovations.

Research on corporate ESG performance and its impact on green technological innovation

Long et al. discovered that corporate ESG performance was able to boost green technological innovation activities. Moreover, their research showed that company size and revenue growth rate had notable positive impacts on green technological innovation [32]. Xu et al. pointed out that corporate ESG performance could improve a firm's green technological innovation ability, and this effect was more evident in state-owned enterprises, companies situated in the eastern regions, and high-tech industries. Mechanism analysis proposed that reducing financing restrictions and increasing research and development expenditure were the two main ways through which ESG performance could encourage green technological innovation [33]. Yang et al. contended that corporate ESG performance mainly enhanced green technological innovation via intermediary means such as cutting debt financing costs, lessening information asymmetry, and enhancing the quality of information disclosure [34]. Qian and Liu determined that ESG ratings could significantly stimulate green technological innovation, and the effect was more prominent in state-owned enterprises and high-pollution industries [35]. Mechanism analysis demonstrated that ESG ratings could enhance green technological innovation by easing financing constraints and increasing analyst focus. Fan et al. maintained that ESG performance and green technological innovation were positively related, with better ESG performance resulting in more widespread green technological innovation activities [36]. Tan et al. hypothesised that corporate ESG performance spurred green technological innovation, having a significant positive influence on green technological innovation [37]. Even after taking endogeneity problems into account, the research findings remained reliable. Tan and Zhu argued that ESG performance mainly promoted green technological innovation by intensifying environmental investments, alleviating financing constraints, and improving the internal control quality of firms. ESG performance was found to promote green technological innovation, and digital transformation could positively moderate the impact of ESG performance on green technological innovation [38]. Human capital structure played a mediating part in the relationship between ESG performance and green technological innovation. Sun et al., in their study of the listed company Sun Paper, found that outstanding performance in environmental, social, and governance (ESG) aspects not only promoted green technological innovation and enhanced competitiveness but also contributed to the company's long-term viability [39].

Although scholars have made significant progress in understanding the relationship between ESG and green technological innovation, some gaps remain in the existing literature. First, current research mainly focuses on the direct effects of ESG performance on green technological innovation, yet there is a lack of in-depth analysis of the underlying mechanisms. For example, how ESG performance promotes the development of green technological innovation through influencing factors such as financing constraints and innovation efficiency still requires further exploration. Second, existing studies face certain limitations in sample selection and data acquisition. For instance, some studies have conducted empirical analyses on enterprises in specific industries or regions, limiting the generalisability of the findings. Additionally, challenges in data collection have affected the accuracy and reliability of the results. Future research could further expand the study of the relationship between ESG and green technological innovation.

For instance, it can investigate the mechanisms through which ESG performance affects green technological innovation and examine the disparities in the effect of different dimensions of ESG performance on innovation. Moreover, cross-industry and cross-regional research could be reinforced to improve the generalizability and precision of the results. Additionally, future studies could integrate emerging topics like digital transformation and sustainable development to explore novel trends and routes in the relationship between ESG and green technological innovation.

The three dimensions of ESG have differential impacts on green technological innovation

In the context of the "dual-carbon" strategy, the effects of the three aspects of ESG – Environmental, Social, and Governance on enterprises' green technological innovation are not homogeneous. Instead, they exert influence through differentiated mechanisms and pathways.

Environmental dimension (E): The core driver directly propelling green technological innovation

The environmental dimension focuses on enterprises' impacts on the ecological environment, including pollutant emission control, energy efficiency improvement, and green investment. It is the dimension most directly linked to green technological innovation.

Improvements in environmental performance (such as emission reduction targets and cleaner production requirements) directly stimulate demand for green technologies. For instance, to reduce carbon emissions or meet environmental regulations, enterprises will proactively invest in R&D of cleaner production technologies and circular economy technologies (e.g., wastewater recycling technologies in the textile industry). This highly aligns with the core goals of green technological innovation, which aim to cut down energy usage and pollutant discharges [9].

Enterprises with excellent environmental performance tend to place greater emphasis on green investments, such as establishing environmental R&D funds and introducing environmental protection equipment. These resource inputs are directly transformed into outputs of green technological innovation [38]. Studies have shown that increased environmental investment is a crucial route by which ESG fosters green innovation, especially in high-pollution sectors (such as the textile industry), where enhancements in the environmental aspect have a more substantial influence on green patent outputs [35].

Strong performance in the environmental dimension is more aligned with dual-carbon Policies and environmental rules, enabling enterprises to have a higher chance of getting policy support like government subsidies and tax incentives, which further reduces the costs of green technological innovation [10]. For example, enterprises with high environmental ratings are more likely to be included in green credit support lists, providing financial guarantees for their green technology R&D.

Social dimension (S): Indirectly enabling green innovation through reputation and resource integration

The social dimension focuses on enterprises' responsibilities to stakeholders (employees, communities, consumers, etc.), including the fulfilment of social responsibilities, protection of employees' rights and interests, and fairness in the supply chain. Its impact on green is indirect.

Enterprises with excellent social performance (e.g., ensuring employee welfare and participating in public welfare projects) can enhance their brand reputation and social recognition, attracting consumers and investors with environmental awareness [6]. This "social identity" will drive enterprises to strengthen their "responsible" image through green technological innovation, forming a positive cycle of "social reputation → increased market share → increased investment in green innovation". For example, if a textile enterprise performs well in the social dimension (e.g., ensuring labour rights in the supply chain), it is more likely to gain consumers' recognition for its green products (e.g., eco-friendly fabrics), thereby motivating it to continuously develop green textile technologies.

Good performance in the social dimension helps enterprises build stable stakeholder networks. For instance, positive interactions with communities and non-governmental organisations can provide access to more environmental technology information; investment in employee training (a key indicator of the social dimension) can enhance the green technological innovation capabilities of internal R&D teams [39].

Stability in the social dimension (e.g., high employee satisfaction and smooth supply chain collaboration) can reduce operational risks for enterprises, providing a stable internal environment for long-term green technological innovation. For example, reducing labour disputes or supply chain disruptions can ensure the continuity of green R&D projects.

Governance dimension (G): Ensuring the efficiency and sustainability of green innovation through institutional optimisation

The governance dimension focuses on enterprises' internal management mechanisms, including board structure, quality of information disclosure, and internal controls. Its core role is to reduce agency problems and improve resource allocation efficiency through institutional optimisation, providing institutional guarantees for green technological innovation.

Improvements in the governance dimension (e.g., high board independence and strong decision-making transparency) can reduce "short-sighted behaviour", ensuring that enterprises prioritise resource allocation to green technological innovation projects with higher long-term value rather than short-term profit projects [33]. For example, independent boards are more likely to support high-investment, long-cycle green R&D, preventing management from cutting innovation investments due to short-term performance pressures.

High-quality performance in the governance dimension (e.g., Standardized information disclosure and strict internal controls can decrease information asymmetry between enterprises and investors, facilitating the acquisition of financial support like green credit and equity financing. thereby solving the funding bottleneck for green technological innovation [34].

Supervision mechanisms in the governance dimension (e.g., audit committees and ESG performance assessments) can ensure that green innovation resources are not misused, improving innovation efficiency. For example, incorporating green technological innovation indicators into management evaluation systems can strengthen their motivation to promote innovation [22].

In summary, the environmental dimension is the "direct engine" of green technological innovation, the social dimension is the "indirect enabler", and the governance dimension is the "institutional guarantor". Enterprises need to differentially improve their performance in each ESG dimension based on their industry characteristics (e.g., asset-intensive industries need to strengthen the environmental dimension, while technology-intensive industries need to optimise the governance dimension) and development stages, so as to more accurately promote green technological innovation.

THEORETICAL ANALYSIS AND RESEARCH HYPOTHESES

ESG performance and green technological innovation

In the context of China's pledge to reach the "carbon peak" and "carbon neutrality" goals, enterprises ought to implement development strategies focused on green innovation to meet environmental regulations and advance the actual process of green transformation. First, the theory of sustainable development highlights the equilibrium among economic growth, environmental protection, and social welfare. This theory contends that firms should not merely pursue economic gains but also take environmental protection and social responsibility into account to attain long-term sustainable development. Under the ESG framework, by boosting environmental performance, increasing social responsibility, and fortifying corporate governance, companies can elevate their reputation and competitiveness in the market, thereby drawing more investors and consumers. Robust ESG performance reflects a firm's dedication to sustainable development, which not only aids in reducing environmental burdens but also strengthens the company's long-term competitiveness. Excellent ESG performance can spur investments in sustainable development, thus promoting green innovation.

Additionally, signalling theory indicates that companies communicate their real value and development prospects to the market via various signals like financial reports, dividend policies, and corporate social responsibility initiatives. Under the ESG framework, strong ESG performance acts as a crucial signal, transmitting to the market the company's determination to fulfil social responsibilities, prioritise environmental protection, and improve governance. Good ESG performance (such as better environmental performance, greater social responsibility, and stronger corporate governance) can signal to the market that the company is committed to sustainable development. These signals can improve the company's reputation and competitiveness, attracting more investors and consumers, thus offering funding and market incentives for green innovation.

Based on the above analysis, the following hypothesis is put forward:

H1: Strong ESG performance can facilitate corporate green innovation.

The mediating effect of analyst attention

As crucial information intermediaries in the capital market, analysts offer professional guidance to investors by thoroughly examining specific company information. Based on the information asymmetry theory, excellent ESG performance conveys extra information to the market, suggesting that the company has substantial growth potential and investment worth, thus drawing more attention from analysts. Moreover, because of the preference for companies with high ESG ratings in China, enterprises with remarkable ESG performance are more prone to attract analysts' notice. Hence, robust ESG performance transmits incremental information that lures more focus from analysts. Relying on the hypothesis of information asymmetry, analysts' professional analysis of ESG incremental information can effectively lessen the information asymmetry between investors and the company. Via analysts' reports, investors can obtain a more comprehensive knowledge of the company's green innovation endeavours, preventing undervaluation of the value of green innovation, thereby motivating managers to engage in more innovative activities.

According to the market pressure hypothesis, continuous analyst attention exerts pressure on companies and supervises the entire process of corporate green innovation. On the one hand, analysts, through field research and face-to-face communication, can identify potential issues within companies and directly supervise company managers, reducing speculative behaviour. On the other hand, sustained analyst attention may trigger a "supervision spillover effect", attracting the attention of other external supervisors, which means the company's green innovation activities will be subject to broader external oversight. This improves the efficiency of green innovation financing and speeds up the green innovation process.

In summary, strong ESG performance helps to attract analyst attention, and analysts' focus, through information interpretation and external supervision, enhances management's innovation motivation and the efficient use of green innovation funds, ultimately driving the achievement of green innovation.

Based on this, the following hypothesis is put forward:

H2: ESG performance improves corporate green innovation levels by drawing analyst attention.

RESEARCH DESIGN

Sample selection and data sources

Sample Selection: After screening, the total number of valid observations of textile enterprises from 2015 to 2023, the number of those listed on the Shanghai and Shenzhen A-shares is 668. According to the "Guidelines for the Classification of Listed Companies' Industries" of the China Securities Regulatory Commission and textile industry practices, the sample enterprises are divided into the following segments:

- Cotton textile and printing & dyeing industry: accounting for 38%, mainly covering enterprises engaged in spinning, weaving, printing and dyeing of natural fibres such as cotton and linen, including cotton yarn production and grey fabric manufacturing.
- Chemical fibre manufacturing industry: accounting for 27%, including enterprises producing chemical fibre raw materials such as polyester, nylon and viscose, as well as filaments and staple fibres.
- Garment and apparel manufacturing industry: accounting for 25%, covering enterprises producing terminal products such as clothing, shoes, hats

and home textiles, focusing on clean production processes (such as waterless dyeing) and low-carbon supply chain management.

- Other textile segments: accounting for 10%, including textile machinery manufacturing and industrial textiles (such as medical and filtering materials). These segments have relatively high technological intensity, and green innovation focuses on material improvement and energy efficiency enhancement.

Financial industry companies were excluded from the sample. Companies at risk of delisting or under special treatment due to significant risks were removed. Companies with missing data for specific years were excluded. The bottom and top 1% of all continuous variables were truncated.

ESG rating data were obtained from the Wind database; data regarding green patent applications and the overall number of patent applications were sourced from the green patent database and the listed company patent database on the China Research Data Service Platform (CNRDS). Other company characteristic data, such as company scale, profitability, debt-to-equity ratio, board size, proportion of independent directors, and company age, were obtained from the Guotai'an (CSMAR) database.

Variable selection

Independent variable: Corporate ESG performance

Following Jiao et al., ESG rating data were used. The Huazheng ESG evaluation system was employed, where scores from 1 to 9 were assigned based on the performance level. Higher scores signify better ESG performance [40].

In the robustness checks, Bloomberg's ESG performance scores were employed as alternative independent variables to guarantee the robustness of the study's outcomes. The reason for choosing the Huazheng Index is as follows:

- The Huazheng Index updates its data quarterly since 2019 and discloses ratings retrospectively, providing continuous and authoritative ESG ratings for the majority of China's listed companies.
- The continuous release of ESG ratings by the Huazheng Index increases investor trust and loyalty towards the rating information.
- Other mainstream ESG rating agencies in China, such as Shandao Ronglv and Shetou Meng, generally align with the Huazheng Index in terms of overall rating trends. Thus, this study uses the Huazheng Index ESG ratings as the source of data for the event study method.

Dependent variable: Green Technological Innovation (GTI)

In measuring corporate green technological innovation, both input and output methods are commonly used. However, given that it is challenging to distinguish the proportion of resources allocated to green technological innovation from the input perspective, this study adopts an output-based approach, employing the quantity of green patents filed by listed firms in a specific year as an indicator of their green technological innovation achievement. As per Li et al., the quantity of green patent applications was logarithm-transformed, adding 1 to prevent zero values in the computation [41].

Control variables

Given that other economic characteristics at the firm level may also impact green technological innovation, this study selects several relevant factors as control variables [42–44]. The size of the firm (Size) is gauged by the natural logarithm of total assets. Profitability (ROA) is shown by the return on assets, which mirrors the firm's capacity to earn profits from its total assets. Firms with greater profitability might have more resources to put into green technological innovation. The debt-to-equity ratio (Lev) shows the firm's ability to fulfil its debt obligations and its financial risk, which impacts its financing ability and operational stability, thus influencing green technological innovation. The size of the board (Board) is measured by the total number of directors on the board. The proportion of independent directors (Index) is computed by dividing the number of independent directors by the total number of board members. The age of the firm (Age) is measured by the natural logarithm of the company's years of operation, with 1 added to prevent taking the logarithm of zero. Industry dummy variables (Industry) are set in line with the China Securities Regulatory Commission's industry classification standards to control the heterogeneous impact of different industries on corporate results [45–47]. Year dummy variables (Year) are set to control for factors such as macroeconomic conditions and policy changes that vary over time and may influence the company's performance [48–50].

Mediating variable

Analyst attention (ANA) is chosen as the mediating variable. It is gauged by the natural logarithm of the quantity of analysts following the company (table 1).

Modelling

To examine the influence of corporate ESG performance on green technology innovation and the role of financing constraints between them, this paper successively constructs the following regression models [51–53]. For hypothesis 1, the following regression equation is built for testing:

$$Envrpat_{i,t} = \beta_0 + \beta_1 ESG_{i,t} + \beta_2 \Sigma Controls_{i,t} + \Sigma Year + \Sigma Industry + \varepsilon_{i,t} \quad (1)$$

where i and t denote the enterprise and the year, respectively, and $Envrpat_{i,t}$ stands for the logarithm of the quantity of green patents applied for by listed companies during period t, after adding 1. $ESG_{i,t}$ indicates the quantity of green patents applied for by listed companies during period t, and $ESG_{i,t}$ represents the value of the quantity of green patents applied for by listed companies during period t, after adding 1. $ESG_{i,t}$ denotes the ESG ratings of listed firm i in period t. $Controls_{i,t}$ represents the matrix of control variables for economic features of listed firms, including

Table 1

DATA SOURCES AND EXPLANATIONS			
Variable type	**Variable name**	**Variable symbol**	**Variable explanation**
Explained variables	Green Technology Innovation	GTI	Take the logarithm after adding 1 to the number of firms' green patent applications.
Explanatory variables	Corporate ESG Performance	ESG	Huazheng ESG Score
Mediating variables	Analyst Focus	ANA	Natural log of the quantity of analysts followed
Control variables	Firm size	lnTA	Natural logarithm of total assets
	Firm age	Age	Natural logarithm of the number of years of the company's existence plus 1 to take the natural logarithm
	Total Return on Assets	ROA	Ratio of net profit to total assets
	Gearing	Lev	Ratio of total liabilities to total assets
	Board size	Board	Total number of the board of directors
	Percentage of independent directors	Index	Number of independent directors/total number of board of directors
	Industry	Industry	Dummy variable for industry
	Annual	Year	Dummy variable for age

firm scale, debt-to-equity ratio (Lev), firm age, profitability, board size, and the proportion of independent directors (Index). $\Sigma Year$ and $\Sigma Independent$ directors are the two crucial variables. $\Sigma Year$ and $\Sigma Industry$ are year and industry control variables, respectively, and $\varepsilon_{i,t}$ are residual terms. When the regression coefficient β_1 of $ESG_{i,t}$ in Model 1 satisfies $\beta_1 > 0$ and is significant, it shows that the ESG performance of enterprises has a significant positive influence on green technological innovation, and the hypothesis 1 holds.

ANALYSIS OF EMPIRICAL RESULTS

Descriptive statistics

STATA18 was used to analyse the descriptive statistics of the explanatory variables and control variables selected in this paper, as presented in table 2.

Table 2 presents the descriptive statistics of the main variables employed in this research. The mean value of corporate green technological innovation was 0.058, having a minimum value of 0 and a maximum value of 1.792. This shows that there was substantial variation in green technological innovation among the sample firms. The average ESG performance score was 3.996, with a minimum of 1 and a maximum of 7, implying that the ESG performance of the sample companies was generally at a B-level rating.

Table 2

DESCRIPTIVE STATISTICS ANALYSIS TABLE					
Variable	**Obs**	**Mean**	**Standard deviation**	**Min**	**Max**
ESG	668	3.996	1.103	1	7
GTI	668	0.058	0.231	0	1.792
lnTA	668	21.916	0.95	19.893	25.114
Board	668	2.1	0.181	1.609	2.639
Index	668	0.379	0.057	0.308	0.6
Age	668	2.976	0.278	2.079	3.638
Lev	668	0.36	0.172	0.049	0.925
ROA	668	0.039	0.07	–0.353	0.244
ANA	668	1.275	1.189	0	3.664

Correlation analysis

The table of correlation analysis indicates that there exists a notable correlation between the chosen independent and dependent variables. The key independent variable (ESG) displays a significant positive correlation with the dependent variable (GTI), which aligns with the research anticipations (table 3).

Multicollinearity analysis

To further avoid interference from correlations between variables, this study conducted a multicollinearity analysis. As shown in table 4, the Variance Inflation Factor (VIF) was used before conducting the baseline regression. The VIF values of all variables were under 10, suggesting that there was no serious multicollinearity among the variables.

F-Test and Hausman Test

A fixed effects model or a pooled (mixed) effects model was more appropriate. An F-test was carried out to figure out which one. The test gave an F-value of $F(110, 550) = 2.35$ and a p-value of 0.0000, showing statistical significance. As a result, the pooled effects model was discarded in favour of the fixed effects model.

After that, a Hausman test was done to choose between the fixed effects model and the random effects model. The outcomes, presented in table 5, showed a p-value of 0.0000, which was lower than the 0.1 threshold. This outcome supported the choice of the fixed effects model.

Table 3

CORRELATION ANALYSIS TABLE									
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
(1) GTI	1.000								
(2) ESG	0.154*	1.000							
	(0.000)								
(3) lnTA	0.135*	0.263*	1.000						
	(0.000)	(0.000)							
(4) Board	0.162*	0.184*	0.204*	1.000					
	(0.000)	(0.000)	(0.000)						
(5) Index	–0.056	–0.078*	–0.144*	–0.709*	1.000				
	(0.149)	(0.043)	(0.000)	(0.000)					
(6) Age	0.070	0.146*	–0.021	0.027	0.056	1.000			
	(0.072)	(0.000)	(0.591)	(0.492)	(0.148)				
(7) Lev	0.034	–0.131*	0.348*	0.077*	–0.109*	0.016	1.000		
	(0.386)	(0.001)	(0.000)	(0.046)	(0.005)	(0.677)			
(8) ROA	0.019	0.238*	0.093*	0.082*	–0.015	–0.116*	-0.421*	1.000	
	(0.627)	(0.000)	(0.016)	(0.034)	(0.701)	(0.003)	(0.000)		
(9) ANA	0.020	0.293*	0.424*	–0.005	0.052	–0.245*	–0.091*	0.421*	1.000
	(0.601)	(0.000)	(0.000)	(0.902)	(0.182)	(0.000)	(0.018)	(0.000)	

Note: *** p<0.01, ** p<0.05, * p<0.1.

Table 4

MULTICOLLINEARITY ANALYSIS		
Variables	**VIF**	**1/VIF**
Board	2.137	0.468
Index	2.067	0.484
ANA	1.69	0.592
lnTA	1.641	0.609
Lev	1.547	0.646
ROA	1.525	0.656
ESG	1.269	0.788
Age	1.151	0.869
Mean VIF	1.628	

Table 5

RESULTS OF THE HAUSMAN TEST	
	Coef.
Chi-square test value	6.506
P-value	0.482

These results verified that the model specification was suitable, enabling the regression analysis to continue.

Benchmark regression analysis

Table 6 shows the benchmark regression outcomes by taking textile industry enterprises as samples. It systematically validates the influence of ESG performance (ESG) on green technological innovation (GTI) in textile enterprises through gradually bringing in control variables. In the basic Model 1 that merely contains enterprise, individual, and year fixed effects, the coefficient of ESG is 0.078, which is significant at the 1% level, suggesting a notable positive correlation between ESG performance and green technological innovation in textile industry enterprises. As control variables are gradually included (Models 2 to 7), the coefficient of ESG stays stable between 0.078 and 0.080, and the significance doesn't weaken in the least. This result firmly demonstrates that in the context of the textile industry, the promoting effect of ESG performance on green technological innovation has extremely high robustness, and the impact of the core explanatory variable is not disrupted by other potential factors.

Regarding control variables, the coefficient of enterprise size (lnTA) is positive (0.012–0.017) in Models 2 to 7, but none reach a statistically significant level (p > 0.1). This suggests that the expansion of enterprise size in the textile industry does not significantly promote green technological innovation, which may reflect that the resource advantages brought by size are partially offset by industry characteristics (such as the inertia of traditional production modes). The coefficient of enterprise age (Age) is positive (0.110–0.204) in Models 3 to 7, but it is also not significant (p>0.1), indicating that the length of enterprise survival has a limited contribution to green technological innovation in the textile industry, and the industry pays more attention to current practices rather than historical accumulation. The return on total assets (ROA) coefficient is negative (ranging from –0.097 to –0.125) in Models 4 to 7, but all are not significant (p>0.1), implying that the improvement

Table 6

BENCHMARK STEPWISE REGRESSION RESULTS							
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
	GTI	**GTI**	**GTI**	**GTI**	**GTI**	**GTI**	**GTI**
ESG	0.078***	0.078***	0.078***	0.079***	0.079***	0.080***	0.080***
	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)
lnTA		0.017	0.014	0.016	0.012	0.012	0.012
		(0.027)	(0.027)	(0.028)	(0.031)	(0.031)	(0.031)
Age			0.204	0.177	0.172	0.110	0.111
			(0.270)	(0.272)	(0.273)	(0.279)	(0.279)
ROA				–0.125	–0.104	–0.101	–0.097
				(0.159)	(0.175)	(0.175)	(0.177)
Lev					0.031	0.039	0.040
					(0.108)	(0.108)	(0.109)
Board						–0.113	–0.134
						(0.103)	(0.153)
Index							–0.073
							(0.389)
_cons	–0.229***	–0.588	–1.094	–1.062	–0.974	–0.570	–0.490
	(0.046)	(0.589)	(0.892)	(0.893)	(0.943)	(1.013)	(1.101)
Individual firm fixed effects	YES	YES	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES	YES	YES
Observations	668	668	668	668	668	668	668
R^2	0.118	0.119	0.120	0.121	0.121	0.123	0.123

Note: *, **, and *** denoted Significance at the 1%, 5%, and 10% levels, respectively. Robust standard errors were presented in parentheses; the same rule applied below.

of short-term financial profitability in the textile industry has not effectively driven green technological innovation, possibly because green technology investment is long-term and has a certain conflict with short-term profit goals. The coefficient of asset-liability ratio (Lev) is positive (0.031–0.040) in Models 5 to 7, but all are not significant (p>0.1), It shows that the direction of the impact of liability level on the green patent output of textile enterprises is unclear, and financial leverage is neither a key constraint nor a promoting factor for green technological innovation. In Models 6 and 7, the coefficient of board size (Board) is negative (–0.113 to –0.134). Among them, the coefficient of Model 6 is close to the 10% significance level, but overall, it is still not significant (p > 0.1). This might reflect that an overly large board size in the textile industry has a certain inhibitory effect on green technological innovation investment because of reduced decision-making efficiency, yet the effect is weak. In Model 7, the coefficient of the proportion of independent directors (Index) is –0.073 (p > 0.1), which fails to reach significance, suggesting that the proportion of independent directors has no significant influence on the green technological innovation of textile enterprises, and the independent director mechanism in the corporate governance structure plays a limited role in green innovation decision-making.

Then we construct figure 1 based on the synergistic effect of the three dimensions (the document confirms that ESG promotes green innovation through analyst attention), the index is constructed using a weighted composite method:

ESG Innovation Index = (Standardized ESG Score × × 40%) + (Standardized Analyst Coverage × 30%) + + (Standardized Green Patent Quality × 30%) (2)

A higher score indicates better synergistic performance between ESG and green innovation. For example, state-owned enterprises may have higher scores due to better ESG performance (consistent with the document's heterogeneity analysis), while non-state-owned enterprises may need to improve patent quality to enhance the index.

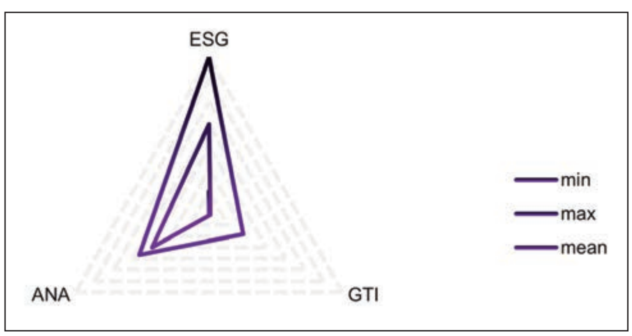

Fig. 1. Textile ESG-Innovation radar chart

Robustness tests

Winsorisation

Table 7 reports the regression results after winsorising all continuous variables at the 1 per cent tails [54, 55]. The positive and significant ESG coefficient persisted, confirming that the findings were not driven by outliers.

Table 7 shows the outcomes of Robustness Test 1 (winsorization) for the textile industry sample. It aims to validate the robustness of the benchmark regression conclusions by eliminating extreme values. In Model (1), which only controls for firm-specific and year fixed effects, the coefficient of corporate ESG performance (ESG) is 0.075 (t-statistic = 7.5), significant at the 1% level. This is very close to the positive influence of ESG on green technological innovation (GTI) in the benchmark regression (0.078), initially suggesting that the core conclusion remains unaffected by extreme values after winsorization. As control variables are gradually included (Models 2 to 7), the ESG coefficient stays stable between 0.075 and 0.078, with no significant changes in significance. This further validates the robust positive correlation between ESG performance and green technological innovation in the textile industry, enhancing the reliability of the main findings.

Regarding control variables: The coefficient of firm size (lnTA) varies between –0.006 and 0.015 in Models 2 to 7, none of which reach statistical significance ($p > 0.1$). Consistent with the benchmark regression results, this shows that the expansion of firm size has a limited driving effect on green technological innovation in the textile industry, as industry features (e.g., inertia of traditional production modes) may weaken the resource advantages brought by scale. The coefficient of firm age (Age) becomes negative (–0.048 to –0.193) in Models 3 to 7 but remains insignificant ($p > 0.1$). This reflects a slight change in the direction of the impact of firm age on green technological innovation after winsorization, though the statistical significance is still unclear, indicating that green innovation in the textile industry depends more on current ESG practices than historical accumulation. The coefficient of return on total assets (ROA) is negative (–0.201 to –0.283) in Models 4 to 7, with Model 4 approaching the 10% significance level (t-statistic ≈ –1.5) but overall remaining insignificant ($p > 0.1$). This implies that the inhibitory effect of short-term financial profitability on green technological innovation is slightly strengthened after winsorization, though not significantly, showing that corporate investment in green technology in the textile industry still needs to break free from the restrictions of short-term profit goals. The coefficient of asset-liability ratio (Lev) turns positive (0.124 to 0.137) in Models 5 to 7 but remains insignificant ($p > 0.1$), consistent with the benchmark regression results. This indicates that the direction of the impact of liability levels on green patent output of textile firms remains unclear, and financial leverage is not a key constraint or driver of green innovation. The coefficient of board

Table 7

REGRESSION RESULTS OF THE ROBUSTNESS TEST FOR THE REDUCED-TAIL TREATMENT

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	GTI	GTI	GTI	GTI	GTI	GTI	GTI
ESG	0.075***	0.075***	0.075***	0.076***	0.077***	0.078***	0.078***
	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)
lnTA		0.013	0.014	0.015	–0.003	0.001	–0.006
		(0.031)	(0.031)	(0.031)	(0.035)	(0.035)	(0.036)
Age			–0.048	–0.074	–0.088	–0.192	–0.193
			(0.269)	(0.269)	(0.269)	(0.276)	(0.275)
ROA				–0.283	–0.226	–0.220	–0.201
				(0.189)	(0.196)	(0.196)	(0.196)
Lev					0.124	0.129	0.137
					(0.111)	(0.111)	(0.111)
Board						–0.180*	–0.354**
						(0.107)	(0.158)
Index							–0.605
							(0.405)
_cons	–0.232***	–0.521	–0.405	–0.339	0.044	0.614	1.340
	(0.046)	(0.672)	(0.935)	(0.935)	(0.996)	(1.050)	(1.157)
Individual firm fixed effects	YES	YES	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES	YES	YES
Observations	613	613	613	613	613	613	613
R^2	0.128	0.128	0.128	0.132	0.135	0.139	0.143

size (Board) is negative (–0.180* to –0.354**) in Models 6 and 7, with Model 6 significant at the 10% level (t-statistic ≈ –1.7) and Model 7 significant at the 5% level (t-statistic ≈ –2.2). Compared with the insignificant results in the benchmark regression, the inhibitory effect of board size becomes more evident after winsorization, suggesting that in the textile industry, excluding extreme values reveals a more significant inhibitory effect of overly large board sizes on green technological innovation investment due to reduced decision-making efficiency. The coefficient of the proportion of independent directors (Index) is –0.605 in Model 7 ($p > 0.1$), failing to reach significance, consistent with the benchmark regression results, showing that the ratio of independent directors has no notable influence on green technological innovation in textile companies.

Excluding epidemic effects

Table 8 shows the outcomes of Robustness Test 2 (excluding the influence of the pandemic years) for the textile industry sample, to verify the applicability of the core conclusions in non-pandemic periods. In the basic Model 1 that only controls for firm-specific and year fixed effects, the coefficient of corporate ESG performance (ESG) is 0.077, significant at the 1% level, which is very close to the benchmark regression result (0.078). This initially implies that after excluding the pandemic years, the positive impact of ESG on green technological innovation (GTI) remains stable. As control variables are gradually included (Models 2 to 7), the ESG coefficient stays stable between 0.077 and 0.079, and there is no substantial alteration in significance. This further validates the stable positive correlation between ESG performance and green technological innovation in the context of the textile industry, verifying the cross-period applicability of the core conclusion.

Regarding control variables, the coefficient of firm size (lnTA) is positive (0.010 to 0.016) in Models 2 to 7, but none of them reaches the statistical significance level ($p > 0.1$). Consistent with the results of the benchmark regression and the winsorization test, this shows that the expansion of firm size has a limited driving impact on green technological innovation in the textile industry. Industry characteristics (such as the inertia of traditional production modes) may continue to diminish the resource advantages brought by scale.

The coefficient of firm age (Age) is positive (0.084 to 0.163) in Models 3 to 7, but still not significant ($p > 0.1$). This reflects that after excluding the pandemic years, the direction of the impact of firm survival time on green technological innovation has not changed notably, and green innovation in the textile industry still depends more on current ESG practices rather than historical accumulation.

The coefficient of return on total assets (ROA) becomes positive (0.015 to 0.044) in Models 4 to 7, but the values are small, and all are significant ($p > 0.1$). This suggests that in non-pandemic periods, the inhibitory effect of short-term financial profitability on green technological innovation weakens,

Table 8

ROBUSTNESS REGRESSION RESULTS EXCLUDING EPIDEMIC EFFECTS

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	GTI	**GTI**	**GTI**	**GTI**	**GTI**	**GTI**	**GTI**
ESG	0.077***	0.077***	0.077***	0.077***	0.077***	0.079***	0.079***
	(0.010)	(0.010)	(0.010)	(0.010)	(0.011)	(0.011)	(0.011)
lnTA		0.016	0.014	0.013	0.011	0.011	0.010
		(0.028)	(0.028)	(0.028)	(0.032)	(0.031)	(0.032)
Age			0.160	0.163	0.160	0.084	0.086
			(0.274)	(0.276)	(0.277)	(0.284)	(0.284)
ROA				0.015	0.029	0.034	0.044
				(0.186)	(0.206)	(0.206)	(0.208)
Lev					0.018	0.028	0.031
					(0.113)	(0.113)	(0.114)
Board						–0.134	–0.177
						(0.107)	(0.159)
Index							–0.146
							(0.399)
_cons	–0.225***	–0.568	–0.960	–0.963	–0.915	–0.428	–0.263
	(0.048)	(0.608)	(0.905)	(0.907)	(0.957)	(1.031)	(1.126)
Individual firm fixed effects	YES	YES	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES	YES	YES
Observations	597	597	597	597	597	597	597
R^2	0.122	0.123	0.124	0.124	0.124	0.127	0.127

but it is not significant. The contradiction between corporate investment in green technology and short-term profit goals in the textile industry still demands attention.

The coefficient of asset-liability ratio (Lev) is positive (0.018 to 0.031) in Models 5 to 7, but all are not significant ($p > 0.1$). In line with the benchmark regression outcomes, this shows that the direction of the influence of liability levels on the green patent output of textile companies remains unclear, and financial leverage is not a crucial limiting or facilitating factor for green innovation.

The coefficient of board size (Board) is negative (–0.134 to –0.177) in Models 6 and 7, among which the coefficient of Model 6 is close to the 10% significance level (t-value is about –1.25), but overall it is still not significant ($p > 0.1$). Compared with the insignificant results in the benchmark regression, the inhibitory effect of board size slightly strengthens after excluding the pandemic years, which may reflect that in normal periods, an overly large board size has a more prominent inhibitory effect on investment in green technological innovation due to decreased decision-making efficiency.

The coefficient of the proportion of independent directors (Index) is –0.146 in Model 7 ($p > 0.1$), which does not reach significance. This indicates that, in line with the benchmark regression results, the proportion of independent directors has no significant impact on the green technological innovation of textile firms.

Substitution with the IV-GMM model

Table 9 showcases the outcomes of Robustness Test 3 (utilising the IV-GMM model) for the textile industry sample. This test, by applying the instrumental variable generalised method of moments (IV-GMM) approach, intends to alleviate possible endogeneity problems (like reverse causality between ESG practices and green technological innovation or omitted variable bias) and further confirm the dependability of the core conclusions. In the IV-GMM Model 1 with firm and year fixed effects, the coefficient of corporate ESG performance (ESG) is 0.065, significant at the 1% level. After incorporating all control variables in Model 2, the ESG coefficient drops to 0.046 but still stays significant at the 5% level. Even though the coefficient is smaller than that in the benchmark regression (0.078***), the significance is maintained, suggesting that the positive influence of ESG performance on green technological innovation in the textile industry remains stable after dealing with endogeneity. The reliability of the core conclusion is verified via a more strict econometric method.

Regarding control variables, in Model 2, the coefficient of firm size (lnTA) is 0.022 (t-value = 2.0), significant at the 5% level. Different from the non-significant outcome in the benchmark regression, under the IV-GMM model, the positive influence of firm size on green technological innovation becomes more obvious. This might indicate that after dealing with endogeneity, larger firms in the textile industry can better utilise their resource advantages (such as R&D investment capabilities) to promote green technological innovation.

Table 9

REPLACEMENT MODEL ROBUSTNESS REGRESSION RESULTS

Variables	IV-GMM Model	IV-GMM Model
	GTI	GTI
ESG	0.065***	0.046**
	(0.021)	(0.021)
lnTA		0.022**
		(0.011)
Age		0.047
		(0.039)
ROA		–0.032
		(0.129)
Lev		0.060
		(0.062)
Board		0.258**
		(0.116)
Index		0.471
		(0.319)
_cons	–0.250***	–1.543***
	(0.088)	(0.458)
Individual firm fixed effects	YES	YES
Year fixed effects	YES	YES
Observations	552	552
R^2	0.153	0.170

The coefficient of firm age (Age) is 0.047 (t-value ≈ 1.2), non-significant, implying that the impact of a firm's longevity on green technological innovation is still unclear. The industry still depends more on current ESG practices rather than historical accumulation.

The coefficient of return on total assets (ROA) is –0.032 (t-value ≈ –0.25), non-significant, showing that the inhibitory effect of short-term financial profitability on green technological innovation remains non-significant under the IV - GMM model. The conflict between green technology investment and short-term profit goals in the textile industry still deserves attention.

The coefficient of asset-liability ratio (Lev) is 0.060 (t-value ≈ 0.97), non-significant, suggesting that the impact direction of liability levels on green patent output is still unclear, and financial leverage is not a crucial constraint or promoter of green innovation.

In Model 2, the coefficient of board size (Board) is 0.258 (t-value = 2.2), significant at the 5% level, which is contrary to the non-significant negative effect in the benchmark regression. Under the IV-GMM model, board size has a positive impact on green technological innovation. This may reflect that after handling endogeneity, a larger board size supports green technology investment because of its richer professional resources or diverse decision-making capabilities, which may be related to industry characteristics (e.g., the requirement for diverse expertise in complex technological decisions).

The coefficient of the proportion of independent directors (Index) is 0.471 (t-value ≈ 1.5), non-significant, indicating that the proportion of independent directors exerts no significant impact on green technological innovation in textile firms.

In summary, The IV-GMM results not only confirmed the notable positive influence of corporate ESG performance on green technological innovation, but also showed a considerably increased ESG coefficient after instrument adjustment, further strengthening the causal effect of ESG investment on the boost of green patent output.

HETEROGENEITY ANALYSIS

Firm nature heterogeneity

Table 10 shows the outcomes of the property rights heterogeneity analysis for the textile industry sample [56–58]. By differentiating between state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs), it uncovers the disparities in the influence of ESG performance on green technological innovation (GTI) among enterprises with distinct property rights. In the SOE sample, the coefficient of ESG is 0.124, significant at the 5% level, suggesting that the ESG performance of SOEs has a notably positive effect on green technological innovation. In the non-SOE sample, the coefficient of ESG is 0.077, significant at the 1% level; the direction of impact is consistent with that of SOEs, but the coefficient value is smaller. This result suggests that although ESG practices promote green technological innovation in both types of enterprises, SOEs have a stronger ability to convert ESG practices into technological innovation due to their resource endowments, policy support, or governance characteristics (such as greater pressure from stricter ESG assessment).

Regarding control variables, in the state-owned enterprise (SOE) sample, the coefficient of the board size (Board) is –2.531 (t-value = –2.37), significant at the 5% level. This shows that the enlargement of the board size in SOEs has a notably inhibitory influence on green technological innovation. It might be because the decision-making process of SOE boards is intricate and inefficient, thus impeding the allocation of resources to green technology investment. In the non-SOE sample, the coefficient of Board is 0.013 ($p > 0.1$), not significant, which means the board size of non-SOEs has no significant effect on green technological innovation. The proportion of independent directors (Index) in the SOE sample is –3.738 (t-value = –1.86), significant at the 10% level. It implies that an increase in the proportion of independent directors in SOEs may restrain green technological innovation because of excessive decision-making supervision or lack of professionalism. In the non-SOE sample, the coefficient of Index is 0.397 ($p>0.1$), not significant, indicating that there is no

Table 10

FIRM NATURE HETEROGENEITY		
Variables	State-owned enterprises	Non-state-owned enterprises
	GTI	GTI
ESG	0.124**	0.077***
	(0.055)	(0.009)
lnTA	0.136	–0.009
	(0.197)	(0.033)
Age	–0.736	0.023
	(1.286)	(0.267)
ROA	0.088	–0.248
	(0.966)	(0.162)
Lev	–0.339	0.084
	(0.846)	(0.099)
Board	–2.531**	0.013
	(1.067)	(0.134)
Index	–3.738*	0.397
	(2.009)	(0.366)
_cons	5.791	–0.311
	(6.727)	(1.090)
Individual firm fixed effects	YES	YES
Year fixed effects	YES	YES
Observations	83	583
R^2	0.309	0.157

significant association between the proportion of independent directors in non-SOEs and green technological innovation [59–61].

The coefficient for firm size (lnTA) is 0.136 ($p > 0.1$) in the SOE sample and –0.009 ($p > 0.1$) in the non-SOE sample, both of which are not significant, indicating that the influence of enterprise size on green technological innovation under property-rights heterogeneity remains unclear. The coefficients of enterprise age (Age), return on total assets (ROA). Asset-liability ratio (Lev) is all insignificant ($p > 0.1$) in both types of enterprises, suggesting that the impact of these factors on green technological innovation shows no significant differences under property rights heterogeneity, consistent and weak marginal effect on GTI across both ownership types.

Integration into assessment mechanisms: Under the dual-carbon strategy, state-owned enterprises (SOEs), as the “main force” in policy implementation, have explicitly incorporated green development indicators (such as energy consumption per unit of output, carbon emission intensity, and the number of green patents) into their performance appraisal systems. For example, the Guidelines on Encouraging Central Enterprises to Speed up the Development of Green and Low-carbon Industries, issued by the State-owned Assets Supervision and Administration Commission of the State Council (SASAC) in 2022, mandate SOEs to “associate ESG performance with the salaries and career advancement of responsible individuals”, directly motivating SOEs to spur green technological innovation by enhancing ESG performance. (e.g., increasing environmental protection investment and disclosing social responsibility reports). Resource inclination support: SOEs are more likely to obtain policy resources such as government special subsidies and green credit. The document mentions that "SOEs can utilise policy directions and resource advantages to increase green R&D investment", and high ESG scores serve as an important credential for them to access these resources, forming a positive cycle of "ESG improvement → acquisition of policy resources → acceleration of green innovation".

Non-state-owned enterprises (non-SOEs) face stricter market financing reviews. The mechanism analysis in the document notes that "ESG performance can alleviate information asymmetry by attracting analysts' attention", but the impact of ESG on non-SOEs is weaker, reflecting that their green innovation relies more on market recognition rather than policy-driven forces. For example, investors (especially institutional investors) pay more attention to the ESG of non-SOEs, but due to limited financial strength, non-SOEs have lower efficiency in converting ESG inputs into green patents.

Non-SOEs need to break through differentiated competition. The document suggests that they "leverage scale advantages and ESG to build brands", but constrained by higher financing costs (such as bond interest rates and equity financing thresholds), their green innovation is more dependent on short-term market returns, resulting in a weaker long-term driving effect of ESG on innovation compared to SOEs.

In summary, in the institutional context, the policy incentives (for SOEs) and market pressures (for non-SOEs) jointly result in the heterogeneity of ESG's influence on green innovation. This supplement further explains the behavioural differences among different types of textile enterprises in the sample and enhances the institutional adaptability of the research conclusions.

Firm size

Table 11 shows the outcomes of the firm size heterogeneity analysis for the textile industry sample. It divides the sample into two groups: small-scale enterprises and large-scale enterprises, and then probes into the differences in the influence of ESG performance on green technological innovation (GTI) among enterprises of varying sizes. In the small-scale enterprise group, the coefficient of ESG is 0.049, significant at the 1% level; in the large-scale enterprise group, the coefficient of ESG is 0.106, also significant at the 1% level. Even though ESG has a notably positive impact on GTI in both kinds of enterprises, the ESG coefficient of large-scale enterprises (0.106) is markedly higher than that of small-scale enterprises (0.049). This suggests that as the scale of enterprises grows, the driving effect of ESG practices on green technological innovation gets stronger. This might be because large-scale enterprises have more ample resources (such as R&D investment ability and technical cooperation capabilities) to turn ESG concepts into practical innovation results.

Table 11

HETEROGENEITY ANALYSIS OF FIRM SIZE

Variables	Small-scale enterprises	Large-scale enterprises
	GTI	GTI
ESG	0.049***	0.106***
	(0.011)	(0.019)
lnTA	0.021	0.138
	(0.055)	(0.093)
Age	–0.043	0.335
	(0.300)	(0.543)
ROA	–0.075	–0.371
	(0.155)	(0.443)
Lev	0.025	–0.086
	(0.129)	(0.226)
Board	–0.051	0.035
	(0.177)	(0.300)
Index	–0.011	0.176
	(0.414)	(0.781)
_cons	–0.338	–4.431
	(1.351)	(2.692)
Individual firm fixed effects	YES	YES
Year fixed effects	YES	YES
Observations	334	334
R^2	0.126	0.139

In terms of control variables, the coefficients of firm size (lnTA) in both groups are not significant (0.021 for small-scale enterprises and 0.138 for large-scale enterprises, $p > 0.1$). This suggests that after grouping, the impact of the enterprises' own size on GTI is no longer prominent. It may be because the grouping is based on size, and the lnTA in the control variables more reflects other unclear size-related characteristics. The coefficients of firm age (Age), Total asset return (ROA) and asset-liability ratio (Lev) are both insignificant in both groups ($p > 0.1$), suggesting that under the firm-size heterogeneity, the influence of these factors on GTI has no significant differences. The coefficients of board scale (Board) and the proportion of independent directors (Index) are also not significant in both groups ($p > 0.1$), indicating that the impact of governance structure on green technological innovation is weak in enterprises of different sizes.

In summary, capital-intensive firms, owing to their asset and capital-intensive nature, were the most responsive to ESG-driven innovation. Supported by their reliance on human capital, labour-intensive industries also presented a notable positive correlation between ESG and GTI. Conversely, even though technology-intensive companies had a robust R&D basis, the marginal impact of ESG on green technological innovation was comparatively moderate. This analysis provided empirical support for developing industry-specific strategies for green development.

Further discussion of the impact of the mediating mechanism of analysts' concerns

Table 12 shows the outcomes of the mediating effect test for the textile industry sample. By conducting a two-stage regression analysis, it initially confirms the possible mediating function of analyst attention (ANA) between ESG performance and green technological innovation (GTI). In Model 1, where GTI serves as the explained variable, the coefficient of corporate ESG performance (ESG) is 0.080, significant at the 1% level. This shows that ESG practices in the textile industry have a notable positive influence on green technological innovation, which aligns with the findings of the benchmark regression. Concerning control variables, the coefficients of firm size (lnTA), firm age (Age), return on total assets (ROA), asset-liability ratio (Lev), board size (Board), and the proportion of independent directors (Index) are all non-significant ($p > 0.1$). This implies that in the textile industry, these conventional factors have restricted driving effects on green technological innovation, and ESG performance is the key influencing factor [62–64].

In Model 2, where ANA serves as the explained variable, the coefficient of ESG is 0.093, significant at the 1% level. This indicates that more active ESG performance of textile enterprises draws greater analyst attention. Among the control variables, the coefficient of firm size (lnTA) is 0.557, presenting a significant positive correlation, meaning that larger enterprises are more prone to attract analyst attention. The coefficient of return on total assets (ROA) is 2.062, showing a significant positive correlation, which implies that enterprises with high profitability receive more analyst attention. The coefficient of firm age (Age) is –1.933, significantly negatively correlated at the 5% level, suggesting that enterprises with a longer existence time may have less analyst attention because of their relatively stable business models. The coefficients of other variables (Lev, Board, Index) are all non-significant ($p > 0.1$) [65–67].

Combining the results of the two stages, it can be preliminarily inferred that analyst attention is an important mediating path through which ESG affects green technological innovation [68, 69, 70]: improved ESG performance attracts more analyst attention (Model 2), and analysts, through information mining and dissemination, may force enterprises to strengthen green technological innovation to meet market expectations (Model 1). In the textile industry, a traditional high-pollution and high-energy-consumption field, the above findings have important practical significance: corporate ESG practices not only directly promote green technological innovation but also form external supervision pressure by increasing analyst attention, further promoting green transformation [71–73]. Policy makers may consider strengthening ESG information disclosure requirements and guiding analysts to pay attention to green technological innovation indicators, thereby building a positive cycle of "ESG practices–analyst supervision–green innovation" to help the textile industry achieve the goal of low-carbon development [74–77].

Table 12

TWO-STEP MEDIATED EFFECTS REGRESSION RESULTS

Variables	(1)	(2)
	GTI	ANA
ESG	0.080***	0.093***
	(0.010)	(0.030)
lnTA	0.012	0.557***
	(0.031)	(0.094)
Age	0.111	–1.933**
	(0.279)	(0.846)
ROA	–0.097	2.062***
	(0.177)	(0.537)
Lev	0.040	–0.045
	(0.109)	(0.329)
Board	–0.134	0.108
	(0.153)	(0.462)
Index	–0.073	0.618
	(0.389)	(1.179)
_cons	–0.490	–6.009*
	(1.101)	(3.335)
Individual firm fixed effects	YES	YES
Year fixed effects	YES	YES
Observations	668	668
R^2	0.123	0.279

CONCLUSIONS

This research examines the influence of ESG performance on green technological innovation (GTI) in Chinese textile enterprises within the dual-carbon strategy, utilising panel data of A-share listed textile firms from 2015 to 2023. By means of fixed-effects models, robustness checks, heterogeneity analyses, and mediating effect tests, the main findings are summarised as follows:

ESG performance notably boosts green technological innovation in textile enterprises. Benchmark regression outcomes indicate that ESG performance has a steadily positive and significant effect on GTI (coefficient range: 0.078–0.080), with this effect remaining robust after winsorization, excluding pandemic years, and addressing endogeneity via the IV-GMM model. This confirms that strong ESG practices directly drive green innovation in the textile industry, a traditional high-pollution and high-energy-consumption sector. Heterogeneity in the impact of ESG performance, by ownership, state-owned enterprises (SOEs) exhibit a stronger positive effect of ESG on GTI (coefficient: 0.124) compared to non-SOEs (0.077), likely due to SOEs' superior resource endowments, policy support, and stricter ESG assessment pressures. By firm size: large-scale enterprises show a more pronounced ESG-driven GTI effect (coefficient: 0.106) than small-scale enterprises (0.049), reflecting that larger firms' abundant resources (e.g., R&D capacity, technical cooperation) better convert ESG concepts into innovation outcomes. Analyst attention acts as a critical mediating mechanism. ESG performance enhances analyst attention (coefficient: 0.093), and analysts, through information dissemination and external supervision, incentivise enterprises to strengthen green technological innovation to meet market expectations. This forms an "ESG practices–analyst supervision–green innovation" transmission path. Limited role of traditional control variables. Factors such as firm size, age, profitability (ROA), leverage (Lev), board size, and independent director ratio generally show insignificant impacts on GTI in textile enterprises, indicating that ESG performance is a core driver of green innovation in this sector, outweighing traditional firm characteristics.

Overall, this study verifies that enhancing ESG performance is an efficient strategy for textile enterprises to boost green technological innovation under the dual-carbon goal. The results offer theoretical backing for comprehending ESG-driven green innovation and practical advice for enterprises, investors, and policymakers to facilitate sustainable industrial transformation.

POLICY RECOMMENDATIONS

For firms: Integrate ESG into core strategy and enhance green innovation capability

Strengthen ESG management systems: Implement a comprehensive ESG indicator framework covering environmental, social, and governance dimensions. Highlight crucial areas like environmental investment and social responsibility disclosure. Through enhancing ESG ratings, companies can draw more analyst interest and obtain external resources. For instance, following the Huazheng ESG evaluation framework, firms should identify and address weaknesses (e.g. environmental performance), develop improvement plans, and regularly disclose progress to build market confidence.

Formulate differentiated strategies based on firm type and industry characteristics: SOEs should leverage policy direction and resource advantages to increase investment in green technology R&D and establish best□practice models for ESG-innovation synergy. Private firms can utilise the benefits of scale expansion and differentiate their brand through ESG, using green patent portfolios to enhance competitiveness. Asset-intensive firms (e.g., chemical, energy sectors) should integrate ESG into equipment upgrades and process optimisation. Labour-intensive firms (e.g., textiles) should focus on innovations in clean production, and technology-intensive firms (e.g., electronics) should embed ESG-oriented goals into existing R&D frameworks.

For investors: Develop an ESG Analyst attention investment framework

Prioritise firms with high ESG ratings and rising analyst coverage, especially in asset intensive sectors, where green innovation potential more readily translates into long-term value. For example, in the energy sector, take into account companies that have ESG ratings of B or higher and steadily growing analyst coverage across three quarters, combined with growth in green patenting, to assess investment appeal.

Track ESG-related commentary in analyst reports to identify breakthrough green innovation initiatives and avoid underestimating their value due to information asymmetry. A dynamic monitoring framework could include "ESG rating → analyst coverage → green patents". When a firm's ESG rating improves and analyst coverage surges, closely evaluate its green innovation projects for commercial potential.

For government: Improve the ESG-Innovation Ecosystem

Enhance ESG disclosure and rating standards by promoting the adoption of authoritative ESG rating systems like Huazheng's. Require quarterly disclosure of key ESG metrics (e.g., carbon emissions, green R&D investment) by listed companies to enhance transparency and improve the effectiveness of analyst attention. For example, provide subsidies to companies that meet disclosure standards, and include consistently improving firms in green financing programmes.

Implement industry-specific incentive policies by introducing ESG-innovation subsidies for asset-intensive sectors (e.g., a 10 per cent subsidy for every RMB 10,000 of green R&D expenditure), and tax incentives for clean-production technology in labour-intensive sectors. Facilitate cross-department collaboration across finance, environment, and industry ministries to create a virtuous cycle of "policy incentives → ESG improvement → innovation drive".

Suggestions for refining ESG strategies in sub-sectors of textile enterprises

Cotton Textile Enterprises should focus on cleaner production technology innovation and water resource management. Align ESG environmental goals with the high water consumption and high pollution pain points of the cotton textile industry. Prioritise R&D investments in advanced clean production technologies, such as in-depth printing and dyeing wastewater treatment technologies (e.g., membrane separation, advanced oxidation) and low liquor ratio dyeing processes. Enhance ESG environmental scores through the layout of green patents. For example, establish quantifiable ESG indicators such as "wastewater reuse rate" and "energy consumption per unit output value", and link them to R&D investments. Set up a cross-departmental ESG management team, with production, R&D, and environmental protection departments collaborating to formulate a roadmap for cleaner production technologies.

Regularly disclose progress in technological upgrades (e.g., reductions in wastewater treatment costs, proportion of green processes applied) to strengthen analysts' recognition of their ESG performance.

Chemical fibre enterprises should strengthen circular economy patent layout and raw material substitution innovation. Addressing the chemical fibre industry's reliance on fossil resources and the difficulty of waste, focus ESG environmental goals on R&D of circular regeneration technologies (e.g., PET bottle chip recycling, spinning, chemical depolymerisation) and bio-based chemical fibres (e.g., PLA, PHA). Enhance the synergy between ESG and green innovation by patenting technologies in areas such as "recycled fibre preparation" and "degradable material modification". Highlight achievements in low-carbon supply chain transformation in ESG disclosures – for instance, collaborating with upstream petrochemical enterprises to develop low-carbon raw materials and publicly disclosing the proportion of recycled fibres in products. This will attract brand customers focused on sustainable consumption (e.g., sportswear companies), forming a positive cycle of "ESG improvement → increased market demand → greater innovation investment".

Garment manufacturing enterprises should promote green supply chain management and low-carbon design innovation.

Focus on energy conservation and emission reduction in garment production (e.g., waterless printing technology) and the construction of a waste garment recycling system. Refine ESG indicators into metrics such as "low-carbon fabric utilisation rate" and "product recycling rate", and protect eco-friendly designs (e.g., detachable, easily degradable garment structures) through green patents. Integrate labour rights protection (e.g., reasonable working hours, skill training) into the ESG framework, especially in labour-intensive garment processing links. By improving employee satisfaction to reduce turnover rates, it indirectly ensures the stable implementation of green production processes.

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Antifungal characteristics of warp-knitted cotton fabrics treated with various metal complexes

DOI: 10.35530/IT.077.01.202599

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ABSTRACT – REZUMAT

Antifungal characteristics of warp-knitted cotton fabrics treated with various metal complexes

This study investigates the antifungal properties of warp-knitted cotton fabrics treated with metal-based compounds containing sodium tetrahydroxocuprate (Cu), silver diamine (Ag), and sodium zincate (Zn), synthesised via novel, efficient methods designed to reduce processing complexity and cost. Treatments were applied at concentrations of 0.5% and 1%, and antifungal efficacy was assessed against Candida albicans over 28 days. Surface morphology and chemical composition analyses were conducted using scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and Fourier-transform infrared spectroscopy (FTIR). Results revealed uniform particle distribution on fabric surfaces. It was found that Cu-based particles tended to accumulate more densely and demonstrated stronger adhesion on the yarn surfaces. In contrast, in comparison, this effect became gradually weaker in the samples containing Ag and Zn particles. Antifungal testing demonstrated that Cu-treated fabrics exhibited the highest reduction in fungal load, achieving a 4 $\log_{10}$ (10,000-fold) decrease at 1% concentration by day 7, with sustained activity through day 28. Ag treatments resulted in up to a 3.04 $\log_{10}$ reduction, while Zn treatments showed reductions up to 3.22 $\log_{10}$ at 1%. The 1% metal complex concentration consistently outperformed 0.5% across all metals. Findings highlight Cu compounds as particularly effective for healthcare textiles due to rapid and robust antifungal activity, whereas Ag and Zn compounds offer stable, long-term protection.

Keywords: *antifungal textiles, metal-based coatings, chemical synthesis, warp-knitted cotton fabric, Candida albicans*

Caracteristicile antifungice ale tricoturilor din urzeală din bumbac tratate cu diferiți complecși metalici

Acest studiu investighează proprietățile antifungice ale tricoturilor din urzeală din bumbac tratate cu compuși pe bază de metal care conțin tetrahidroxocuprat de sodiu (Cu), diamină de argint (Ag) și zincat de sodiu (Zn) sintetizați prin metode noi și eficiente, concepute pentru a reduce complexitatea și costul procesării. Tratamentele au fost aplicate la concentrații de 0,5% și 1%, iar eficacitatea antifungică a fost evaluată împotriva Candida albicans timp de 28 de zile. Morfologia suprafeței și analizele compoziției chimice au fost efectuate folosind microscopia electronică de baleiaj (SEM), spectroscopia cu dispersie de energie (EDS) și spectroscopia în infraroșu cu transformată Fourier (FTIR). Rezultatele au evidențiat o distribuție uniformă a particulelor pe suprafețele tricoturilor. S-a descoperit că particulele pe bază de Cu au avut tendința de a se acumula mai dens și au demonstrat o aderență mai puternică pe suprafața firului, în timp ce, în comparație, acest efect a devenit treptat mai slab în probele care conțin particule de Ag și Zn. Testele antifungice au demonstrat că tricoturile tratate cu Cu au prezentat cea mai mare reducere a încărcăturii fungice, obținând o scădere de 4 $\log_{10}$ (10.000 de ori) la concentrația de 1% până în ziua 7, cu activitate susținută până în ziua 28. Tratamentele cu Ag au dus la o reducere de până la 3,04 $\log_{10}$, în timp ce tratamentele cu Zn au prezentat reduceri de până la 3,22 $\log_{10}$ la 1%. Concentrația de 1% a complexului metalic a depășit în mod constant concentrația de 0,5% pentru toate metalele. Rezultatele evidențiază compușii de Cu ca fiind deosebit de eficienți pentru textilele utilizate în domeniul medical datorită activității antifungice rapide și robuste, în timp ce compușii Ag și Zn oferă o protecție stabilă, pe termen lung.

Cuvinte-cheie*: textile antifungice, acoperiri pe bază de metal, sinteză chimică, tricoturi din urzeală din bumbac, Candida albicans*

INTRODUCTION

Cotton represents a significant share of natural textile resources and is extensively utilised in modern society. It is valued for its softness, comfort, hydrophilic property, biocompatibility, and demanded mechanical strength. However, its high moisture retention, natural characteristics, and porous structure render it more vulnerable to microbial growth [1, 2]. Thus, antimicrobial treatment of cotton fabrics is an essential process to enhance their resistance against microbial growth, thereby improving hygiene, durability, and wearer comfort [3]. Metal-based bactericidals and therapeutic agents are commonly used for the antimicrobial treatment of textiles through coating [4, 5], sol-gel coating [6], electroless-plating [7], microencapsulation [8], padding-drying-curing [9], exhausting [10], plasma treatment [11], spraying [12, 13], electrospraying [14], photodeposition [15], and atomic layer deposition [16], etc. Extensive research is still being conducted to improve the antimicrobial properties of cotton textiles through alternative treatment techniques, as well as the various synthesising methods of metal complexes.

Silver (Ag) has been widely utilised for its antimicrobial properties, particularly in the treatment of cotton fabrics to provide antifungal protection through disrupting microbial cell membranes and inhibiting enzymatic activity [17–19]. Studies have shown that Ag-treated cotton exhibits strong antifungal efficacy against common textile-deteriorating fungi such as *Aspergillus niger* and *Candida albicans*, making it an ideal choice for medical textiles, sportswear, and other functional fabrics [20–22]. However, factors such as particle size, concentration, and binding methods significantly influence the long-term effectiveness of Ag coating [23]. Numerous laborious and complicated studies have been conducted on the synthesis of Ag-containing chemical compounds for their application in the production of antifungal cotton fabrics. Arenas-Chávez et al. investigated the antifungal properties of a nanocomposite based on Ag nanoparticles and carboxymethyl chitosan against *Candida albicans* using various qualitative and quantitative methods. Results demonstrated that the functionalized cotton fabric exhibited strong antifungal effects, suggesting its potential use in hospital garments to reduce nosocomial infections [24]. Hedayati et. al. synthesised silver nanoparticles (AgNPs) on a β-CD/ ketoconazole composite and applied it to cotton fabric using a cross-linking agent. The findings indicated that AgNPs on the composite increased antifungal properties, enhanced washing durability, and potential suitability for medical applications, wound dressings, and sportswear for sensitive skin [25]. For maintaining long-lasting hygiene in textiles and reducing the limitations of traditional antimicrobial treatments, reliable alternative research is still needed in terms of silver ion-based antifungal applications.

Copper has gained significant attention for its antimicrobial properties, particularly in the antifungal treatment of cotton fabrics [26]. Copper ions (Cu^{2+}) exhibit strong biocidal activity by disrupting fungal cell membranes, generating reactive oxygen species, and interfering with essential enzymatic functions [27]. Compared to silver, copper offers a more cost-effective alternative while still ensuring high antimicrobial performance [28]. Recent studies revealed that various innovative methods have been recorded in the literature. Nosheen et al. designed a pilot-scale setup incorporating a jigger dyeing machine, a high-pressure hydraulic roll-press (padder), and a stenter machine to expose the cotton fabric to the electroless deposition in a $CuSO_4$-based bath with controlled pH. Treated samples exhibited 91% (1.87 log10) reduction in the fungal spores of *Aspergillus niger* [29]. Swierczynska and Kudzin reported an alternative antimicrobial cotton material by utilising chemical deposition of copper sulfide. The process consisted of two phases, which included the chelation of copper sulfate onto the cellulose chains, and second, the precipitation of copper as copper sulfide. Antifungal effectiveness was evaluated against *Chaetomium globosum* and *Aspergillus niger*, and the results presented that clear inhibition zones with sizes of 1 to 2 mm were detected, without any evident growth of micro-organisms [30]. To establish more efficient hygiene management, researchers continue to overexert about developing new, durable, non-toxic, and biodegradable compounds regarding the adoption of copper-based antifungal treatments of textiles.

Zinc (Zn) has been widely explored for its antimicrobial properties, particularly in the antifungal treatment of cotton fabrics. Zn-based complexes are commonly used due to their broad-spectrum antimicrobial activity, biocompatibility, thermal conductivity, low production cost, and UV-protective properties [2, 31]. Lately, investigations indicated that Zn-based agents at the same dose had both bactericidal influence on micro-organisms and non-toxic effects on human cells [32]. Latest studies have been published in the literature regarding a novel approach to the treatment of antifungal textiles with Zn compounds. Roy et. al. synthesised Zinc Oxide nanoparticles (ZnO NPs) and applied them onto cotton fabrics by using the dip coating technique through different mole (M) concentrations. Disk diffusion test method revealed that 2M ZnO-coated cotton fabric has shown the highest zone of inhibition (14 mm) against *Aspergillus niger*. Researchers have also indicated that as the size of nanoparticles increases, their adhesion to cotton fabric decreases, making them more easily removed during washing. In contrast, smaller nanoparticles exhibit stronger adhesion and greater penetration into the fabric. However, at specific molar concentrations, nano-sized particles were prone to agglomeration, which might impact their effectiveness [33, 34]. Kudzin et. al. coated cotton fabric with Zn by utilising a DC magnetron sputtering system. The antifungal activity of the coated samples was evaluated against *Aspergillus niger* and *Chaetomium globosum* fungal mould species. Findings presented apparent zones of fungal growth inhibition around the coated samples in Petri dishes [35]. Since Zn-based metals exhibit less soluble characteristics [35, 36], exploring new Zn-based compounds is strongly encouraged to develop more effective antifungal treatments for textile materials.

This study aims to yield various facile and viable metal-based compounds incorporating Cu, Ag and Zn through alternative and novel synthesis methods by eliminating long processing time, complex and expensive equipment, and multiple steps for deposition. The other objective of the current research is to evaluate the antifungal efficacy of the warp-knitted cotton fabrics treated with varying concentrations of the synthesised metal-based compounds.

EXPERIMENTAL

Materials and methods

Materials

During the experiments, 100% cotton bandages were produced in the FITTEX (model 080S) warp knitting machine with a gauge of 14 needles per inch. The properties of the open-end cotton yarn used during production and the warp knitted cotton fabric manufactured are presented in table 1 and table 2, respectively.

Table 1

PROPERTIES OF THE PRODUCED WARP KNITTED COTTON FABRIC

Related properties	Values
Yarn count	Ne 29.5
Linear density of the yarn (tex)	20
Fabric weight (g/m^2)	54.2
Tensile strength (N)	42
Elongation (%)	11.4
Length of produced knitted bandage (m)	5
Width of produced knitted bandage (cm)	14
Humidity ratio (%)	6
Air permeability (1 atm) (dm^3/m^2*sec)	1420

Table 2

CHARACTERISTICS OF 100% CARDED COTTON OPEN-END YARN

Related properties	Average value
Linear density of yarn (tex)	20.1
Coefficient of variation in linear density (%)	1.6
Breaking load (cN)	281.2
Coefficient of variation for breaking load (%)	9.8
Specific breaking load (cN/tex)	13.9
Elongation (%)	3.93
Breakage at 1000 cycles/hour	54

Chemical compounds used for the synthesis of antifungal agents

Analytical grade silver nitrate ($AgNO_3$), copper sulfate ($CuSO_4$ $5H_2O$), and zinc acetate ($Zn(O_2CCH_3)_2$ in pure form used in this research were purchased from Ural Bor (Uralsk, Russia). Ascorbic Acid ($C_6H_8O_6$) was supplied by Luwei Pharmaceutical Group (China). Analytical grade aqueous ammonia (NH_4OH) was ordered from JSC Kupavnareaktiv (Russia).

Experimental processes

Experimental research was carried out in the M. Auezov Engineering Testing Laboratory (Kazakhstan) and an accredited training and testing laboratory in Tashkent (Uzbekistan).

Before carrying out the experimental work, 14x14 cm warp knitted cotton fabrics were boiled at 100 ºC for 30 minutes with the addition of 3% NaOH. Then, the samples were washed with distilled water for neutralisation. Then, they were dried in a drying cabinet (SNOL 75/350, Russia) at 95–100ºC for 30 minutes. Finally, the samples were kept in a desiccator at a constant standard humidity of 8%.

Deposition of copper particles

Initially, copper sulfate solutions with varying concentrations of 0.5% and 1% were prepared. 14×14 cm knitted fabrics were placed in separate beakers. Then, 100 ml of copper sulfate solutions of various concentrations were poured into each beaker. Approximately 40% sodium hydroxide (NaOH) solution was added to each solution to completely dissolve the copper hydroxide ($Cu(OH)_2$), which was formed in the initial stage. As a result of the chemical interaction, a complex molecule of sodium tetrahydroxocuprate (II) $Na_2[Cu(OH)_4]$ is generated, which served as an intermediary (precursor) compound in the process (Chemical reactions a and b). To ensure complete impregnation of the samples with copper ions, the knitted fabrics were kept in the solution for 10 min.

a) Formation of copper hydroxide: Adding a NaOH solution to a $CuSO_4$ solution results in the precipitation of $Cu(OH)_2$.

$$CuSO_4 + 2NaOH \rightarrow Cu(OH)_2\downarrow + Na_2SO_4$$

b) Dissolving copper hydroxide in an excess amount of sodium hydroxide: With further addition of NaOH, copper hydroxide dissolves and a complex compound, sodium tetrahydroxocuprate (II), is formed.

$$Cu(OH)_2 + 2NaOH \rightarrow Na_2[Cu(OH)_4]$$

The samples were then squeezed from the surplus precursor solution and placed in another solution containing 4 g/l ascorbic acid, which is stirred for 10–15 seconds before being rinsed with distilled water to eliminate any excess reducing agent. After that, samples were dried in a drying cabinet (SNOL 75/350, Russia) at 95–100ºC for 30 minutes, before being transferred to a desiccator to maintain a constant normalised humidity of 8%.

Deposition of silver particles

At the outset, varying concentrations (0,5% and 1%) of silver nitrate ($AgNO_3$) solutions were obtained. Knitted bandages measuring 14×14 cm were placed in different beakers. Following that, 100 ml of ($AgNO_3$) solutions of varying concentrations were added to each beaker. During the process, silver chloride (AgCl) was formed and precipitated. In order to completely dissolve the AgCl and make its distribution in the solution homogeneous, 1–2 ml of 25% ammonia solution ($NH_3 \cdot H_2O$) was added to the mixture (Chemical reactions c and d). The samples were left in the solution for 10 minutes to ensure that the silver ions were completely absorbed into the fabric and impregnated equally throughout the material.

c) Formation of silver chloride precipitate: If chloride ions are present in the silver nitrate solution (as a contaminant), a silver chloride (AgCl) precipitate may occur.

$$AgNO_3 + NaCl \rightarrow AgCl\downarrow + NaNO_3$$

d) Dissolving silver chloride in ammonia: Once 25% ammonia is added, the silver chloride precipitate dissolves, yielding a complex silver diamine compound.

$$AgCl + 2NH_3 \rightarrow [Ag(NH_3)_2]^+ + Cl^-$$

Afterwards, the samples were squeezed out of the excess precursor solution and immersed in a 4 g/l ascorbic acid solution for 10–15 seconds. Following that, they were washed with distilled water to remove any remaining reducing agent. Ultimately, specimens were dried in the drying cabinet (SNOL 75/350, Russia) at 100 ºC until they had completely dried, before being transferred to a desiccator to maintain a constant normalised humidity of 8%.

Deposition of zinc particles

At this stage, zinc acetate ($Zn(CH_3COO)_2$) solutions were prepared at concentrations of 0,5% and 1%. Knitted fabric samples of 14×14 cm were placed separately in each of five beakers. Then, 100 ml of ($Zn(CH_3COO)_2$) solution was added to each beaker. NaOH solution was added to the mixture until the zinc hydroxide $Zn(OH)_2$, which was formed in the first step, was completely dissolved, which led to the formation of sodium zincate, an intermediate compound (precursor) (Chemical reactions e and f). The samples were left in the solution for 20 minutes to ensure that the chemical agent was completely absorbed by the fabric.

e) Formation of zinc hydroxide: When NaOH is introduced to the zinc acetate solution, zinc hydroxide is formed.

$$Zn(CH_3COO)_2 + 2NaOH \rightarrow Zn(OH)_2 + 2CH_3COONa$$

f) Dissolution of zinc hydroxide to generate sodium zincate: By continuing to add NaOH to the mixture, zinc hydroxide dissolves to form sodium zincate:

$$Zn(OH)_2 + 2NaOH \rightarrow Na_2[Zn(OH)_4]$$

Next, the fabrics were soaked in a 4 g/l ascorbic acid solution for 15–20 seconds. They were subsequently washed with distilled water to get rid of any residual reducing agent. Finally, they were put in a drying cabinet (SNOL 75/350, Russia) at 80 ºC until totally dried, before being transferred to a desiccator to maintain a constant normalised humidity of 8%.

SEM and EDS analyses of the samples

The surface morphology and elemental composition of sputter-coated (80/20%; gold/palladium) untreated and treated warp-knit cotton fabrics were analysed using scanning electron microscopy (SEM; Jeol JSM 5910LV), at an accelerating voltage of 20 kV, coupled with energy-dispersive spectroscopy (EDS; Oxford Instruments Inca X-Sight 7274).

FTIR analyses of the samples

FTIR analysis was performed using a Shimadzu IRPrestige-21 spectrometer equipped with a Pike Total Internal Reflection (TIR) accessory (USA). The measurements were taken at a resolution of 2 cm^{-1} with 50 scans over a wavenumber range of 500 to 4000 cm^{-1}. The data were analysed using IRSolution software version 1.6.

Antifungal test procedure

Chemicals for microbiological testing

Phosphate Buffered Saline (PBS, pH 7.2): Prepared by dissolving 8.0 g NaCl, 0.2 g KCl, 1.44 g Na_2HPO_4 and 0.24 g KH_2PO_4 in 1 L of distilled water. After adjusting the pH to 7.2, it was sterilised by autoclaving at 121 ºC for 15 minutes.

PBS containing 0.2% Tween 80: 0.2% (v/v) Tween 80 was added to the prepared PBS, then filter sterilisation (0.22 µm) was applied and made ready for use.

Sabouraud Dextrose Agar (SDA): Commercial powder form was prepared according to the manufacturer's instructions (65 g/L), dissolved by boiling and sterilised at 121 ºC for 15 minutes. After cooling, it was poured into Petri dishes in a sterile environment and used.

Antifungal test procedure

Candida albicans (ATCC 10231) strain was used as a test organism to evaluate the antifungal activity of textile samples. Warp-knitted cotton fabrics were cut into 1×1 cm squares and sterilised under UV light. Fungal suspension containing approximately 10^6 CFU/mL was prepared using phosphate-buffered saline (PBS) at pH 7.2. The suitability of the suspension was confirmed by inoculating with serial dilutions at 1:10 and 1:100 on Sabouraud Dextrose Agar (SDA) by the spread plate method and colony formation in the range of 30–300 CFU. The antifungal activity test protocol was based on modifications of the JIS L 1902:2002 and ISO 20743:2013 standards for antimicrobial testing of textiles [37].

Each procedure was carried out with four parallel samples. Accordingly, sixteen samples from each fabric type were placed in sterile Petri dishes. 0.1 mL of previously verified fungal suspension was applied to each piece of fabric by taking it with a pipette. This application was recorded as T_0 (start). Petri dishes were kept partially closed at 22±3 ºC and 50±5% relative humidity for 4 hours in order to ensure the interaction of fungal cells with the fabric. After this period, the dishes were kept at 30°C in dark conditions for incubation.

Incubation periods were determined as 7, 14, 21 and 28 days. At each time point, the fabric pieces were taken into separate sterile tubes and 5 mL of sterile PBS (containing 0.2% Tween80) was added and vortexed for 30 seconds, thus ensuring complete separation of fungal cells from the fabric. Serial dilutions were prepared from the obtained suspensions at 1:10 and 1:100 ratios; 0.1 mL of each dilution was taken and plated on the SDA surface using the spread plate method. The plates were incubated at 30 ºC for 48 hours; then the colonies formed were counted manually. The countable colony range was accepted as 30–300 CFU.

RESULTS AND DISCUSSION

SEM Analysis

Figures 1–4 present the SEM images and EDS spectra of untreated and treated warp-knitted cotton fabrics. The SEM micrograph of the untreated fabric (figure 1, *a*) revealed a smooth fibre surface, with no detectable chemical particles. Furthermore, EDS analysis of the untreated cotton fabric (figure 1, *b*) identified carbon (C) and oxygen (O) as the primary elemental constituents. The weight, atomic, and theoretical percentages of these elements aligned with the expected composition of cellulose-based materials under standard conditions [38].

In contrast, SEM analysis of the treated samples demonstrated a uniform distribution of chemical particles across the fibre surface, with no evidence of particle agglomeration. It was observed that fibre deposition of chemical particles was lower at 0.5% concentration (figure 2, *a*, figure 3, *a* and figure 4, *a*) and higher at 1% concentration (figure 2, *b*, figure 3, *b* and figure 4, *b*). Furthermore, it was observed that copper-based particles were more densely distributed and exhibited stronger adhesion on the yarn surfaces, whereas this effect diminished progressively in the silver- and zinc-based samples. Additionally, EDS elemental analysis of the treated samples confirmed that the weight and atomic ratios were in agreement with the theoretical values.

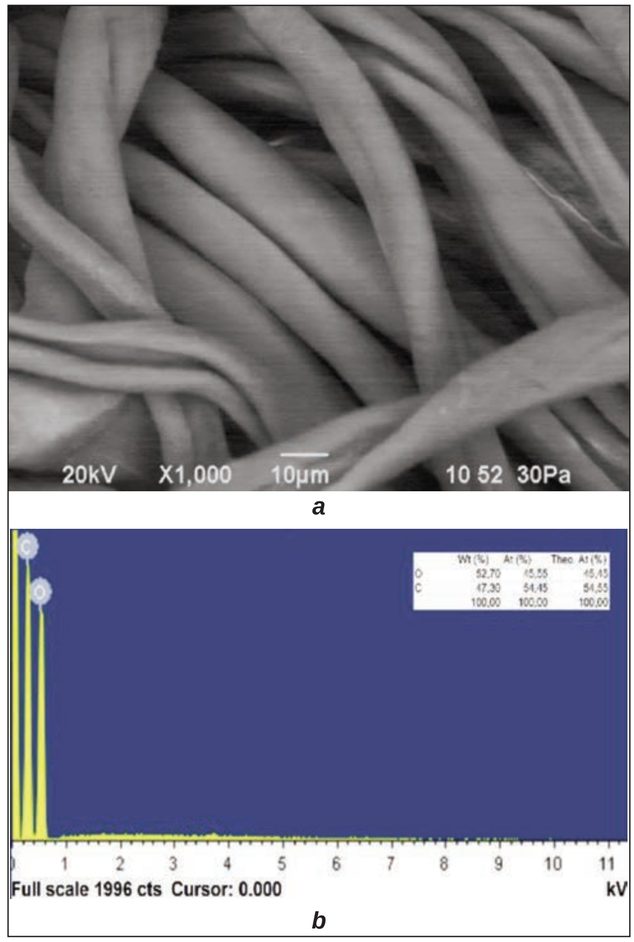

Fig. 1. SEM and EDS micrographs of untreated cotton fabric: *a* – SEM; *b* – EDS

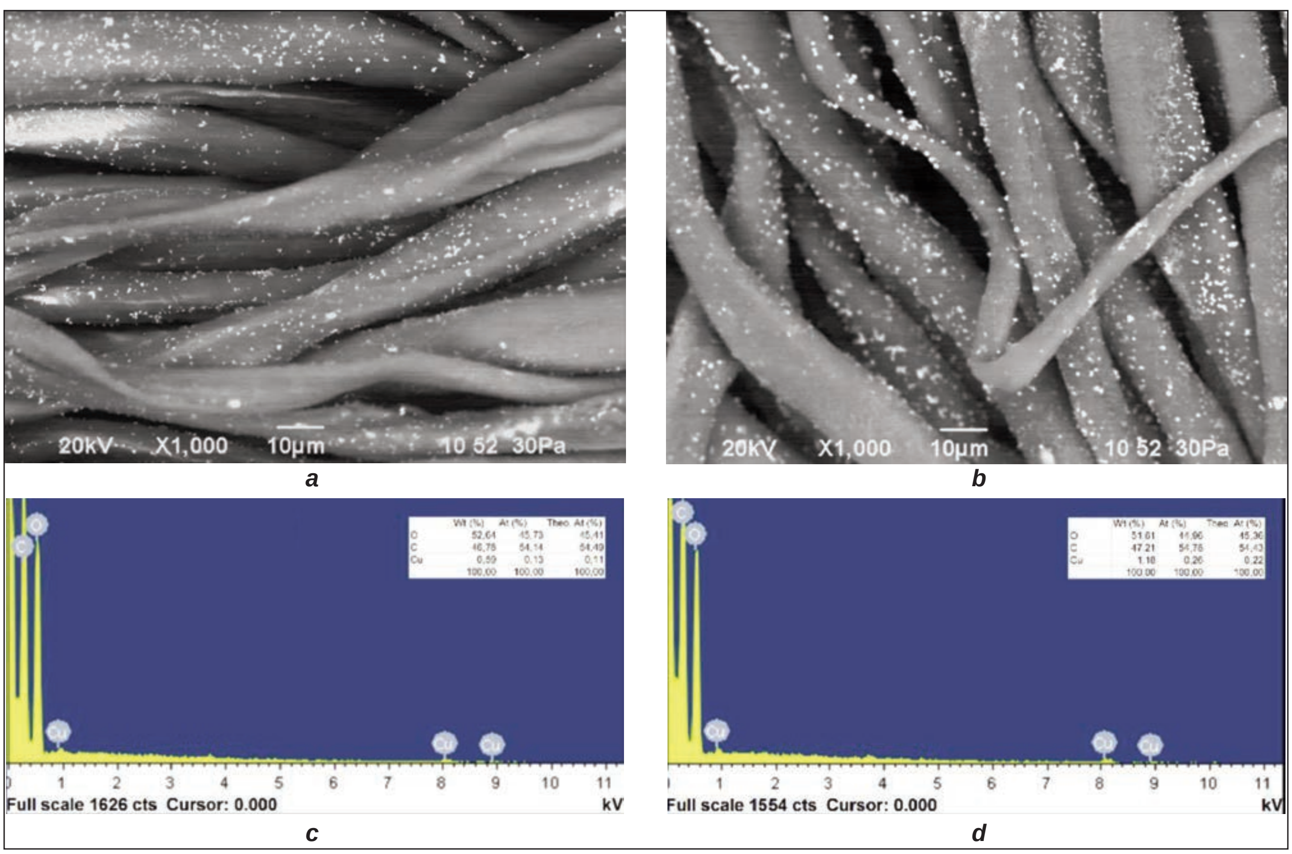

Fig. 2. SEM and EDS micrographs of Cu treated cotton fabric: *a* – SEM pictures of Cu-0.5%; *b* – SEM pictures of Cu-1%; *c* – EDS spectra of Cu-0.5%; *d* – EDS spectra of Cu-1%

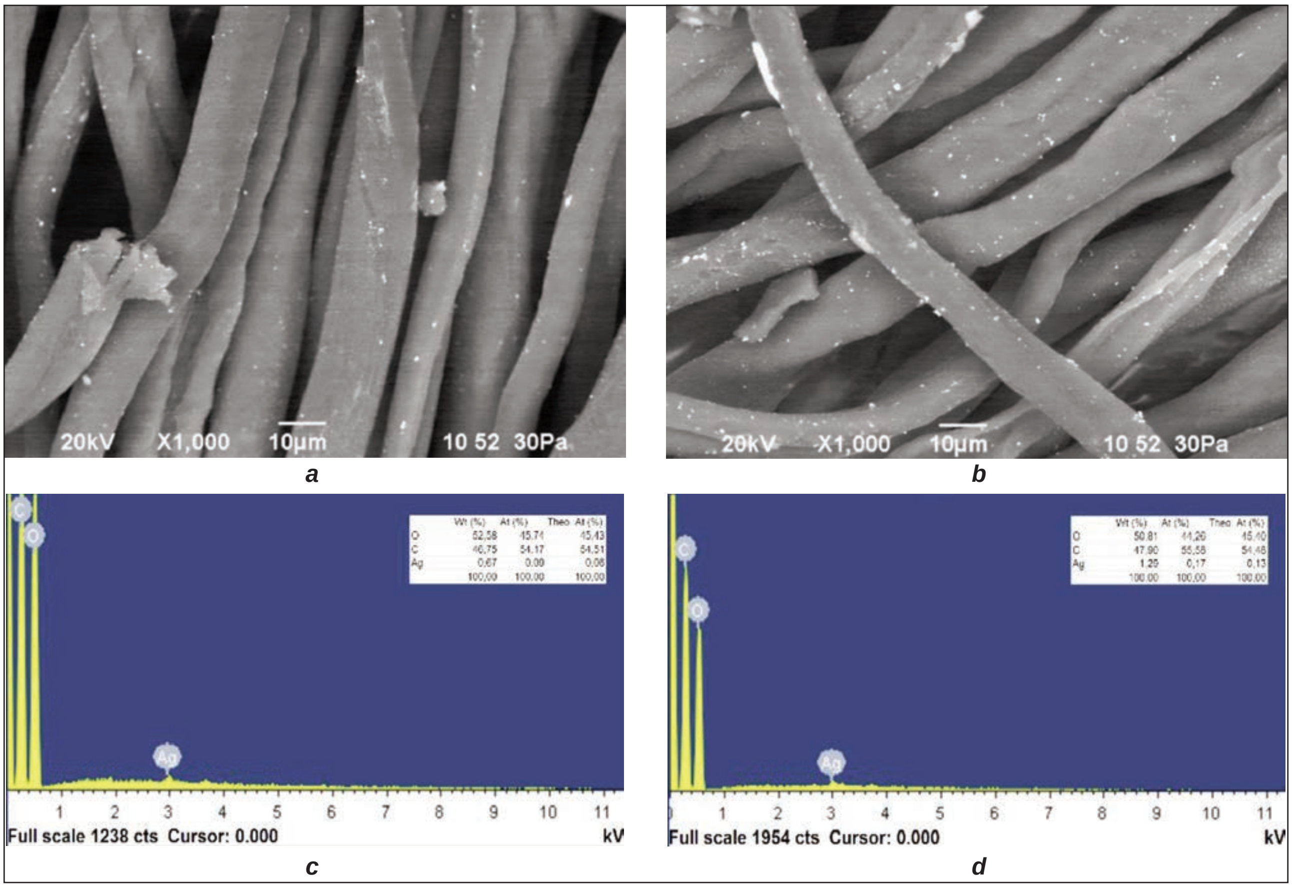

Fig. 3. SEM and EDS micrographs of Ag-treated cotton fabric: *a* – SEM pictures of Ag-0.5%; *b* – SEM pictures of Ag-1%; *c* – EDS spectra of Ag-0.5%; *d* – EDS spectra of Ag-1%

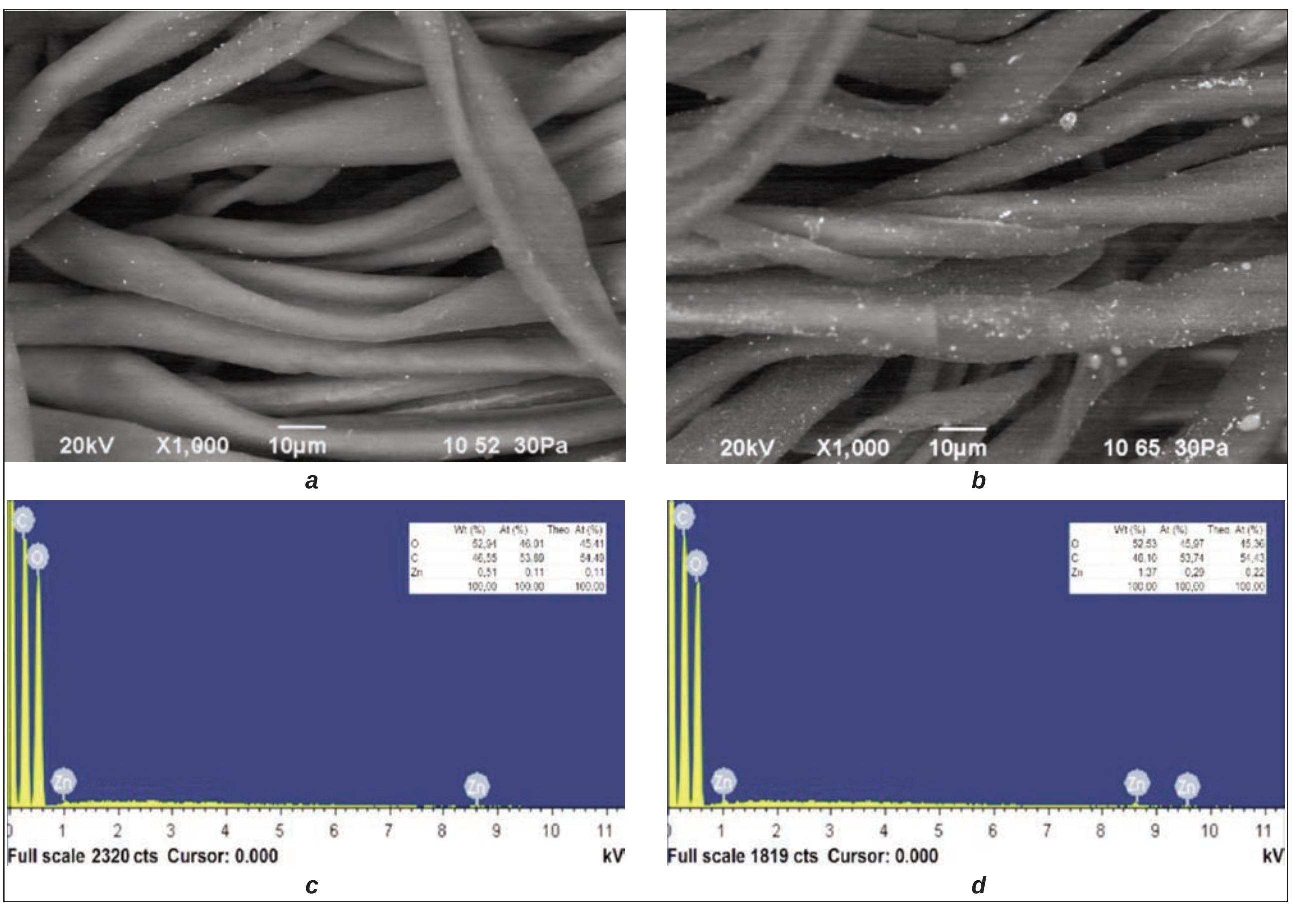

Fig. 4. SEM and EDS micrographs of Zn-treated cotton fabric: *a* – SEM pictures of Zn-0.5%; *b* – SEM pictures of Zn-1%; *c* – EDS spectra of Zn-0.5%; *d* – EDS spectra of Zn-1%

FTIR analysis

FTIR analysis of cotton fabric treated with sodium tetrahydroxocuprate (II)

FTIR spectrum of untreated and sodium tetrahydroxocuprate (II) (Cu) treated cotton fabric samples is depicted in figure 5. The peak observed at 3300 cm^{-1} corresponds to O–H stretching and appears as a broad band due to hydrogen bonding between the -OH groups. This frequency range also encompasses both intermolecular and intramolecular hydrogen bond vibrations in cellulose. A broad peak observed between 3000–2800 cm^{-1} is attributed to C–H stretching, a characteristic feature of all hydrocarbons [39–41]. The peak at 1428 cm^{-1} is associated with CH_2 scissoring, which shifts to 1420 cm^{-1} for the Cu-1% sample, accompanied by a decrease in intensity [42]. The peak at 1161 cm^{-1} is related to the anti-symmetric C(1)–O–C(4) bridge stretching mode, which slightly shifts to 1156 cm^{-1} for the Cu-0,5% and Cu-1% samples, respectively [43, 44]. The peak at 1105 cm^{-1} represents the asymmetric ring stretching mode and disappears in the treated cotton samples [45]. The peak at 1050 cm^{-1} is assigned to C–O stretching, with a notable reduction in intensity for the treated cotton fabrics [46]. The peak at 897 cm^{-1} is linked to the β-linkage of cellulose that can determine the degree of crystallinity [42, 47, 48]. The peak at 1024 cm^{-1}, associated with the C–O bond [49], shifts to 1020 cm^{-1} for the treated samples. Additionally, the peak at 665 cm^{-1}, attributed to -OH out-of-plane bending of cellulose, shows a significant decrease in intensity for the treated samples [42]. It is also observed that the peaks in the fingerprint region (550–600 cm^{-1}) for untreated and Cu-0,5% samples nearly vanish in the Cu-1% sample.

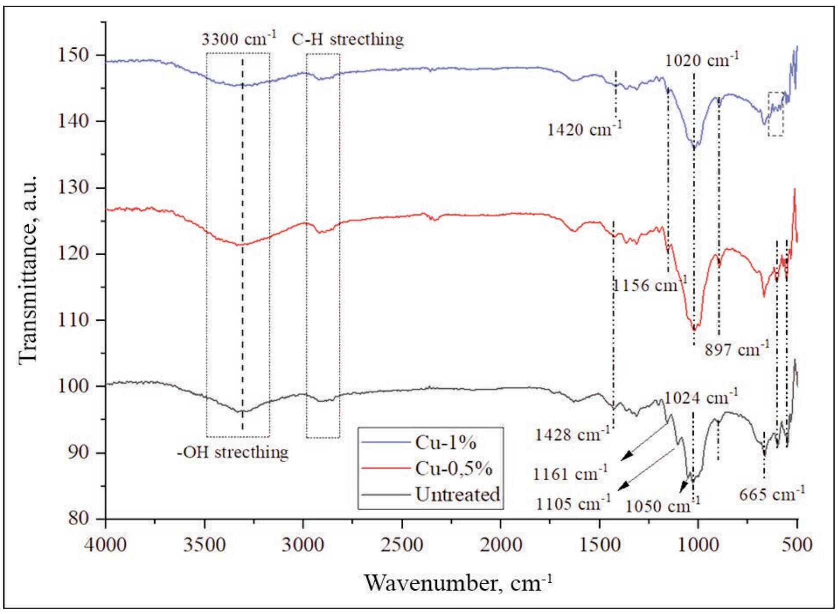

Fig. 5. FTIR spectra of untreated and Cu treated cotton fabrics

FTIR analysis of cotton fabric treated with diamine silver compound

Figure 6 presents the FTIR spectra of untreated and treated cotton fabrics impregnated with diamine silver compound (Ag). In general, the untreated cotton sample displays characteristic peaks corresponding to cotton cellulose. However, for the treated samples, some of these peaks exhibit shifts, and their intensities have been modified. The broad peak observed at 1620 cm^{-1}, which is typically associated with the bending vibration of OH groups [50], shifts to 1636 cm^{-1} for Ag-0.5% and Ag-1% samples.

Additionally, the peak at 1105 cm^{-1}, corresponding to the C-O-C glycosidic ether bond, almost completely disappears in the treated samples [51]. Another prominent peak, characteristic of cotton cellulose at 897 cm^{-1}, shifts to 893 cm^{-1} in the treated fabrics. These changes in peak positions and intensities suggest potential molecular interactions between the cellulose and the diamine silver compound.

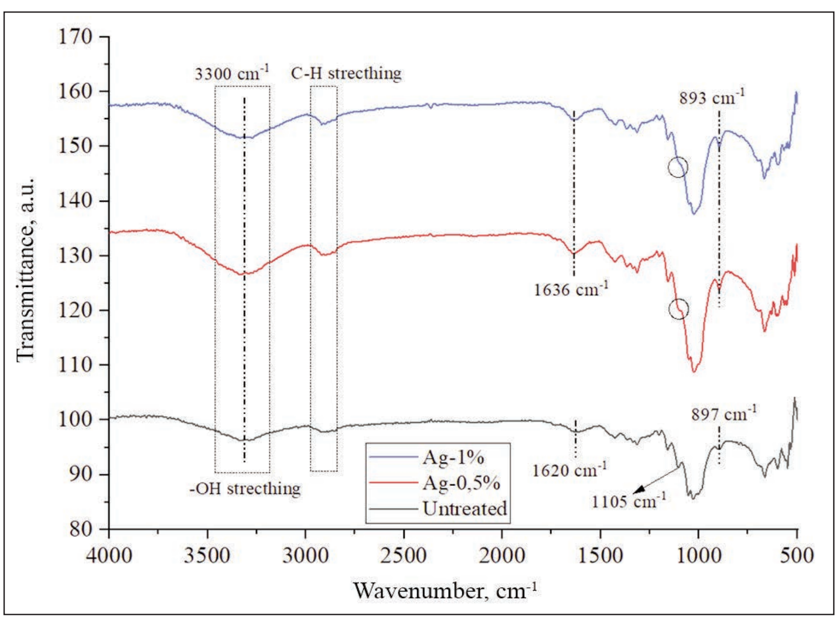

Fig. 6. FTIR spectra of untreated and Ag-treated cotton fabrics

FTIR analysis of cotton fabric treated with sodium zincate

Figure 7 illustrates the FTIR spectra of untreated and treated cotton fibres coated with sodium zincate (Zn). Overall, the untreated cotton sample exhibits distinct peaks associated with cotton cellulose; however, for the treated samples, some of these peaks undergo shifts, and their intensities are altered. The broad peak at 1620 cm^{-1}, typically attributed to the bending vibration of OH groups [50], shifts to 1644 cm^{-1} for the Zn-0.5% sample and completely disappears for the Zn-1% sample. The peak at 1428 cm^{-1}, corresponding to CH_2 scissoring [45], is absent in the treated samples. Additionally, the peak at 1050 cm^{-1}, assigned to C–O stretching, shows a noticeable reduction in intensity for the treated cotton fibres [46]. These observed changes in peak positions and intensities suggest the occurrence of molecular interactions between the cellulose and the sodium zincate.

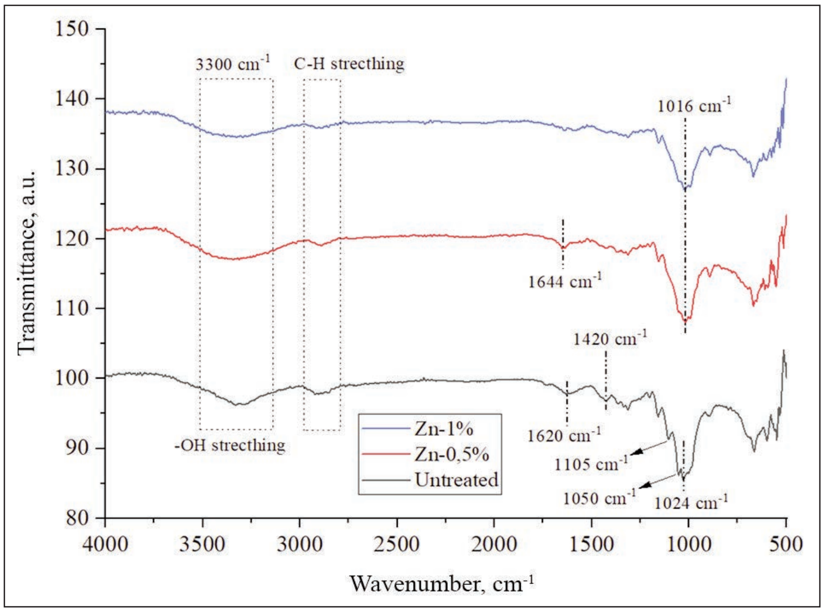

Fig. 7. FTIR spectra of untreated and Zn-treated cotton fabrics

Antifungal activity of the treated samples

The antifungal efficacy of Cu-, Ag-, and Zn-based compounds, applied at varying concentrations, was assessed based on their impact on *Candida albicans* over incubation periods of 7, 14, 21, and 28 days (the initial stage of the loaded petri dishes has been presented in figure 8). All tests were initiated with a fungal load of 10^6 CFU, and reductions in viable fungal cells were quantified as log_{10} values. The residual CFU counts were presented on a logarithmic scale. The corresponding quantitative results are summarised in table 3. Based on these findings, the temporal variation in antifungal activity at concentrations of 0.5% and 1% for each metal compound is graphically illustrated in figures 9 and 10, respectively.

The highest antifungal effect was observed in samples containing Cu. At the end of the 7th day, the fungal load decreased to the level of 10^2 with a decrease of 4 log_{10} (10,000-fold decrease) for Cu-1% sample as well as 3.74 log_{10} for Cu-0,5%. Although this effect partially decreased over time, the fabrics treated with Cu maintained their strong antifungal properties even on the 28th day. This is consistent with previous reports by Nosheen et al. [52], who demonstrated significant antifungal activity in copper-treated fabrics using electrolytic deposition techniques. The antifungal effect, which persisted over four weeks, may be due to disruption of the fungal cell membrane, the formation of reactive oxygen species (ROS), and the mechanism of enzymatic systems, as reported by Swierczynska and Kudzin [53]. These versatile mechanisms of action enable copper ions (Cu^{2+}) to act rapidly and extensively on fungal cells, making copper one of the most promising antifungal agents for long-term hygienic applications [54–56].

In Ag-treated samples, a maximum reduction of 3.04 log_{10} was achieved on day 7 (approximately 1000-fold) for Ag-1% sample as well as 3 log_{10} for Ag-0,5%. This is consistent with previous studies by Arenas-Chávez et al. [57], which highlighted the inhibitory potential of Ag-based nanocomposites against *Candida albicans*. The level of antifungal effect was largely maintained over time, with only a small decrease observed. The stability of the antifungal effect of silver over 28 days confirms the findings of Hedayati et al. [58], who emphasised the sustained release of Ag

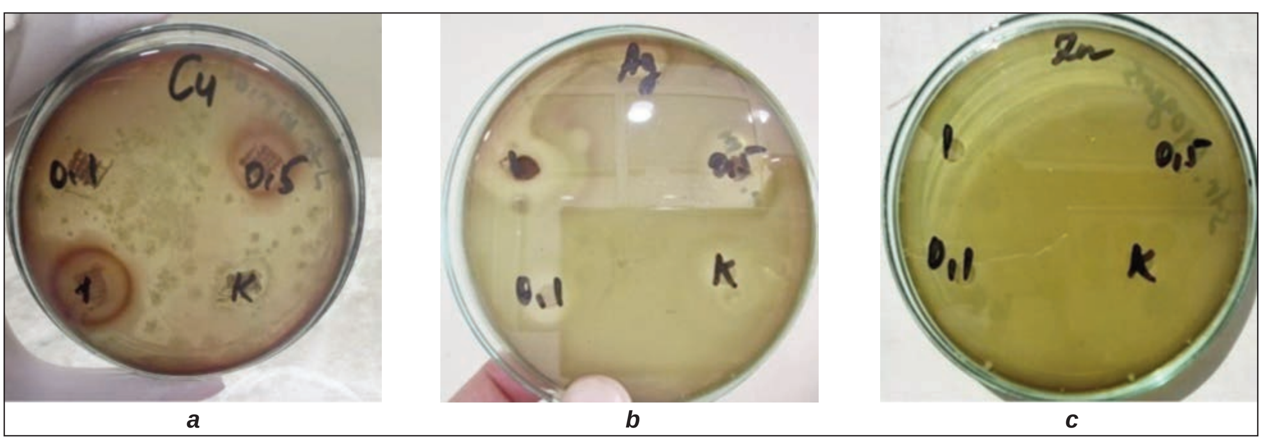

Fig. 8. Initial stage of the antifungal tests of metal coated warp knitted cotton samples: *a* – Petri dish including Cu coated samples; *b* – Petri dish having Ag-treated samples; *c* – Petri dish with Zn-coated samples

Table 3

ANTIFUNGAL TEST RESULTS OF THE TREATED SAMPLES				
Microorganism/day	**Cu-1%**		**Cu-0.5%**	
	Final CFU*	**Logarithmic decrease**	**Final CFU***	**Logarithmic decrease**
Candida albicans 7th day	0	log 4	18	log 3.74
Candida albicans 14th day	21	log 3.67	62	log 3.20
Candida albicans 21st day	41	log 3.42	73	log 3.12
Candida albicans 28th day	59	log 3.23	81	log 3.07
Microorganism/day	**Ag-1%**		**Ag-0.5%**	
	Final CFU*	**Logarithmic decrease**	**Final CFU***	**Logarithmic decrease**
Candida albicans 7th day	90	log 3.04	101	log 3
Candida albicans 14th day	94	log 3.02	117	log 2.93
Candida albicans 21st day	96	log 3.01	135	log 2.86
Candida albicans 28th day	97	log 3.01	151	log 2.82
Microorganism/day	**Zn-1%**		**Zn-0.5%**	
	Final CFU*	**Logarithmic decrease**	**Final CFU***	**Logarithmic decrease**
Candida albicans 7th day	60	log 3.22	145	log 2.83
Candida albicans 14th day	71	log 3.14	172	log 2.76
Candida albicans 21st day	76	log 3.12	178	log 2.74
Candida albicans 28th day	79	log 3.1	183	log 2.73

Note: *Following the antifungal assessment of the metal-coated samples, a residual microbial load of 10^6 colony-forming units (CFU) was detected in the culture medium.

and its surface interaction with microbial membranes. Although silver is generally known for its strong antimicrobial effect, in this study, its effect on *Candida albicans* was slightly weaker than Cu. This may be due to the lower ion exchange rate of Ag in the fabric matrix or the intrinsic resistance of *Candida albicans* to silver; this was also noted by Nasrollahi et al. [37]. Furthermore, factors such as particle size and coating homogeneity may have influenced the effectiveness of Ag, as previously shown in studies by Perelshtein et al. [59] and Gutarowska & Michalski [60].

Antifungal activity in textile samples treated with zinc ions was shown to be between 3.22 $\log_{10}$ for Zn-1% sample as well as 2.83 $\log_{10}$ for Zn-0,5% on the 7th day, supporting previous studies by Roy et al. [61] and Kudzin et al. [62] demonstrating that ZnO nanoparticles are effective antifungal agents when dispersed homogeneously. Although Zn ions are less soluble than Cu and Ag ions [62, 63], their interaction with microbial enzymes and membrane destabilisation mechanisms remains important [64]. The lower but stable antifungal performance observed here is consistent with the findings of Emam and Abdelhameed [65], who highlighted the photostability of Zn-based coatings on cotton surfaces. Furthermore, the relatively lower toxicity of zinc compared to copper

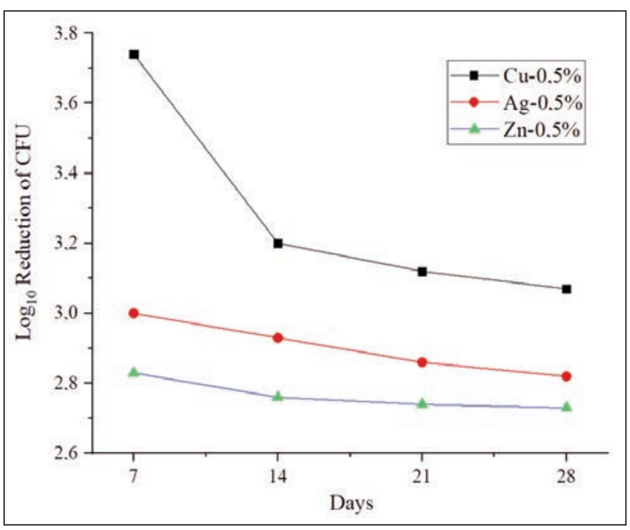

Fig. 9. Antifungal activity of 0,5% metal treated samples over 28 days

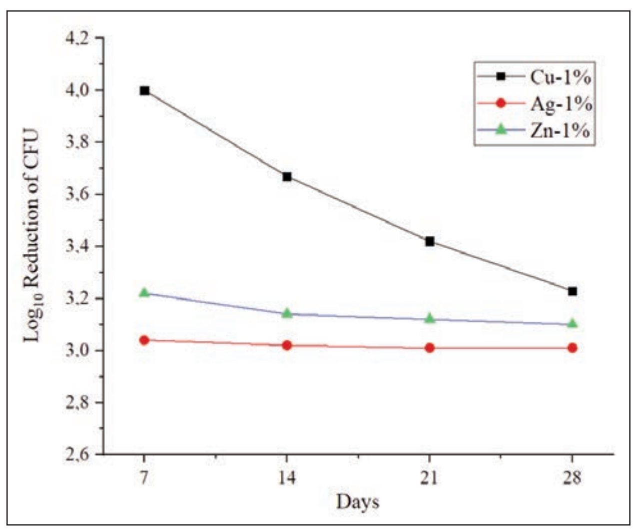

Fig. 10. Antifungal activity of 1% metal treated samples over 28 days

makes it a suitable candidate for applications where prolonged skin contact is expected.

The comparative analysis demonstrates that textiles treated with a 1% concentration of metal complexes exhibited superior antifungal efficacy compared to those treated with a 0.5% concentration. It has also been observed that Cu based compound is particularly suitable for antifungal needs in healthcare or high-risk health environments. Ag and Zn-based compounds, although less effective, are thought to provide more stable and predictable long-term protection in applications where gradual ion release is critical [57, 64, 66]. The cost-effectiveness of Cu [56], combined with the biocompatibility of Zn and the broad-spectrum activity of Ag [67, 68], suggests that the appropriate metal selection should be tailored to the intended textile application.

CONCLUSION

This study demonstrated effective synthesis and application of copper, silver, and zinc metal complexes onto warp-knitted cotton fabrics, verified by SEM, EDS, and FTIR analyses, which confirmed uniform particle distribution and molecular interactions with cellulose. Antifungal testing against *Candida albicans* revealed that copper-treated fabrics at 1% concentration achieved the highest antifungal activity, reducing fungal load by 4.00 log_{10} (from 10^6 to 10^2 CFU) within 7 days and maintaining significant efficacy through 28 days. Copper at 0.5% concentration also showed strong activity with a 3.74 log_{10} reduction at day 7. Silver treatments at 1% and 0.5% concentrations yielded reductions of 3.04 and 3.00 log_{10}, respectively, on day 7, maintaining stable antifungal performance over 28 days. Zinc-treated fabrics at 1% and 0.5% concentrations showed reductions of 3.22 and 2.83 log_{10} at day 7, with consistent but lower activity compared to copper and silver. Across all metals, 1% concentration treatments outperformed 0.5%, confirming the positive impact of higher metal loading on antifungal efficacy. The rapid and sustained reduction in fungal viability highlights copper's superior biocidal action, making it optimal for healthcare and high-risk applications. Silver and zinc offer reliable and biocompatible alternatives suited for applications requiring prolonged antimicrobial effects. These quantitative results provide a basis for selecting appropriate metal-based antifungal treatments tailored to specific textile applications, balancing efficacy, durability, cost, and safety.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to Akdeniz University (Antalya, Turkey) and Accredited Training and Testing Laboratory "CENTEXUZ" (Tashkent, Uzbekistan) for supporting the experimental part of this study, as well as for the cooperation between the universities.

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Proof-of-concept evaluation of textile waste upcycling through patchwork bedspread design

DOI: 10.35530/IT.077.01.2025114

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ABSTRACT – REZUMAT

Proof-of-concept evaluation of textile waste upcycling through patchwork bedspread design

This pilot study investigates the performance characteristics of bedspreads produced through an upcycling-oriented design approach using the patchwork technique, compared to conventionally manufactured counterparts. Textile waste materials sourced from Zorluteks Tekstil Sanayi ve Ticaret A.Ş., certified by OEKO-TEX® STANDARD 100 and OEKO-TEX® STeP, were reprocessed into single-bed-sized bedspreads in accordance with sustainable design principles. Both upcycled and conventional bedspreads were composed of three layers, including regenerated fibre filling and 100% cotton woven fabric. Comprehensive testing was conducted to assess washing fastness, perspiration fastness (acidic and alkaline), rubbing fastness, water fastness, dimensional stability, tensile strength, and seam slippage tests in accordance with ISO standards. Exploratory statistical analysis indicated no clear differences in most fastness properties, except for alkaline perspiration fastness, where patchwork samples showed slightly reduced performance due to fabric heterogeneity. Notably, upcycled samples demonstrated higher tensile strength, attributed to increased stitching density, but exhibited greater seam slippage, likely due to multi-fabric assembly. These findings suggest that upcycled textile products, when manufactured using optimised methods, can match or exceed the mechanical and functional performance of conventional products, positioning upcycling as a viable industrial strategy for sustainable textile production.

Keywords: *upcycling, bedspread, patchwork, textile waste, sustainability*

Evaluarea practică a reciclării deșeurilor textile prin proiectarea de cuverturi de pat realizate prin tehnica patchwork

Acest studiu pilot investighează caracteristicile de performanță ale cuverturilor de pat produse printr-o abordare de design orientată spre reciclare, utilizând tehnica patchwork, în comparație cu cele fabricate în mod convențional. Deșeurile textile provenite de la Zorluteks Tekstil Sanayi ve Ticaret A.Ş., certificate de OEKO-TEX® STANDARD 100 și OEKO-TEX® STeP, au fost reprocesate în cuverturi de pat de dimensiuni pentru o persoană, în conformitate cu principiile de design durabil. Atât cuverturile reciclate, cât și cele convenționale erau compuse din trei straturi, inclusiv umplutură din fibre regenerate și țesătură 100% bumbac. Au fost efectuate teste cuprinzătoare pentru a evalua rezistența la spălare, rezistența la transpirație (acidă și alcalină), rezistența la frecare, rezistența la apă, stabilitatea dimensională, rezistența la tracțiune și testele de alunecare a îmbinărilor, în conformitate cu standardele ISO. Analiza statistică exploratorie nu a indicat diferențe clare în majoritatea proprietăților de rezistență, cu excepția rezistenței la transpirație alcalină, unde probele peticite au prezentat o performanță ușor redusă din cauza eterogenității țesăturii. În mod remarcabil, probele reciclate au demonstrat o rezistență la tracțiune mai mare, atribuită densității crescute a îmbinărilor, dar au prezentat o alunecare mai mare a cusăturilor, probabil din cauza asamblării mai multor țesături. Aceste constatări sugerează că produsele textile reciclate, atunci când sunt fabricate folosind metode optimizate, pot egala sau depăși performanțele mecanice și funcționale ale produselor convenționale, poziționând reciclarea ca o strategie industrială viabilă pentru producția durabilă de textile.

Cuvinte-cheie*: reciclare, cuvertură de pat, tehnica patchwork, deșeuri textile, durabilitate*

INTRODUCTION

Sustainability consists of a multilayered structure including sustainable materials, water and energy consumption, circular economy and recycling, social sustainability, and ethical production. Natural ingredients and recycled materials have frequently been used in studies on sustainable materials. Shen et al., by assessing the carbon footprint of recycled PET (rPET) fibres, found that they had a 32% lower environmental impact compared to conventional polyester production. Additionally, cotton was identified as the least preferred option due to its high ecotoxicity effects, eutrophication, and water and land use [1]. Another study highlighted the environmental benefits of natural fibres as composite materials by conducting a comprehensive review. Biodegradable composites have been found to show significant potential for use in sustainable packaging [2]. Sandin et al. analysed the environmental impacts of recycled cotton and polyester using a comparative life cycle assessment (LCA) method. The study describes potential barriers to achieving environmental benefits by increasing the reuse and recycling of textiles [3].

Apart from these, many biologically based materials such as mycelium [4], spider silk [5], bacterial cellulose [6], pineapple fibres [7] are also used for sustainability purposes.
Sustainable resource management and circular economy approaches aim to minimise material waste in production and consumption systems and use natural resources more efficiently. In this context, recycling and upcycling stand out as two important methods of waste management. While both approaches aim to utilise waste, they differ in terms of method, output, and environmental impact. Recycling is the reintegration of waste materials into the production process by transforming them into raw materials through physical or chemical processes. The principle of sustainability is achieved through recycling practices for textile products obtained from different production sources, such as yarn production, weaving, knitting, and ready-made clothing, which can be used in many industries [8]. Upcycling is the reprocessing of waste or unused products in a way that increases their value and transforms them into new functional products. Unlike recycling, in this method, the recycled material is produced without altering the physical or chemical structure of the material, resulting in a new product with a higher value or quality than the original product [3]. Upcycling techniques are divided into many areas, including physical methods, deconstruction & reconstruction, patchwork, function-based repurposing, and modular upcycling. The upcycled product created with the patchwork technique is a unique product with higher value than the original and can be reused and recycled many times [9].
This study compared the performance characteristics of a bedspread produced using patchwork, a frequently used upcycling method for home textile waste, with a traditionally produced bedspread, and evaluated their potential uses. To this end, the production processes, fabric parameters, and tests for washing, perspiration (acid and alkali), rubbing, water, dimensional stability, tensile strength, and seam slippage were conducted on two different home textile products. The test results were statistically analysed. This study was carried out with a limited sample and is a conceptual pilot trial.

GENERAL INFORMATION

Upcycling is a type of recycling process that transforms low-value materials into higher-value products. Because many fashion apparel products contain non-biodegradable chemicals that can harm the environment after disposal, the recycling of waste textiles has gained importance [10]. In this regard, many physical, thermal, and chemical processes are performed. Thermochemical conversion processes are technologically and economically viable options for processing low-value carbonaceous raw materials [11]. Pyrolysis, the thermal decomposition of carbonaceous components in an oxygen-free environment, is the most common thermochemical method [12]. Composite grinding is frequently used in mechanical recycling. The ground materials can be used as fillers in short-fibre composites [13]. While these conversion methods generally focus on the repurposing of industrial waste, the upcycling approach is not limited to industrial waste. In the textile sector, upcycling applications shaped by creative and aesthetic concerns are also gaining increasing importance. Upcycling applications in textiles involve the dismantling of outdated clothing and transforming it into new design products, adding aesthetic and functional value through techniques such as patchwork. In this context, patchwork is considered not only a sustainable production method but also a form of artistic expression that preserves cultural heritage. Patchwork is the art of creating a new surface by combining small pieces of fabric. Patchwork is a part of popular art and a language that expresses the culture and traditions of each nation [14].

METHODOLOGY

Materials

The study used 100% cotton woven fabric and 100% regenerated fibre, supplied by Zorluteks Tekstil Sanayi ve Ticaret A.Ş., holding OEKO-TEX® STANDARD 100 and OEKO-TEX® STeP certifications. The bedspreads are composed of three layers. The surface, produced using a patchwork technique using 100% cotton fabric and waste materials, is combined with 100% cotton fabric and a layer of regenerated fibre is added in between. Similarly, the bedspread, which contains no waste materials, was also produced using the same materials.

Methods

In this study, unused waste fabrics at Zorluteks Tekstil Sanayi ve Ticaret A.Ş. were repurposed using the patchwork method to fit the dimensions of a single bedspread. Within the scope of the study, a single bedspread made of reinforced fabrics was produced in accordance with the design principles. During the production process, unused or torn bedspread fabrics were cut to specific sizes, brought together, and stitched together (figure 1). In the later stages, the bedspread was prepared as a two-layered bed cover using regenerated fibre material (figure 1, *a*) and cut to fit the single size. 100% cotton woven white fabric was preferred for the back part, figure 1, *b*, and piping was used to close the edges of the bedspread. In the final stage, before the three layers of the bedspread were joined, an overlock process was applied, and then the edges were closed with piping. Stitching was done to secure the three layers. All sewing operations were carried out using a JUKI-CP-180 lockstitch sewing machine and a JUKI MO-6814S, YUKI YK 500T 02 piping machine. With this method, waste fabrics were re-evaluated, and environmental sustainability goals were contributed to. Within the scope of the study, fabric parameters, washing fastness, perspiration fastness (acid and alkali), rubbing fastness, water fastness, dimensional

a b c

Fig. 1. Parts of the bedspread formed in 3 layers: *a* – regenerated fibre; *b* – outer patchwork surface; *c* – 100% cotton fabric

Table 1

TEST METHODS STANDARDS	
Tests	**Test methods**
Washing fastness-staining	ISO105C06 60°C ECE + sodium perborat (50 ml)
Perspiration fastness	ISO105E04
Rubbing fastness	ISO105X12'
Water fastness	ISO105E01
pH value	ISO3071-2020
Fabric weight	ISO3801-NEXTTM20
Dimensional stability	ISO63302A 60°C Tumble Dry
Tensile strength	ISO13934-1(100 mm/sec).
Seam slippage	13936-1 seam opening 6 mm (50 mm /sec)

stability, tensile strength, and seam slippage tests were performed. The test standards for the measurements are given in the table 1.

RESULTS AND DISCUSSIONS

Production of bedspreads and the characteristic properties of fabrics

Within the scope of the study, Zorluteks Tekstil Sanayi ve Ticaret A.Ş. produced a three-layer bedspread, currently in mass production, and a bedspread made using a patchwork technique from scrap pieces from mass production. The bedspread (B), produced using a patchwork technique, was assembled from 17 different pieces and has the same fibre and backing as the mass-produced sample (A). The fabric parameters for both products are provided in table 2.

The data obtained in the study were analysed using the SPSS 25.0 statistical package program.

Descriptive statistics were used for the study using mean and standard deviation values. In this study, an independent samples t-test was used to compare the test results of two different fabric types. Normality analyses were conducted using the Kolmogorov-Smirnov test, skewness, and kurtosis values.

A significance level of $p<0.05$ was accepted in the analyses.

Washing fastness

As part of the study, colour fastness analysis was conducted. The results showed that both samples achieved values between 4 and (table 3). This result indicates a high level of colour fastness. The fact that sample code B demonstrated this performance demonstrates that the reassembled fabric pieces maintained their quality standards. It is known that upcycled products can achieve colour fastness values

Table 2

FABRIC PROPERTIES OF BEDSPREADS					
Coding	**Weight (g/m^2)**	**pH**	**Weft fabric count (thr/cm)**	**Warp fabric count (thr/cm)**	**View**
A	487.7	6.2	50	80	
B	760.3	6.8	60	90	

like conventional products when processed using the correct techniques [10].

Table 3

COLOUR FASTNESS TO WASHING						
Coding	**Washing fastness-staining**					
	CA	**CO**	**PA**	**PET**	**PAN**	**WO**
A	4-5	4-5	4-5	4-5	4-5	4-5
B	4-5	4-5	4-5	4-5	4-5	4-5

Perspiration fastness

In the perspiration fastness measurements carried out within the scope of the study, a decrease of 4-5 points was observed in samples A and B in an acidic environment, while a decrease of 2-3 points was observed in sample B in an alkaline environment (tables 4 and 5). The decrease in sample B indicates the instability of patchwork pieces, especially those consisting of different colours and weaves, in the alkaline environment. This supports the assertion that the variety of fabrics used in upcycling can make a difference in chemical fastness [3].

Table 4

COLOR FASTNESS TO PERSPIRATION (PH:5.5 ACID)						
Coding	**Perspiration fastness-staining (PH:5.5 ACID)**					
	CA	**CO**	**PA**	**PET**	**PAN**	**WO**
A	4-5	4-5	4-5	4-5	4-5	4-5
B	4-5	4-5	4-5	4-5	4-5	4-5

Table 5

COLOR FASTNESS TO PERSPIRATION (PH:8 ALKALI)						
Coding	**Perspiration fastness-staining (PH:8 ALKALI)**					
	CA	**CO**	**PA**	**PET**	**PAN**	**WO**
A	4-5	4-5	4-5	4-5	4-5	4-5
B	4	2-3	4	4-5	4-5	4

Rubbing fastness

In the rub fastness tests, sample A scored 4-5, and sample B scored 4 (table 6). In this case, both products were at acceptable levels, but the difference in surface thread density due to the patchwork technique caused a slight decrease in sample B. Natural fibres like cotton are known to have high rub resistance [1]. In upcycled products, this resistance depends on the number of layers and stitch density.

Table 6

COLOR FASTNESS TO RUBBING		
Coding	**Rubbing fastness-staining**	
	Dry	**Wet**
A	4-5	4-5
B	4	4

Water fastness

This test is performed to determine the tendency of a textile material to dissolve and migrate into its surroundings when it encounters water. Water fastness measurements were in the 4-5 range for both samples. This indicates that both products were dyed and fixed using high-quality dyeing and fixing processes. The different fabric production techniques did not significantly affect water fastness.

Table 7

COLOR FASTNESS TO WATER						
Coding	**Water fastness-staining**					
	CA	**CO**	**PA**	**PET**	**PAN**	**WO**
A	4-5	4-5	4-5	4-5	4-5	4-5
B	4-5	4-5	4-5	4-5	4-5	4-5

Fastness data analysis

In this study, five different test results of fabrics A and B were compared using the independent samples t-test. In the Washing fastness-staining, Perspiration fastness-staining (ACID) and Water fastness-staining tests, the means of both fabric types were the same (4.50±0.52) and no observed difference between samples was found ($p>0.05$). While no clear difference was observed in the Rubbing fastness-staining test ($p=0.139$, exploratory analysis), fabric A exhibited lower performance than fabric B in the alkaline perspiration fastness test ($p=0.045$, exploratory analysis) (table 8). Fabric A (3.92±0.79) exhibited lower performance than fabric B (4.50±0.52) in alkaline perspiration fastness ($p=0.045$, exploratory analysis).

Table 8

COMPARISON OF FASTNESS TEST RESULTS OF BEDSPREADS					
Coding	**Washing fastness-staining**	**Perspiration fastness-staining-ACID**	**Perspiration fastness-staining-ALKALI**	**Water fastness-staining**	**Rubbing fastness-staining**
A	4.50±0.52	4.50±0.52	4.50±0.52	4.50±0.52	4.5±5.78
B	4.50±0.52	4.50±0.52	3.92±0.79	4.50±0.52	4.0±0.0
Variance Homogeneity	0.988	0.988	0.887	0.988	0.059
P-Value	1.000	1.000	0.045	1.000	0.139

Dimensional stability

Dimensional stability indicates the percentage of dimension change (shrinkage or elongation) in the warp and weft directions of the fabric after any treatment. Dimensional stability is directly related to the weave type and the amount of yarn used [15]. According to the results obtained, the shrinkage of sample B produced by upcycling is higher. This is a result of the multiple stitch lines and fabric tension differences in sample B. While the average of fabric A was –3.35±1.63, the average of fabric B was found to be –1.25±1.06. The homogeneity of variance was calculated as 0.799, and the p-value as 0.007. (exploratory analysis). This result shows that there is an observed difference between samples between the two groups in the Dimensional stability test results ($p<0.05$) (table 9 and figure 2).

Table 9

DIMENSIONAL STABILITY TO WASHING AND COMPARISON OF TENSILE STRENGTH TEST RESULTS

Coding	Seam dlippage
A	–3.35±1.26
B	–1.25±0.82
Variance homogeneity	0.799
P-value	0.007

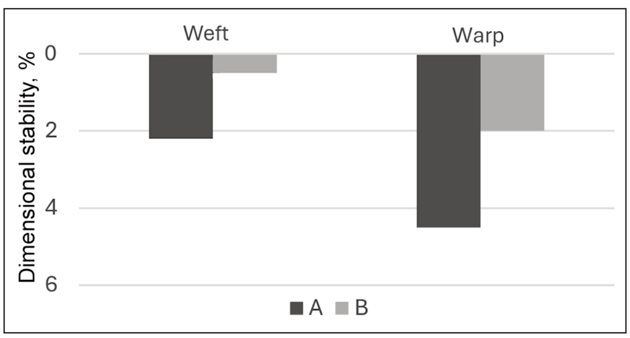

Fig. 2. Dimensional stability to washing and comparison of tensile strength test results

Tensile strength

Tensile strength analysis is a mechanical test performed to determine how long a fabric can withstand tensile forces applied in the warp and weft directions. The change in the rate of strength loss is determined by the material itself and any auxiliary materials that may affect it [16]. The higher tensile strength observed in the upcycled sample may partly stem from its higher fabric weight (760.3 g/m^2) and the presence of more sewing thread, not solely from the patchwork technique. The homogeneity of variance was calculated as 0.895, and the p-value was 0.014 (exploratory analysis). This result indicates an observed difference between samples in the Tensile strength test results between the two groups ($p<0.05$) (table 10 and figure 3).

Table 10

TENSILE STRENGTH OF BEDSPREADS AND COMPARISON OF TENSILE STRENGTH TEST RESULTS

Coding	Tensile strength (N)
A	201.50±42.17
B	255.00±12.05
Variance homogeneity	0.895
P-value	0.014

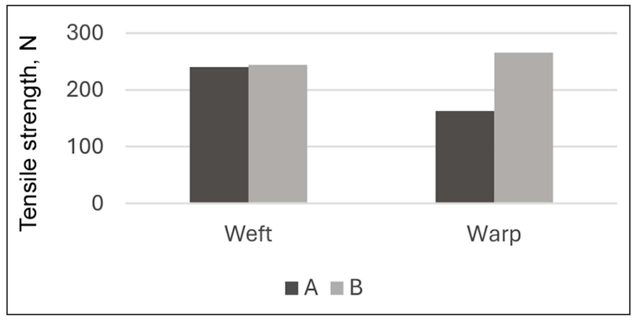

Fig. 3. Tensile strength of bedspreads and comparison of tensile strength test results

Seam slippage

The Seam Slippage is a mechanical test performed to measure the tendency of threads to separate from each other under tensile force in the seamed areas of a fabric. It is the most fundamental parameter determining the quality of the seam and the sewn fabric [17]. It tests whether threads unravel at the seams and the structural stability of the fabric in this area. Because the fabrics used in patchwork products have different properties and are made from multiple pieces, seam slippage increases. The seam slippage value for sample B is observed to be lower than that for sample A. This is due to the uneven tension distribution in the seam areas. When a seam is stretched by opening seam allowances on both sides relative to the seam line, an asymmetrical seam opening is observed. As the stitch density increases, the fabric is subjected to more stress in the seam areas. Due to the difference in material integrity and the high number of stitches, threads are more easily dislodged in some areas in the warp and weft directions in sample B, and seam slippage begins earlier (figure 4). In addition, high fabric weight is an important factor contributing to seam slippage [18–20]. The mean of fabric A was 198.25±19.14, while the mean of fabric B was 158.75±12.12. The homogeneity of variance was calculated as 0.609, and the p-value as 0.013. This result shows that there is an observed difference between the two groups in the Seam Slippage test results ($p<0.05$) (table 11).

Beyond mechanical and fastness properties, upcycling also carries significant environmental implications. Although this study did not conduct a full LCA, insights can be drawn from existing literature. Fatima et al. observed that converting PET bottle recycling into home textiles can significantly contribute to

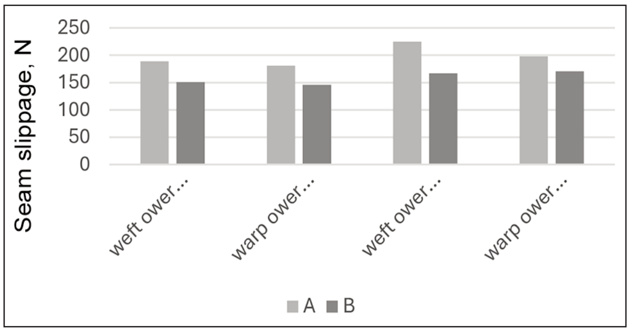

Fig. 4. Seam slippage of bedspreads

Table 11

COMPARISON OF TENSILE STRENGTH TEST RESULTS	
Coding	**Seam slippage (N)**
A	198.25±19.14
B	158.75±12.12
Variance homogeneity	0.609
P-value	0.013

material circularity while reducing environmental and economic burdens [21]. Similarly, Sandin and Peters demonstrated that textile reuse and upcycling may lead to substantial reductions in carbon emissions compared to conventional recycling or disposal pathways [3]. Incorporating a full LCA in future research would allow a quantitative comparison between upcycled patchwork products and conventionally manufactured bedspreads, thereby strengthening the environmental justification of upcycling strategies in home textiles.

Although these findings are promising, they represent preliminary insights due to the limited scope of this pilot study. Larger sample sizes, standardised fabric parameters, and additional replicates are required to validate and generalise these results.

CONCLUSIONS

The textile industry is one of the most environmentally intensive sectors in terms of water consumption, chemical use, and waste production. In recent years, interest in sustainable practices in the textile sector has rapidly increased in line with increased environmental awareness, circular economy principles, and sustainable development goals. In this context, sustainable textile production encompasses strategies focused on the use of environmentally friendly raw materials, water and energy-saving processes, the use of recycled materials, and extending product lifecycles.

This pilot study aims to explain the value and functionality of upcycling in bedspread production using the patchwork technique. It demonstrates that recycling textile waste using the patchwork technique not only preserves material value but can also improve certain mechanical properties, such as tensile strength, without compromising critical performance parameters such as washing and water fastness. While a slight decrease in alkaline perspiration fastness and higher seam slippage were observed in recycled products, these negative effects can be mitigated through optimised sewing techniques and fabric selection. A statistically significant design can produce products that meet industrial quality standards while reducing environmental impact. These findings are preliminary results of this study and are a guide for studies to be carried out with a larger sample. This pilot study is limited by the small number of specimens evaluated, as only two bedspread samples (one conventional and one upcycled) were tested. Larger sample sizes, standardised fabric parameters, and additional replicates are required to validate and generalise these results. Consequently, the observed differences should be interpreted as preliminary trends rather than definitive conclusions. This study is limited by the small number of tested samples and the variation in fabric weight and stitch density between the upcycled and conventional bedspreads. These factors may have influenced certain mechanical outcomes, particularly tensile strength and seam slippage. The findings, therefore, cannot be generalised to all upcycled or conventional bedspreads. To validate these initial observations, future studies should expand sample sizes, incorporate different textile waste compositions, and standardise material properties to better isolate the effects of upcycling techniques. These results highlight the potential of integrating recycling methodologies into large-scale textile production, thereby contributing to waste reduction, resource efficiency, and the promotion of sustainable improvements in tensile strength, and comparable results in colour fastness tests confirm that recycling-focused consumer products. Building on the preliminary findings of this pilot study, a wider range of textile waste types, including different fibres and blends, could use patchwork techniques in industrial contexts. Different usage and performance tests of these products can be applied, or consumer surveys can be conducted. Future research could explore LCA assessment of such products, assess their long-term durability, and develop standardised guidelines for industrial-scale recycling of home textiles.

ACKNOLEDGEMENTS

The authors disclose the receipt of financial support by Zorluteks Tekstil Sanayi ve Ticaret A.Ş. for the analysis and publication of this article.

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