Industria Textilă

ISSN 1222–5347

2/2025

ISI rated** journal, included in the **ISI Master Journal List** of the Institute of Science Information, Philadelphia, USA, starting with vol. 58, no. 1/2007, with **impact factor 1 and AIS 0.108 in 2023.

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

INDUSTRIA TEXTILA journal, edited by INCDTP BUCHAREST, implements and respects Regulation 2016/679/EU on the protection of individuals with regard to the processing of personal data and on the free movement of such data ("RGPD"). For information, please visit the Personal Data Processing Protection Policy link or e-mail to DPO rpd@incdtp.ro

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

Value chain analysis in technical textiles and composite materials sector: a regional case study

DOI: 10.35530/IT.076.02.202415

MEHMET KARAHAN
ALİ ARI
NEVİN KARAHAN

ABSTRACT – REZUMAT

Value chain analysis in technical textiles and composite materials sector: a regional case study

This study has been prepared as the value chain analysis for the Bursa Technical Textile and Composite Materials Cluster. The study aims to identify key actors in the value chain, competencies, and areas to be developed in the cluster ecosystem. The industrial scope of the study covers technical textiles and composite materials together, as, in many ways, Bursa enjoys the presence of sophisticated companies and strong infrastructure to specialize further and be one of the world's leading centres for the industry. Industry-level value chain analysis detailed each value chain process in terms of its main competencies and development areas. The value chain analysis reviewed the parameters of the Diamond Model to form the basis of a strategic vision for the future. Based on the findings, the report has an early-stage action plan for the cluster management team to undertake steps in the very short term, which can go hand in hand with the strategic development stage.

Keywords: *composite materials, technical textiles, value chain analysis, Bursa*

Analiza lanțului valoric în sectorul textilelor tehnice și al materialelor compozite: un studiu de caz regional

Acest studiu a fost elaborat ca analiză a lanțului valoric pentru Clusterul tehnic textil și materiale compozite din Bursa. Studiul urmărește să identifice actorii-cheie din lanțul valoric, competențele și domeniile care trebuie dezvoltate în ecosistemul clusterului. Domeniul de aplicare industrial al studiului acoperă atât textilele tehnice, cât și materialele compozite, deoarece, din multe puncte de vedere, Bursa se bucură de prezența unor companii sofisticate și a unei infrastructuri puternice pentru a se specializa în continuare și a deveni unul dintre cele mai importante centre mondiale pentru această industrie. Analiza lanțului valoric la nivel de industrie a detaliat fiecare proces al lanțului valoric în ceea ce privește principalele sale competențe și domenii de dezvoltare. Analiza lanțului valoric a revizuit parametrii modelului Diamond pentru a forma baza unei viziuni strategice pentru viitor. Pe baza constatărilor, raportul conține un plan de acțiune pentru etapa inițială, pentru ca echipa de management a clusterului să ia măsuri pe termen foarte scurt, care pot merge în paralel cu etapa de dezvoltare strategică.

Cuvinte-cheie*: materiale compozite, textile tehnice, analiza lanțului valoric, Bursa*

INTRODUCTION

The relentless progression of globalization presents an increasingly challenging environment for enterprises to maintain competitiveness [1]. The rapid pace of globalization, international trade, and advancements in communication and transportation technology have necessitated firms to engage in ongoing self-assessments due to the economic, social, and technological changes occurring worldwide [2]. The key aims for firms have been to remain relevant in a changing and evolving world, to get a larger portion of expanding markets, to transform risks into opportunities, and to ensure their survival [3].

The success of highly competitive products and services typically relies on the manufacturing company itself and the collective efforts of all the collaborating companies involved in delivering the final product or service to customers [4]. In the present era, numerous factors contribute to the intricate and ever-changing nature of companies' decision-making processes. These factors include the decreasing lifespan of products and services, necessitating the constant introduction of new offerings, evolving processes that demand swift adaptation, the arrival and departure of business partners, diverse customer preferences, alterations in distribution channels, the rapid pace of technological obsolescence, the impact of globalization, and the influence of government regulations. According to Stonebraker and Liao [5], the extent of environmental turbulence and the strategic orientation of a company directly and positively influence the extent, stages, and scope of value chain integration.

Organizations that pursue these objectives will gain a competitive edge. However, these firms must devote a significant amount of effort to ensure the long-term viability and enhance the competitive edge of enterprises. Enterprises and sectors can achieve a sustained competitive advantage by implementing strategies tailored to their individual needs and characteristics. The adoption of competitive strategies in response to changes in firms reflects the competitive standing of those firms within the industry. This situation is a crucial subject for all companies operating in the sector to consider. Porter's framework model, established to assess competitiveness, holds significant importance in this context. Within this paradigm, the critical factors that determine outcomes are "factor conditions", "demand conditions", "related and supporting industries", and "firm strategy, structure, and competition". The factors of "government" and "chance" also play a role in shaping outcomes. This type is characterized by its dynamic nature and versatility. Using this model, Porter developed a framework to evaluate the factors that determine why certain countries and enterprises, depending on the industry, are more competitive and successful than others. In 1990, Porter aimed [6] to establish a link between strategic management and international economics in his book "Competitive Advantage of Nations". He argued that trade-related theories have primarily focused on cost and needed a comprehensive understanding of competition, including segmented markets, differentiated products, technological differences, and economies of scale. Porter conducted an examination in ten countries for four years to identify factors determining competitiveness and contribute to the development of competitive structures. He developed the Diamond Model to identify factors of competitive advantage and the theoretical underpinnings of the interplay of country and industry competitiveness topics. The model consists of four corners: "factor conditions", "demand conditions", "firm strategy, structure and competition", and "the presence of related and supporting industries". Luck and government factors are also included in the system [7]. Factors affecting competitiveness include assets and skills vital for industry competitive advantage, information creating opportunities, interest group aims, and the company's power to invest and innovate [8].

Industries that rely on technology and innovation, such as composite materials, necessitate a comprehensive comprehension of the different levels or phases that make up the value chain. The basic configuration of the composites value chain consists of four tiers. The study conducted by Shakespeare and Smith [9] offers a comprehensive explanation of the various levels that make up the composite value chain. Currently, organizations prioritize the reduction of production costs for composite items. Over 70% of the manufacturing expenses are estimated to occur during the value chain design stage. Therefore, it is essential to minimize expenses during the initial stages of value chain design rather than during the production phase [10]. Value chain and logistics play a significant role in cost savings, as they account for nearly 80% of the product costs in the procurement value chain [11].

In our previous studies, technical textiles [12] and composite materials [13] market research and added value analysis were examined regionally and globally. According to our research, it has been observed that the demand for high-value-added products such as technological textiles is increasing in world markets. Over the last decade, many countries have restructured their production methods to focus on the production of these goods to increase their economic competitiveness on the global stage. World exports of technical textiles reached around 118 billion dollars, an increase of 3.38 percent compared to the previous year. Türkiye's 2021 exports amounted to 2 billion 413 billion dollars, a decrease of 12.91% compared to the previous year. The Grubel-Lloyd Index calculation for technical textile product groups in Türkiye reveals bilateral intra-industry trade, except for a few product groups. The average index value for all technical textile products was calculated at 0.7968. By 2028, it has been observed that the Mobiltech, Indutech, and Packtech subcategories of technical textiles will dominate the commercial market.

In today's global markets, the need for high-value composite products, such as technical textiles, is increasing. Over the last decade, many countries have shifted their production methods towards these goods to increase their competitiveness in the world economy. According to the data, Türkiye's composite material exports increased by 19.48 percent in 2021 compared to the previous year, reaching a total of 2.7billion lira. Based on the Grubel-Lloyd Index calculation, the study finds that intra-industry trade in Türkiye's composite material product categories is predominantly bilateral, with a few limited deviations. The average index value for composite materials was determined to be 0.6890.

The authors also studied the competitive factors in the technical textiles and composite industries [14]. According to this study, the technical textiles and composite industry has been found to significantly impact the global economy through factors such as production costs, technology, product quality, innovation, and sustainability. The growth and success of the technical textiles and composite industries depend on their ability to transform these competitive features into value-added products. Value-added goods distinguish themselves from commodity goods by offering special features, capabilities, and advantages. This allows businesses to charge higher prices and make more profits.

This paper aims to select, rank, and identify the fundamental correlations between the factors that influence the selection of manufacturing technology in a youthful and dynamic sector, such as the composite materials industry. The industrial scope of the research covers technical textiles and composite materials together, as, in many ways, Bursa enjoys the presence of sophisticated companies and strong infrastructure to further specialize and be one of the world's leading centres for the industry. This research is to perform a value chain analysis for the Bursa Technical Textile and Composite Materials Cluster. The objective of this study is to ascertain the principal participants, skills, and domains that require enhancement within the cluster ecosystem of the

Bursa Technical Textile and Composite Materials Cluster. This research aims to establish the foundation for the subsequent stages of cluster development in Bursa, particularly in terms of formulating the cluster strategy and implementation roadmap.

METHODOLOGY

The approach of cluster analysis has substantial importance to be able to understand and position competences of the cluster in consideration with future trends and directions for creating a competitive framework for the cluster and cluster companies. Unlike any traditional industry, technical textiles and composite materials are highly fragmented and have complex value chains where an in-depth understanding of industry structure, an integrated approach and a review of industry trends are needed. Before starting analysis with well-known tools such as value chain analysis and M. Porters' Diamond framework, there is a need to understand key determinants of the industry first. In the light of this main approach, this study has followed a tailor-made and well-structured analysis framework elaborating cluster environment and the industry by process, material, application and technology (figure 1).

The study is based on three main analysis tools: i) desk review, ii) value chain analysis and iii) cluster analysis (figure 2).

The findings of these analyses have been reviewed and organised through workflow and presented as follows:

1. Desk review: Desk review study aimed to review industry structure and provide a clear understanding of the industry by definition, market segments, market size and growth. Along with the industry overview, former analysis and reports conducted by the project were also reviewed and integrated into the relevant sections of the study about the current status of the industry in Bursa. As constituting secondary data collection of the study, before proceeding with further steps, desk review provided a solid insight for design and development of the tools to best fulfil aims of the work.

2. Primary data collection: The Value Chain Analysis conducted under this study has been the main analysis tool for collecting primary data. A tailor-made work has been designed in line with the industry structure. Primary data was collected through developing a survey sheet and applied through semi-structured interviews with companies and stakeholders. Throughout the study, 57 companies and key stakeholders were interviewed.

3. Data analysis: Primary and secondary data were reviewed and processed through different sector and cluster tools. Value Chain Analysis, Porters Diamond, SWOT used to analyse collected data. A draft value chain map was developed.

4. Data verification: Findings of analysis and draft value chain presented and findings were consulted through 2 workshops undertaken. Value chain map, key competences and areas for development were identified, and findings of the value chain analysis were verified.

5. Reporting: Based on the collected data, analysis and views gathered from stakeholders and cluster companies, the value chain map was finalised and reporting work undertaken.

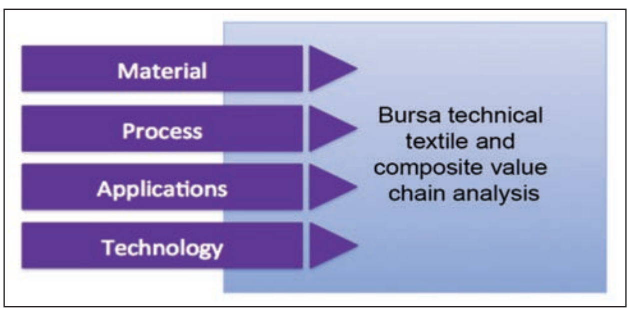


Fig. 1. Value chain analysis context

INDUSTRY DEFINITION

Technical textiles

Technical textiles are high-performance textiles with special functionalities used in various industries, including automotive, personal care [15], hygiene, agriculture, home care, construction, aerospace, protective gear, and healthcare. The global technical textiles market is divided into four segments by process, material, application, and technology [16–19].

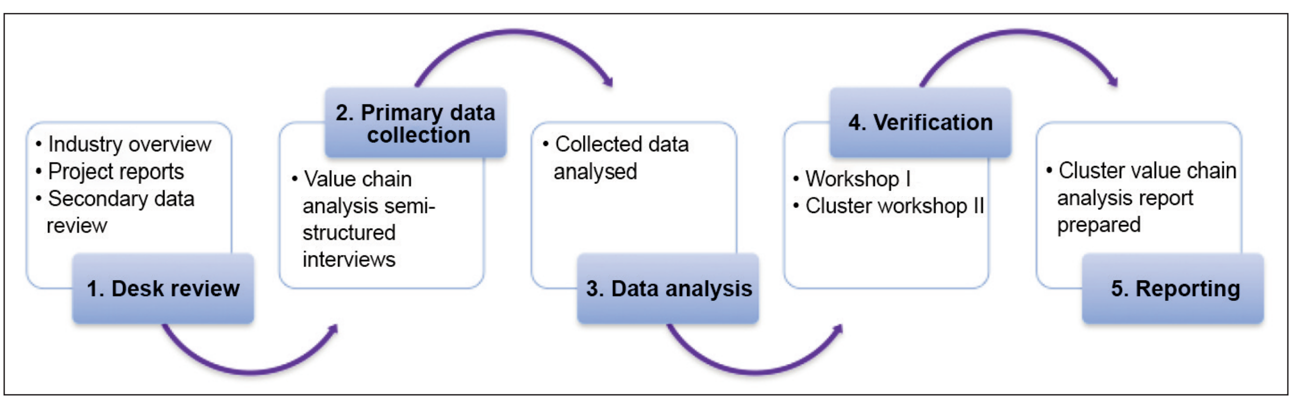


Fig. 2. Workflow

By process, the market is divided into knitted, nonwoven, woven, and other sub-segments. Nonwovens are used for various purposes, such as covers, carry bags, thermal insulation, ballistic protection, and fireproof layers. The growing demand for polypropylene in nonwovens is anticipated to propel the overall growth of the technical textiles market. The woven segment is expected to be the fastest growing in coming years due to ease of production and low cost. The market is also segmented by materials such as recycled fibre, mineral, synthetic polymer, natural fibre, metal, high-performance fibre, and others. High-performance fibres like aramid, carbon, and UHMW polyethylene are also included.

The application market is divided into twelve segments: Geotech, oekotech (echotech), Mobiltech, indutech, packtech, sportech, protech, buildtech, agrotech, hometech, clothtech, and medicaltech. Geotech focuses on agro-based geotextiles and geosynthetics, while oekotech uses technical textiles in environmental engineering and landfill waste management. Mobiltech uses technical textiles in automobiles, aircraft, railways, and shipbuilding.

Indutech focuses on industrial brushes, paper-making fabrics, filtration products, computer printer ribbons, printed circuit boards, composites, ropes & cordages, coated abrasives, AGM glass battery separators, bolting cloth, cigarette filter nods, drive belts, and conveyor belts. Packtech includes leno bags, wrapping fabric, jute hessian and sacks, soft luggage products, tea bag filter paper, woven sacks, sportsech, protech, buildtech, agrotech, hometech, clothtech, and medicaltech.

Technology is segmented into six segments: spinning, weaving, knitting, finishing, nanotechnology, and others. The wide applicability of technical textiles in various industries is a major factor driving market growth.

Composite materials

Composites are a combination of reinforcement material and matrix, with the reinforcement being the main load-bearing component. Its properties are superior to individual components, with fibres, particles, and flakes acting as reinforcement forms [20]. The matrix keeps reinforcement in a specific orientation and protects it from damage. Composites are used when traditional materials don't meet specific application requirements. They can be designed to achieve a wide range of properties by altering constituent materials, orientations, and process parameters. They have high mechanical properties with low weight, making them ideal for automotive and aerospace applications. Composites also offer high fatigue resistance, toughness, thermal conductivity, and corrosion resistance. However, high processing costs limit their wide-scale usage. Textile-reinforced composites consist of a textile form as reinforcement and a polymer matrix. Different textile architectures offer significant potential for designing composite properties.

CONSOLIDATED COMPETENCE MAP OF TECHNICAL TEXTILE AND COMPOSITE MATERIALS MANUFACTURING COMPANIES

A Competency Maps Study has been undertaken within the scope of the Diagnostic Studies of the Project. During this study, competency mapping was used to identify strengths and weaknesses of companies grouped by sub-sectors through a set of indicators. The aim was to better understand the relationship between different indicators and needs to increase competitiveness and facilitate transformation or new investments to technical textile or composite materials manufacturing effectively.

Through this document, based on the data generated within the Competency Map Study, a consolidated competency map has been prepared with selected 10 indicators to analyse the sub-sectors of technical textile and composite materials companies in Bursa. As seen in figure 3, 10 different indicators, including qualified workforce, access to finance, R&D opportunities, foreign trade, quality-technical competence, innovation competence, standardisation and certification, competition in the market, access to raw materials and logistic opportunities were presented.

In the Competence Maps Study, logistic regression models for the prediction of different dependent variables, which were defined by sector experts, have been constructed to determine factors affecting a dependent factor. Data were transformed to binary outcomes, which allow straightforward decisions between two alternatives based on the company's self-scoring in given parameters. For these models, the degree of competency was divided into less competent (between 1 to 5) and more competent (6 to 10). In light of the explained method, in figure 3, competencies were shown between a scale from 3 to 7, in which less competent indicators can be observed between 3 to 5 and more competent ones from 6 to 7. In this document, the scale has been set between 3 to 7 to be able to provide a concise view. Figure 3 presents competency indicators in identifed subsectors – composite, medtech, hometech, clothtech, protech and Mobiltech – in a linear direction from right to left and gives an impression of the grouping of subsectors or the relationship between factors represented by the XY axis. The consolidated composite map provides an integrated look and enables a comparable view for elaborating the relation between selected factors (Axis Y) on areas of identified areas of competences (Axis X) (table 1).

Within the framework of given parameters, it is seen that quality workforce, standards and certification, competition in the market and foreign trade competences are concentrated between 5.00 and 7.00 by Axis X. When relations examined; for example, in Mobiltech segment it can be interpreted that access to coaching and training services has positive implications on qualified workforce. In the composite's subsector, qualified workforce competence is high;

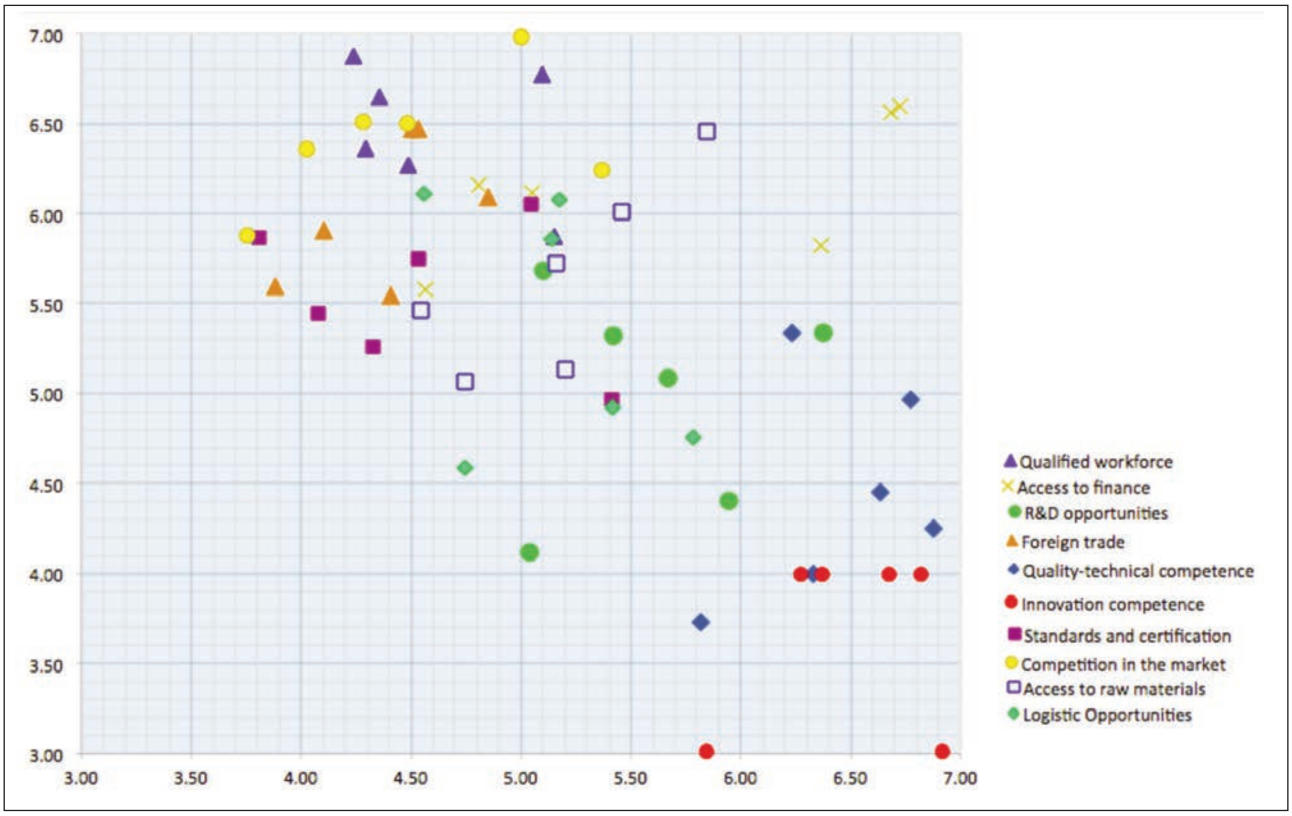


Fig. 3. Consolidated map of company competencies by sub-sectors

Table 1

VALUE GROUPS	
Axis X	**Axis Y**
Qualified workforce	Access to Coaching / Consulting / Training services
Access to finance	Access to government incentives
R&D opportunities	Access to raw materials
Foreign trade	Proximity to the market
Quality- Technical competence	Qualified workforce
Innovation compentence	Qualified workforce
Standards and certification	Quality-technical competence
Competition in the market	Quality-technical competence
Logistic opportunities	Network structure
Access to raw materials	Network structure

even access to training and coaching is at a moderate level. In foreign trade competence, Mobiltech has the strongest relation with proximity.

When the relation between qualified workforce and innovation competence of companies is reviewed, it is seen that innovation competence in composite and Mobiltech are relatively low even qualified workforce indicator given higher scores. Likewise, in other segments, innovation competence has been scored low while qualified workforce has high-level scores. It can be interpreted that innovation competence can be increased not only by a high level of qualified workforce but other determinants may imply. In Mobiltech, for instance, it is seen that the qualified workforce scored almost at the highest level; however, innovation competence scored low.

The relation between access to raw materials and network structure is concentrated at a moderate level from both axes. It can be interpreted that there is a linear relation between two parameters in given sub-sectors. For instance, in Mobiltech, it is seen that a stronger network structure meets with stronger access to raw materials.

It is observed from the consolidated figure 3 that there is a linear relationship between quality technical competence and qualified workforce indicators. An increase in the qualified workforce can have positive implications on quality technical competence. Except for the composite sub-sector, it is seen that companies' level of quality technical competence has been scored at a moderate to high level.

Competence in access to finance and access to government incentives is high in all sub-segments of the industry. A linear relationship is observed between access to finance and access to government incentives. RD opportunities are at a relatively moderate level from both axes between 4.50 and 6.50. An increase in access to raw materials has positive implications for the R&D opportunities of the companies in sub-segments of the technical textile and composite materials industry.
Logistic opportunities about network structure constitute a position from moderate to high level in almost all sub-sectors. Improvements in network structures may have further positive implications on the logistic opportunities of companies.
A consolidated competence map of companies in selected competence parameters reveals that factors conditions such as qualified workforce, network structure, access to training and coaching services, and access to government incentives have linear relation and positive implications on key parameters of competitiveness, including innovation competence, quality technical competence, and competition in the market. Consolidated Map reviews may provide insights for possible decisions on investments and actions to be taken towards competitiveness of the industry.
It has to be remembered that consolidated figure 3 examines the relation between two parameters and cannot be accepted as the conclusion on the level of competences. Figure 3 can be a starting point for further analysis on competences of companies with different tools and analysis methods.

VALUE CHAIN ANALYSIS

The value chain is a concept which can be simply described as the entire range of activities required to bring a product from the initial input-value stage, through various phases of production, to its final market destination [21]. Within the scope of cluster analysis stage, industry value chain analysis has been conducted to understand present actors and value-added processes from input materials to manufacturing of products, supporting industries and actors and finally related end markets. Another aim of undertaking value chain analysis is to increase a sound insight on the current status of Bursa Technical Textile and Composite Materials Value Chain. This ability and knowledge will be used as precious means while analysing trends and identifying which parts, functions and approaches, along with the value chain, should be upgraded.
Value chain analysis study undertaken through semi-structured interviews and application of a specially designed set of survey questions. The analysis study was completed with the participation of 57 companies representing a wide range of actors present in the Bursa technical textile and composite materials value chain. Figure 4 shows the distribution of companies in terms of their perception of their position in the chain.

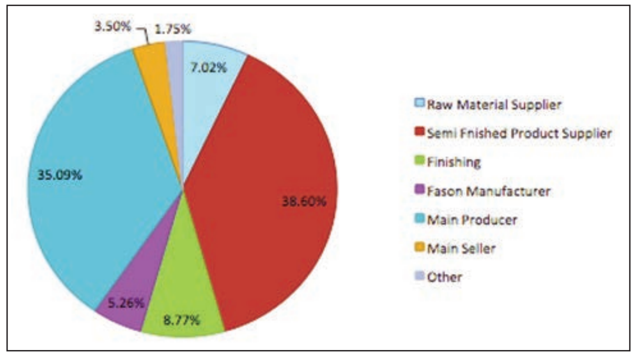


Fig. 4. Companies' perception of value chain position

In technical textiles and composite materials, it is not always possible to distinguish the roles and/or positions of companies as suppliers or manufacturers. As an example, companies defining themselves as manufacturers can be suppliers of companies providing goods for OEMs. In the light of industry structure and linkages – taking company products and operations into consideration – prepared final value chain map. It is seen from figure 4 that 35% of companies are main producers while 38% position themselves as semi-finished product supplier. 7% of the companies provide raw materials, including chemicals. 5.2% as suppliers (named as fason) and 8.7% has finishing operations.
The value chain map has been developed, and an in-depth understanding has been generated regarding key competencies and areas to be further developed. Due to their linkages within the chain, the analysis covers technical textiles and composite materials actors and processes together instead of elaborating on them individually. Additionally, the main processes of the value chain also cover information at national level related actors, which has direct implications on the value chain at Bursa at regional level. It is not possible to elaborate any industry as an isolated system. The below version of the Value Chain Map has been finalised based on the verifications and views received from the participants of two workshops held throughout the study (figure 5).

Fibres and yarns

Fibres are the main input materials used in the manufacture of technical textiles and composite materials. Within the scope of the value chain analysis study and map of Bursa Technical Textile and Composite Materials, fibres were elaborated under four main categories: i) Natural fibres, ii) Regenerated fibres, iii) Synthetic fibres and iv) High Performance Fibres. In technical textiles and the composite sector, material is one of the key determinants of high performance. For the manufacture of composite products, the most commonly used input materials are glass fibre-reinforced polymer (GFRP) and carbon fibre-reinforced polymer (CFRP) composites, followed by composites reinforced by aramid or natural fibres. Reinforced fibres and bio-based materials are gaining importance in parallel with developments and

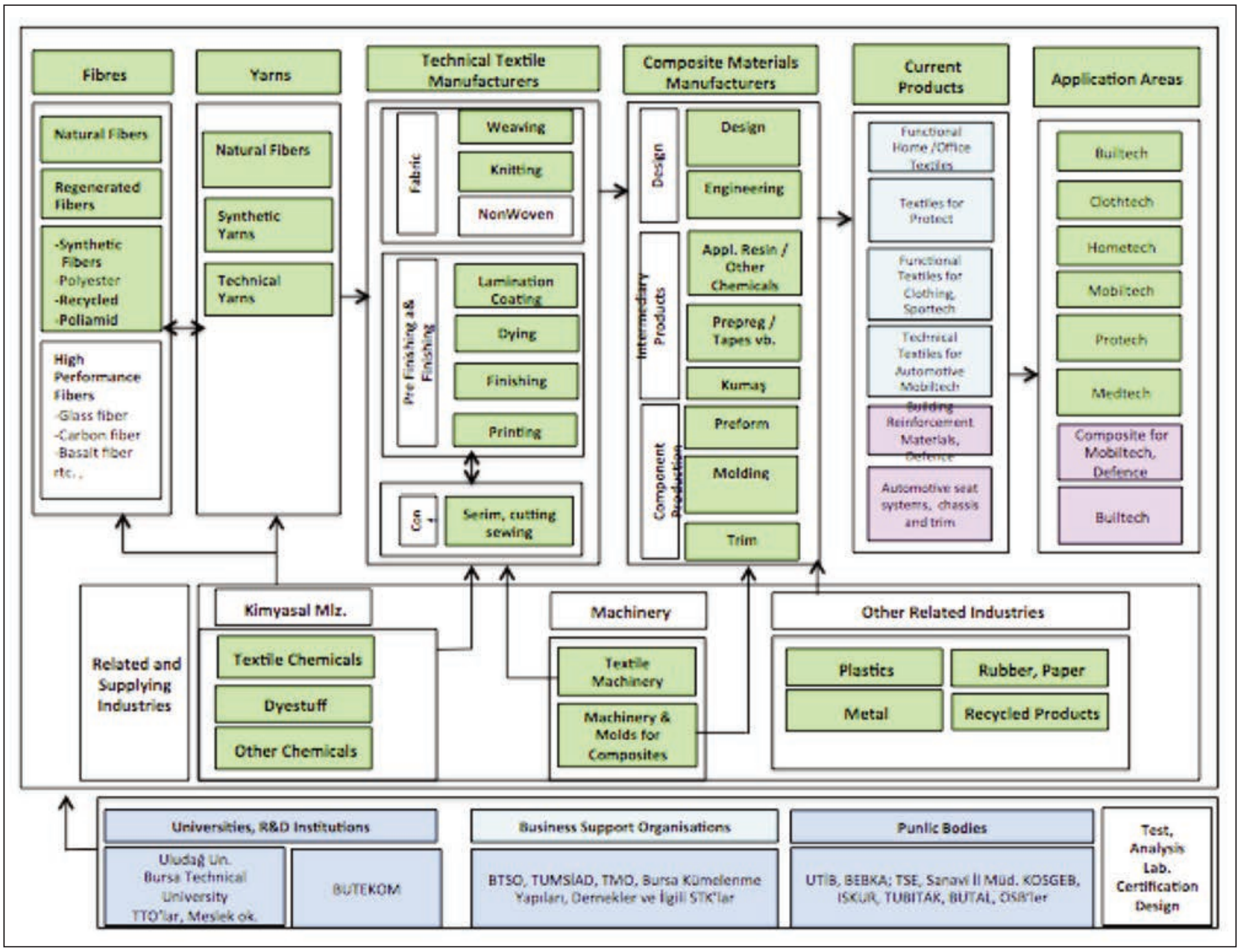


Fig. 5. Value chain map

needs in end industries. The presence of fibres – reinforced, bio-based, etc. – in Bursa in this regard can be considered as one of the "to be developed input material/process" of the value chain. In Bursa, natural and synthetic fibres are present; however, there is very limited manufacturing and/or ongoing studies on manufacturing high-performance fibres, glass fibre, carbon fibre, etc., at any level of scale yet. Currently, there is only one company within the cluster environment which has glass fibre. Carbon fibre is purchased from other regions. As stated earlier in this paragraph, bio-based fibres also gain importance in the textile industry and related industries. Upgrading the "manufacture of high-performance fibres" within the value chain can bring opportunities to Bursa. To conclude, i) developing bio-based fibres, ii) manufacturing and innovating on high tenacity synthetic fibres, and iii) studies on reinforced materials can bring competitive advantages to Bursa.

At this point, it is important to state that Türkiye is one of the global suppliers of glass fibres produced by ŞIŞECAM. In 2019, the total volume of glass fibre was 90.000 tons, and this volume met only half the need in Türkiye.

The manufacture of fibres such as glass, carbon, etc., needs a certain level of investment and may need specific infrastructure. At this stage, the lack of players manufacturing glass or carbon fibre cannot be accepted as a key weakness. However, suppliers of such critical input materials keep the power of bargain and price decision and may limit access to materials. Dependency, especially on glass and carbon or aramid fibres, may put pressure on the competitiveness of the companies. Based on the desk review study undertaken throughout the analysis study, it is seen that "sustainability" will continue to be the determining condition for competitiveness. Since innovation starts from material, studies on alternative and bio-based materials for bio-based fibres to be used in technical textile and composites seem to be one of the key strategic upgrades for the value chain.

Yarn manufacturing: The majority of companies that participated in the cluster analysis study are manufacturing textile products made of synthetic fabric and functions to fabric in most cases provided by chemical applications and at finishing process. Bursa is one of the strongest centres for yarn manufacturing, especially in synthetic yarns. The manufacture of synthetic yarns has direct linkages with the customers along with the value chain both for the needs of textile and technical textile manufacturing purposes and end products. Findings and cluster workshop reveals that in Bursa, along with synthetic yarns, there is production of regenerated and another type of yarns as indicated in the value chain map. The manufacturing of yarns from bio-degradable materials has just started; however, there is a need for further improvements.

Since the majority of technical textile companies also manufacture textile products for home and furniture use, fabrics made of synthetic yarns are widely seen. However, analysis reveals that there is a need for increasing both the number of companies manufacturing high tenacity yarns and increasing capacity to manufacture technical and high tenacity yarns.

Some of the areas high tenacity yarns are used automotive car seat upholstery, technical textile for outdoor products as well as fabrics for the use of protective wear.

Technical textile manufacturers

Technical textile manufacturing as one of the key processes along with the value chain has been analysed and elaborated through three sub-processes including manufacture of fabric, finishing applications and confection. In total, 57 companies participated in the cluster and value chain analysis. Out of 57 companies, 34 companies manufacture technical textile products. Fabric manufacturing in Bursa is mostly based on weaving technologies. Technical aspects or functions of fabrics are mainly given at finishing processes through the application of chemicals and/or substances.

This information has also been supported and is in line with the findings of the Stakeholder Analysis, which was conducted at the initial stage of the Project. As the findings state, "When the technologies utilised in company production are evaluated, that weaving technologies predominate in the Bursa textile industry. Following these technologies are those for weaving preparation, finishing, and dyeing. In companies that claim to only produce traditional textiles, weaving technologies and weaving preparation technologies rank first and second, respectively, while companies that produce technical textiles prioritise finishing and dying technologies. Although there aren't many companies that use knitting technology, it is clear that these companies generally focus on technical textiles. Most of these businesses produce for the automotive industry. It has been reported that weavers also manufacture technical textiles, as shown in figure 6. Dyeing and finishing relationships with technical textiles are assumed to be limited to functional textiles. Even though companies using coating technologies also make technical textiles, it is thought that the majority of them produce fabrics for roller blinds or upholstery".

Technical textile manufacturing technologies and finishing applications are directly linked to needs and areas of use. It is therefore highly important to understand and identify target sectors and application areas for Bursa, to invest, adapt and innovate in fabric manufacturing and finishing processes. For instance, it is known that for Mobiltech, warp-knitting capabilities constitute a substantial place, electrospinning in medical use products. As an early conclusion before developing cluster strategy and roadmap, having strong automotive industry in Bursa, companies should be supported for developing their manufacturing technologies including fabric manufacturing, applications, materials and know-how on how to apply innovative solutions.

Composite products manufacturing

Before proceeding on details of the value chain, it is beneficial to review the definition of composite materials. As stated in the industry definition section, a composite material is a material produced by combining two or more materials with significantly different physical properties, which allows obtaining desired unique properties. The combination of different materials allows obtaining new materials that are stronger, lighter, or less expensive compared to conventional materials.

The composite material is generally a combination of the matrix and the reinforcement. According to the matrix type, the matrix materials are classified into metals, plastics, and ceramics. Based on the polymer type, fibre-reinforced composites are divided into thermosets and thermoplastics. The fundamental difference between thermosets and thermoplastics is that the first type of material is cross-linked and cannot be re-melted, while thermoplastics can be melted and reshaped. Polymer-matrix composites cover the vast majority of the composites market, in which two-thirds correspond to thermoset composites, though the application of thermoplastic composites has increased significantly in recent years [22].

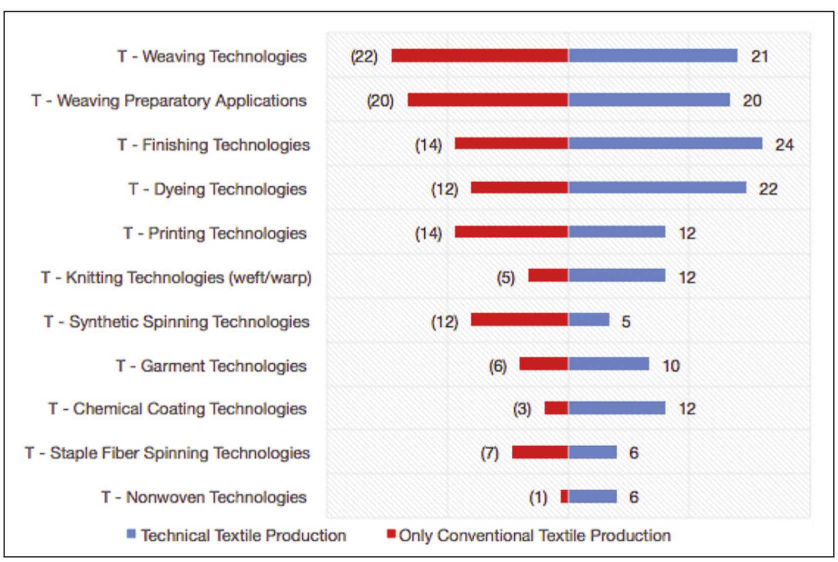


Fig. 6. Manufacturing technologies of companies

The value chain of the composite materials involves many industrial sectors, from raw materials supply up to part production. Their manufacturing processes require equipment and machines but also a wide range of simulation, automation, testing and measurement techniques. The pace of innovation in the sector is extremely high among all parties involved, such as academics, R&D centres, large companies, and deep tech start-ups [23].

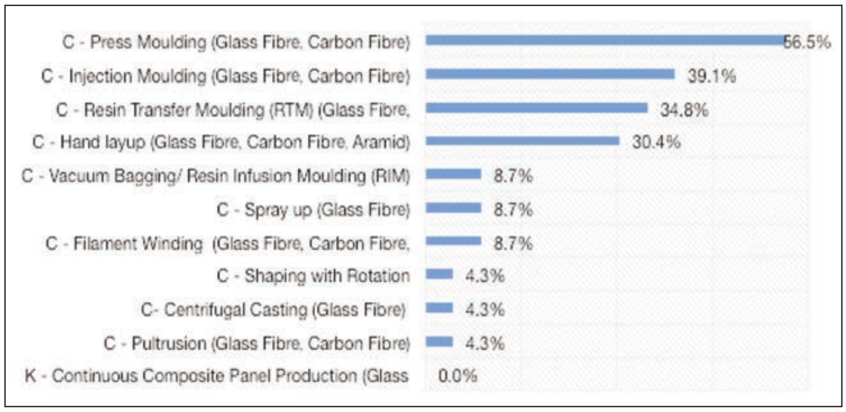


Fig. 7. Composite materials manufacturing process and technologies in Bursa (*Source:* Stakeholder analysis report)

Within the value chain analysis and value chain map, composite materials have been elaborated in three main sub-processes: design, intermediary products and component production. In Bursa, out of 57 companies that participated in the cluster and value chain analysis study, 24 are operating in composite materials. In Bursa, operations related to technical textiles and composites are strongly interconnected with the Mobiltech segment of technical textiles. The presence of OEMs and Tier 1 and Tier 2 suppliers facilitates the production of plastic, metal and composite components for the automotive industry.

As it can be seen in the value chain map, the design of composite materials is the first step before manufacturing processes. In Bursa technical textile and composite materials, there are companies providing design, simulation, mould development and 3D printing services for design and development of composite materials.

The application of resin and other chemical substances constitutes the second process of the value chain in the manufacturing of composite materials. Resin is widely used in manufacturing composite products. Two major groups of resins make up what we call polymer materials: thermosets and thermoplastics. These resins are made of polymers (large molecules made up of long chains of smaller molecules or monomers). Thermoset resins are used to make most composites. They're converted from a liquid to a solid through a process called polymerization or cross-linking. When used to produce finished goods, thermosetting resins are "cured" by the use of a catalyst, heat or a combination of the two. Once cured, solid thermoset resins cannot be converted back to their original liquid form. Common thermosets are polyester, vinyl ester, epoxy, and polyurethane [24].

There is no capacity problem in resin production in Türkiye. The installed capacity of the resin-producing companies for the raw materials used by the composite industry is 310.000 tons. The total annual production in 2019 is 150.000 tons. Firms account for 80% of their total production. They sell a portion of their products to the domestic market and 20% to abroad. When their installed capacities are taken into consideration, it is seen that they have the potential to meet all the resin needs of the European Union.

About resin production, views from cluster and value chain analysis were as follows:

- Although in this section it is stated that Türkiye do not have capacity problems in resin production, companies that participated in cluster analysis studies stated that companies in Bursa are dependent on abroad – this statement may be subject to other regions and will be further reviewed during cluster roadmap development stage – in resin production.
- Regarding composite materials, the current competencies of companies in Bursa, as stated by the companies, are as follows:
- In Bursa, companies have thermoforming, hand layup, vac infusion, RTM, injection, moulding and trim.
- Areas need to be developed; prepreg, preform 2D and 3D, autoclave, type/band, composite textures.

Figure 7 verifies the companies' statements about the current capabilities of the companies in manufacturing composite materials. Figure 7 above shows the main processes of companies manufacturing composite materials. Press moulding is seen in 66% of companies and constitutes major weight, followed by 39.1% injection moulding, 34.8% resin transfer moulding and %30.4 hand layup.

Products, application areas and targeted export regions

Starting from input materials, the industry value chain enjoys the presence of diverse players with complementing competencies. Products and services can be classified as input materials, semi-finished products, finished products, supporting products and services. Seat systems for vehicles, functional home textiles made of technical materials and applications can be seen as the primary product groups. Based on the offered functions of the fabric or materials, application areas, in other words, end markets are automotive, Hometech, Buildtech, Protech, Geotech, Clothtech, Sportech and Medtech.

Within the scope of the value chain analysis study, participating companies were asked to state in which

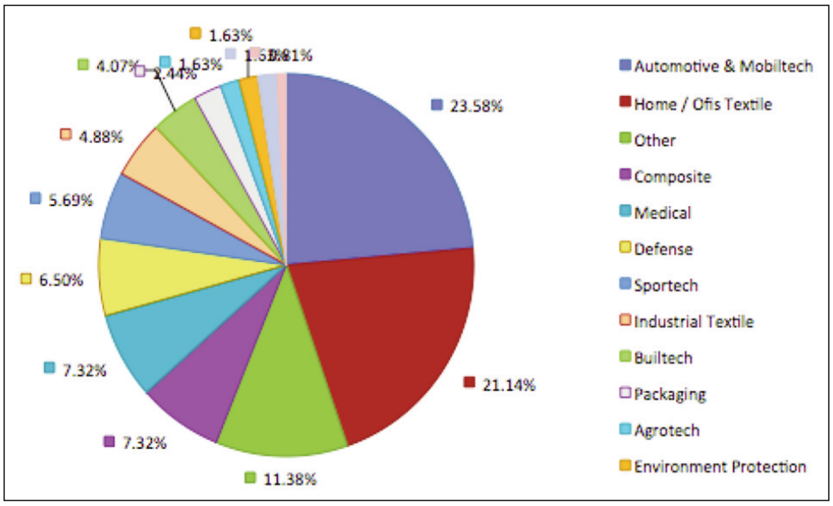


Fig. 8. Application areas of technical textiles and composite materials

end markets their products were being used. Figure 8 indicates the distribution of end markets, in other words, the application areas of the input products, semi-products and final products.

Technical textile and composite materials products, along with the value chain starting from input materials to semi-finished and finished products, find a place in a variety of sub-segments of technical textiles. It is seen that automotive and home/office textiles are stated as the main areas of application. Buildtech, Protech, Sportech, and Buildtech are among other areas of application. From this figure 8, it is possible to say that products manufactured by the companies meet the needs of application areas/end markets by their functions and solutions offered. It is possible to conclude that innovation and new process development of companies will enable the Bursa technical textile and composite materials cluster to be a solution centre for specific areas of the industry.

Findings of the cluster and value chain analysis and findings of the stakeholder analysis outline the areas in which the products of the companies whose goods are utilized in one area are also used in other areas. For example, companies whose products are used in the agriculture sector also have goods used in healthcare, industrial, and automotive transportation. This demonstrates that, while concentrating on technical textile production, more than one sector can be targeted. The diagonal shows the specialized area, and others are supportive areas for that area. If a company's main area is the production of automotive and transportation textiles, the same company may also produce for home-office, clothing industry, and healthcare.

In terms of future end markets and areas for development, based on the cluster and value chain analysis and the views raised in the cluster workshop, the views of companies can be summarised as follows:

- Companies stated defence, aviation, Sportech, Agrotech, Buildtech, Protech, including military purposes, have to be considered among targeted end markets;
- The products and processes stated by the companies are metal lamination/coating, radar absorption, plasma, capsulation, lamination;
- Processes stated about composite materials are thermoplastic composites, automation, and industry 4.0.

Export development is one of the most important areas where clusters can support companies. In terms of targeted regions, value chain analysis reveals that the EU is the primary target market for companies, followed by overseas countries, and finally, Asia and the Middle East markets take place as stated targeted regions.

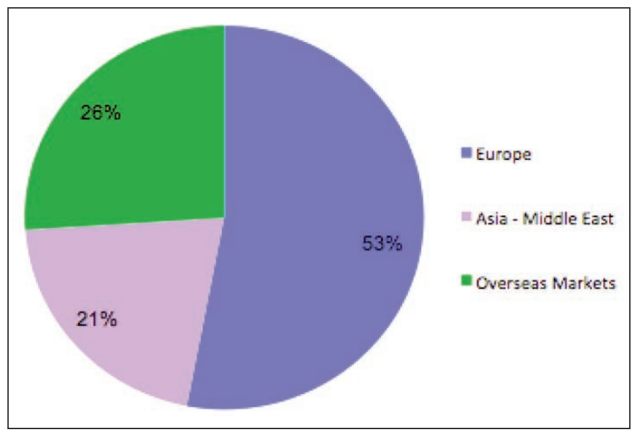


Fig. 9. Targeted export regionss

Insights on value chain upgrade

To be able to develop a solid cluster strategy and roadmap, it is vital to analyse and understand possible areas of the value chain to upgrade in line with the needs of the target markets. At this point, it is also important to draw out key competencies of the regional value chain. In light of this approach, during the cluster workshop held on XX, participants were asked to state and identify both current competencies and areas to be developed in the technical textiles and composite materials value chain in Bursa. Table 2 provides examples of Bursa value chain products and a summary of collected views in brief; a detailed competence matrix can be seen in Annex 1 of this report.

CONCLUSIONS

Analysis reveals that the technical textile and composite materials industry in Bursa is at a transition stage towards a more specialised level with value-added products and solutions offered through a cluster development approach. In terms of product diversification and manufacturing processes, it is seen

Table 2

CURRENT COMPETENCIES AND AREAS FOR DEVELOPMENT
Current capabilities and products
• Baby and kids' strollers with repellent fabric, Cordura outdoor fabrics • Disposable fabrics used for surgeries, surgical drapes, etc. • Polyethylene foam, thermoplastic pre-preg semi-finished product, continuous glass and carbon fibre reinforced composite, sandwich panel • Glass fibre fabrics (Core–Axial) • Vehicle seat group, trim and chassis systems • Water-repellent, flame-retardant textile chemicals • Design, simulation, mould development and 3D printing services • Acoustic curtains, blackout curtains • Glass fibre-reinforced polymer composite materials for Mobiltech • Thermoforming, vac infusion, hand layup, RTM, Injection, moulding and trim are present in Bursa as processes in composite materials
Areas/products to be developed/upgraded
• Bio-based flame-retardant composites • Natural fibre-reinforced technical fabrics, carbon and aramid fabrics • Problems in supplying yarns made of polyamide, aramid, modacrylic fibres • Problems in supplying insulating or conducting yarn mixtures and coatings, especially ones made of metal, copper, etc. • Fabrics for filtration purposes • Use of waste materials in composite production • Hi-tenacity and heat balance providing fabrics • Carbon tape production and products made of carbon tapes • Product tests, product optimisation and marketing support • Use of natural fabrics, increasing manufacture of carbon fibres and fibre filaments for additive manufacturing • Need for improving resin manufacturing capacity • In composites, matrix materials are purchased from abroad, and these input materials are expensive; there is a need for investing in engineering plastics, polymers, etc. • Need for improving capacity in thermoplastic composites • The manufacture of pre-preg is limited in Bursa; pre-preg manufacturing capacity has to be increased • In technical textiles, there is a need for increasing capabilities and capacity in electromagnetic, capsulation lamination, plasma, metal coating • Environmental studies in thermosets and thermoplastic studies should take place • Defence, aviation, Geotech, Sportech and Buildtech, and lightweight industries should be targeted among end markets • Need for increasing capacity in warp knitting and fabrics such as spacer fabrics • Need for studies and actors for improving coating and lamination chemicals • Need for improving capabilities for coating techniques for finished products • For composite materials needing pressure tank tests, there is dependency on foreign test centres in this area • In automotive cluster can increase specialisation in seat systems, under bonnet, trim etc. • Need for improving automation ad industry 4.0 (Digital Transformation) • Need for improving sustainability and green transition implementations • Prepreg, preform 3D, 2D, autoclave, tape fabric, thermosets, epoxy, and peek engineering plastics are areas stated to be developed in Bursa in composite materials • In technical textiles, 3D weaving, braiding, spacer fabric, lamination, nonwoven, fibre laying, and embroidery (conductive technical yarns) are stated as areas to be developed in technical textiles • Technical yarns, meta-aramid, natural, linen, hemp, carbon fibres, glass fibres, moda acrylic, solution acyclic, copper yarns, basalt, silver yarns are among areas stated to be developed in Bursa

that there are areas for upgrading value chain almost at all processes to be competitive with companies in EU and globe. Due to well-developed structure and concentration of automotive, textile and apparel and furniture industries, technical textile and composite materials production flourished at certain level. Seat systems for Mobiltech, upholstery, and curtains made of functional textile, chassis, and trim can be listed among the forefront products of the value chain, thereby the cluster at the current stage of the value chain.

Different from traditional textile products, technical textile is defined by the solutions and functions offered by the product, where composite materials can be defined by strength and performance mostly gained by reinforced materials through unique processes applied. Mobiletech and Hometech are the first two segments in which Bursa can improve manufacturing capabilities, innovation, skills development and knowhow. Through improving its competitive value chain, with supporting industries cluster can provide benefits to companies with tailor made services and help especially SMEs to be part of global value and supply chains.

ACKNOWLEDGMENTS

This work was based on the “Technical Assistance for the Composite Material and Technical Textile Prototype Production and Application Center” project, Reference number EuropeAid/140069/IH/SER/TR, Contract Number TR14C1.1.09-04/001/Service, which was co-funded by the European Union and the Republic of Türkiye.

REFERENCES

[1] Cetinkaya, B., Ewer, G., Piotrowicz, W., Cuthbertson, R., Klaas-Wissing, T., Tyssen, C., S*ustainable Supply Chain Management: Practical Ideas for Moving towards Best Practice*, In: Sustain. Supply Chain Manag. Pract. Ideas Mov. Towar. Best Pract., 2011, 1–283, https://doi.org/10.1007/978-3-642-12023-7/COVER

[2] Hasan, M.R., Wuest, T., *A Review of Sustainable Composites Supply Chains*, In: IFIP Adv. Inf. Commun. Technol., 2022, 663 IFIP, 448–455, https://doi.org/10.1007/978-3-031-16407-1_53

[3] Coronado Mondragon, A.E., Mastrocinque, E., Hogg, P.J., *Technology Selection in the Absence of Standardised Materials and Processes: A Survey in the UK Composite Materials Supply Chain*, In: Prod. Plan. Control, 2017, 28, 158–176, https://doi.org/10.1080/09537287.2016.1252070

[4] Lambert, D.M., Cooper, M.C., *Issues in Supply Chain Management*, In: Ind. Mark. Manag., 2000, 29, 65–83, https://doi.org/10.1016/S0019-8501(99)00113-3

[5] Stonebraker, P.W., Liao, J., *Environmental Turbulence, Strategic Orientation: Modeling Supply Chain Integration*, In: Int. J. Oper. Prod. Manag. 2004, 24, 1037–1054, https://doi.org/10.1108/01443570410558067/FULL/PDF

[6] Porter, M.E., *The Competitive Advantage of Nations*, Free Press 1990, 1, 1–929

[7] Smit, A., *The Competitive Advantage of Nations: Is Porter’s Diamond Framework a New Theory That Explains the International Competitiveness of Countries?,* In: South. African Bus. Rev., 2010, 14

[8] Bakan, İ., Doğan, İ., *Competitiveness of the Industries Based on the Porter’s Diamond Model: An Empirical Study*, In: Int. J. Res. Rev. Appl. Sci., 2012, 11, 441–455

[9] Smith, F., Shakspere, P., *UK Composites 2013. A Study into the Status, Opportunities and Direction for the UK Composites Industry*, London: Composites Leadership Forum, Department for Business, Innovation & Skills, UK, 2013, 12

[10] Ma, W., *Cost Modelling for Manufacturing of Aerospace Composites*, Cranfield University, 2011

[11] Texier, F., *Airbus Fastener’s Supply Chain Optimization*, 2008

[12] Karahan, M., Ahrari, M., Karahan, N., *Technical Textiles Market Research and Added Value Analysis: A Regio-Global Case Study*, In: Recent – Rezult. Cercet. Noastre Teh., 2023, 24, 162–180, https://doi.org/10.31926/recent.2023.71.162

[13] Karahan, M., Ahrari, M., Karahan, N., *Composite Materials Market Research and Export Potential Analysis: A Regio-Global Case Study,* In: Recent – Rezult. Cercet. Noastre Teh., 2023, 24, 113–121, https://doi.org/10.31926/recent.2023.70.113

[14] Ahrari, M., Karahan, M., Karahan, N., *Competitiveness Factors in Textiles and Composites Industry and Transformation into Value-Added Products*, In: Recent – Rezult. Cercet. Noastre Teh., 2023, 24, 132–141, https://doi.org/10.31926/recent.2023.70.132

[15] Ari, A., Karahan, M., Kopar, M., Ahrari, M., *The Effect of Manufacturing Parameters on Various Composite Plates under Ballistic Impact*, In: Polym. Polym. Compos., 2022, 30, 1–15, https://doi.org/10.1177/09673911221144874

[16] Ari, A., Bayram, A., Karahan, M., Karagöz, S., *Comparison of the Mechanical Properties of Chopped Glass, Carbon, and Aramid Fibre Reinforced Polypropylene*, In: Polym. Polym. Compos., 2022, 30, https://doi.org/10.1177/09673911221098570

[17] Ari, A., Bayram, A., Karahan, M., Arslan, O., *Comparative Evaluation of Mechanical Properties of Short Aramid Fibre on Thermoplastic Polymers*, In: Materials Science-Poland, 2023, 41, 161–176, https://doi.org/10.2478/msp-2023-0012

[18] Ali, A., Mehmet, K., Ali, B., Seçgın, K., *Evaluation of the Mechanical Properties of Chopped Carbon Fibre Reinforced Polypropylene, Polyethylene, Polyamide 6, and Polyamide 12 Composites*, In: Industria Textila, 2023, 74, 175–183, https://doi.org/10.35530/IT.074.02.202214

[19] Rad, H.K., Shariatmadar, H., Ghalehnovi, M., *Simplification through Regression Analysis on the Dynamic Response of Plates with Arbitrary Boundary Conditions Excited by Moving Inertia Load*, In: Appl. Math. Model., 2020, 79, 594–623, https://doi.org/10.1016/j.apm.2019.10.054

[20] Ari, A., Karahan, M., Ahmed, H.A.M., Babiker, O., Dehşet, R.M.A., *A Review of Cellulosic Natural Fibres’ Properties and Their Suitability as Reinforcing Materials for Composite Panels and Applications*, In: AATCC J. Res., 2023, 10, 163–183, https://doi.org/10.1177/24723444221147365

[21] United Nations Industrial Development Organization, *Agro-Value Chain Analysis and Development*, Vienna, 2009, 8, 3–38

[22] Shehab, E., Meiirbekov, A., Amantayeva, A., Tokbolat, S., *Cost Modelling for Recycling Fibre-Reinforced Composites: State-of-the-Art and Future Research*, In: Polym., 2023, 15, 150, https://doi.org/10.3390/POLYM15010150

[23] JEC, *JEC Observer Overview of the Global Composites Market, 2021–2026*, Available at: https://www.jeccomposites.com/press/jec-observerbroverview-of-the-globalbrcomposites-market-2021-2026-eco/ [Accessed on January 25, 2024]

[24] Ari, A., Karahan, M., Kopar, M., Ahrari, M., Khan, R.M.W.U., Hussain, M., *Comparative Analysis of Natural Fibres Characteristics as Composite Reinforcement*, In: Industria Textila, 2023, 74, 403–411, https://www.jeccomposites.com/press/jec-observerbroverview-of-the-globalbrcomposites-market-2021-2026-eco/ 10.35530/IT.074.04.2022110

Authors:

MEHMET KARAHAN[1,2], ALİ ARI[3], NEVİN KARAHAN[1]

[1]Vocational School of Technical Sciences, Bursa Uludag University,
16059, Bursa, Türkiye
e-mail: mkarahan@uludag.edu.tr

[2]Butekom Inc., Demirtas Dumlupinar OSB District,
2nd Cigdem Street No:1/4, 16245, Osmangazi, Bursa, Türkiye

[3]Department of Weapon Industry Technician, Vocational School of Higher Education, Ostim Technical University,
06374, Ankara, Türkiye

Corresponding author:

ALİ ARI
e-mail: ali.ari@ostimteknik.edu.tr

Detection of garment manufacturing defects using CFPNet and deep belief network: an image-based approach

DOI: 10.35530/IT.076.02.2024140

DENNISE MATHEW N.C. BRINTHA

ABSTRACT – REZUMAT

Detection of garment manufacturing defects using CFPNet and deep belief network: an image-based approach

The demand for high-quality items and the quickly shifting economic landscape increase the importance of ready-made garment manufacturers in providing the correct quality product. It is difficult work in the textile industry since the efficacy and efficiency of automatic flaw identification determine the quality and cost of every textile surface. In the past, the textile industry used manual human efforts to find flaws in the manufacturing of clothing. The main downsides of the manual garment fault identification technique include lack of concentration, human tiredness, and time requirements. Applications based on digital image processing and computer vision can overcome the aforementioned restrictions and shortcomings. In this article, we use intelligent algorithms like Channel-wise Feature Pyramid Network (CFPNet) based on deep learning-based techniques with Deep Belief Network (DBN) to monitor the quality and predict any occurrences of manufacturing problems in clothing. The suggested algorithm is mostly utilised in the textile industry to find flaws in clothing while estimating client needs based on the environment and the economy to react quickly and meet business objectives. The performance evaluation was used to determine the 12 kinds of garment faults, which included holes, excessive margins, stains, cracks, inappropriate stitch balancing, needle breaks, ink stains, torn clothing, drop stitches, soil content, and broken clothing. The suggested model obtains a 95.85% stain defect detection rate, a 97.33% defect-free garment recognition rate, and a 97.16% hole defect recognition rate.

Keywords: *garment industry, quality assurance, prediction classification parameter optimisation, digital image processing, deep belief network*

Detectarea defectelor de fabricație a articolelor de îmbrăcăminte utilizând CFPNet și rețeaua „Deep belief network”: o abordare bazată pe imagini

Nevoia producătorilor de articole de îmbrăcăminte de a oferi un produs de calitate corespunzătoare este sporită de cererea de articole de înaltă calitate și de peisajul economic în schimbare rapidă. Este o muncă dificilă în industria textilă, deoarece eficacitatea și eficiența identificării automate a defectelor determină calitatea și costul fiecărei suprafețe textile. În trecut, industria textilă folosea eforturile umane manuale pentru a găsi defecte în fabricarea îmbrăcămintei. Principalele dezavantaje ale tehnicii de identificare manuală a defectelor de îmbrăcăminte includ lipsa de concentrare, oboseala umană și cerințele de timp. Aplicațiile bazate pe procesarea digitală a imaginilor și viziunea computerizată pot depăși restricțiile și neajunsurile menționate mai sus. În acest articol, au fost utilizați algoritmi inteligenți precum Channel-wise Feature Pyramid Network (CFPNet) bazați pe tehnici de învățare profundă cu Deep Belief Network (DBN) pentru a monitoriza calitatea și a preconiza orice problemă de fabricație a îmbrăcămintei. Algoritmul sugerat este utilizat în cea mai mare parte în industria textilă pentru a găsi defecte în îmbrăcăminte, în timp ce estimează nevoile clienților pe baza mediului și a economiei pentru a reacționa rapid și a îndeplini obiectivele de afaceri. Evaluarea performanței a fost utilizată pentru a determina cele 12 tipuri de defecte ale articolelor de îmbrăcăminte, care au inclus găuri, margini excesive, pete, fisuri, echilibrare necorespunzătoare a cusăturilor, rupturi de ac, pete de cerneală, cusături desprinse, conținut de murdărie și îmbrăcăminte ruptă. Modelul sugerat a obținut o rată de detecție a defectelor de 95,85%, o rată de recunoaștere a articolelor de îmbrăcăminte fără defecte de 97,33% și o rată de recunoaștere a defectelor de găuri de 97,16%.

Cuvinte-cheie*: industria de îmbrăcăminte, asigurarea calității, optimizarea parametrilor de clasificare a predicțiilor, procesarea digitală a imaginilor, „Deep belief network”*

INTRODUCTION

Manufacturers must offer their clients high-quality but affordable items if they want to increase their competitive advantage and survive in today's aggressive market. This has a significant effect on quality control procedures. Human inspection has always been used to detect clothing flaws; however, this method hides the link between production process variables and product quality [1]. It is difficult to perform effective product assurance without any information discovery from the production processes at a parameter level. It is critical to identify defects in the clothes production process as early as possible to provide clients with high-quality garments at competitive costs. In these conditions, having a system in place that can identify the points where these flaws occur, how frequently they occur, what causes them, and what fixes are available will help the workers produce high-quality clothing. Moreover, this process will be greatly impacted by machinery maintenance [2]. As a result, there is a constant need in the textile sector for data processing and the finding of worthwhile and potentially useful knowledge from these data [3]. It is an inevitable fact that certain events that may occur during the production process can result in variations in product quality [4].

The present Information technology (IT) solutions have not enhanced Human Resources (HR) systems. Even though HR systems were already in place, it appears that no provision has been made for automated decision-making using modern IT trends. To address manufacturing problems related to quality, quality improvement (QI) of industrial processes and products is required [5]. Numerous textile investigations have used a variety of conventional mathematical and statistical methods to process textile data [6]. So, when a projected machinery component failure occurs, users will be informed that the relevant machine is in danger as a result. This work's main contributions are:

- To monitor the quality and predict any occurrences of manufacturing defects in garments using Channel-wise Feature Pyramid Network (CFPNet) algorithms.
- To optimize the production, predicting the customer requirements based on eco system and demand forecasting to respond rapidly and meet business demands using with Deep Belief Network (DBN).
- The following 12 default categories were chosen: hole, excessive margin, ink stain, crack, stain, ripped, drop stitch, broken end, defect-free, and incorrect stitch balance.
- The proposed work achieves a high accuracy value of 95.85%, and the BPN method provides a low accuracy value of 83.33%.

The following sections of this article are arranged as follows: A review of related prior research is presented in the 2nd section, each algorithm utilized in this study is briefly described in the 3rd section, the results and discussions are presented in the 4th section, and the article is concluded in the 5th section.

LITERATURE SURVEY

A technique utilizing the auto correlation function and grey level co-occurrence matrix to detect fabric faults in yarn-dyed fabrics [7]. The Fisher criterion-based deep learning algorithm was chosen by the author [8] for the detection of deformable patterned fabric defects. This work is used to create simple, twill, periodic patterns, and more intricate jacquard warp knit fabrics. An automatic and effective fabric defect detection methodology [9]. This technique was specifically used to identify defects in woven fabrics. A support vector machine classifier for an automated fabric flaw detecting system [10]. Three steps make up this work: threshold comparison, defect image inspection, and calibration. The benefits of this work include high accuracy and success rates with short processing times [11]. A multi-channel feature matrix extraction and joint low rank decomposition-based approach for fabric flaw detection. Wavelet transform was developed [12] to discover fabric flaws to cut production costs, waste, and time in the textile sector. A defect inspection approach based on a back propagation neural network in texture images was proposed [13]. The neural network model of production cycle time prediction is designed to increase forecast accuracy and get a deeper understanding of the production process in the garment manufacturing industry [14]. A sewing defect detection method using a CNN feature map extracted from the initial layers of a pre-trained VGG-16 to detect a broken stitch from a captured image of a sewing operation [15]. To assess the effectiveness of the proposed method, experiments were conducted on a set of sewing images, including normal images, their synthetic defects, and rotated images. A deep learning algorithm on LSTM infers details about the textile using digital images [16]. The LSTM technique is utilized to identify the defects in the fabric. Even with complex designs, the imperfections are visible. The predictive power of alternative machine learning (ML) algorithms in terms of real fit satisfaction (RFS) for customers' clothing fit and to compare the predictive capacities of these algorithms [17]. As test items, skirts composed of various textiles were utilized.

Previous techniques for finding clothing flaws could never guarantee a 100% inspection rate. It is imperative to address the massive dimensionality and complexity of textile data. Certain textile studies may involve complex interactions between several variables and aspects that are challenging to interpret using conventional techniques. Owing to these serious disadvantages, attempts are being made to automate the process of detecting garment defects through the use of a Channel-wise Feature Pyramid Network (CFPNet), which is based on deep learning-based techniques with a Deep Belief Network (DBN). This will help to maintain ongoing garment quality measurement and enhance the probability of the best garments.

METHODOLOGIES

It's crucial to pinpoint the causes of variability in manufacturing to reduce production errors and enhance and sustain process performance. The primary factor harming the textile industry is substandard clothing. Two stages make up the automatic method for identifying clothing defects. Phases of detection or testing and phases of learning or training. The system is trained using photos of clothing that are free of flaws during the learning phase. Following that, feature values that serve as classifier input are calculated. Only the features of interest are taken into account during the detecting phase. By dividing a test image into smaller windows and calculating the necessary statistics for each one, defects can be detected. If a window's required statistic set differs from the original training texture, a problematic region is identified.

Image acquisition

The initial database comes from a scan of the manual on clothing defects. All typical types of flaws found in textile industries are included in the sample of garment photographs that were chosen in this manner. Twelve classes are covered by this algorithm: hairiness, tiny hole, lumpy, horizontal stripes, lumpy, soil stain, oil stain, double end, snarls, and miss. 100 photos total are included in each class; 20 are used for teaching, and 80 are used for testing. For this study, a total of 500 samples were utilized (figures 1 and 2).

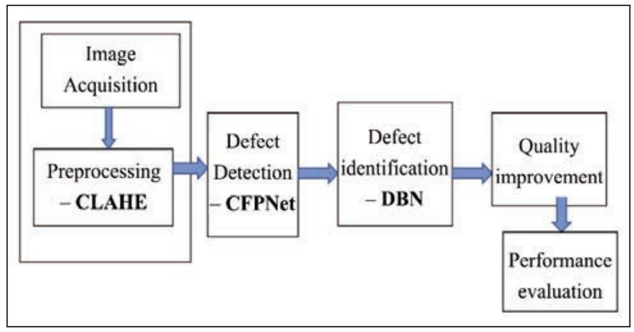


Fig. 1. Proposed framework for garment defect detection

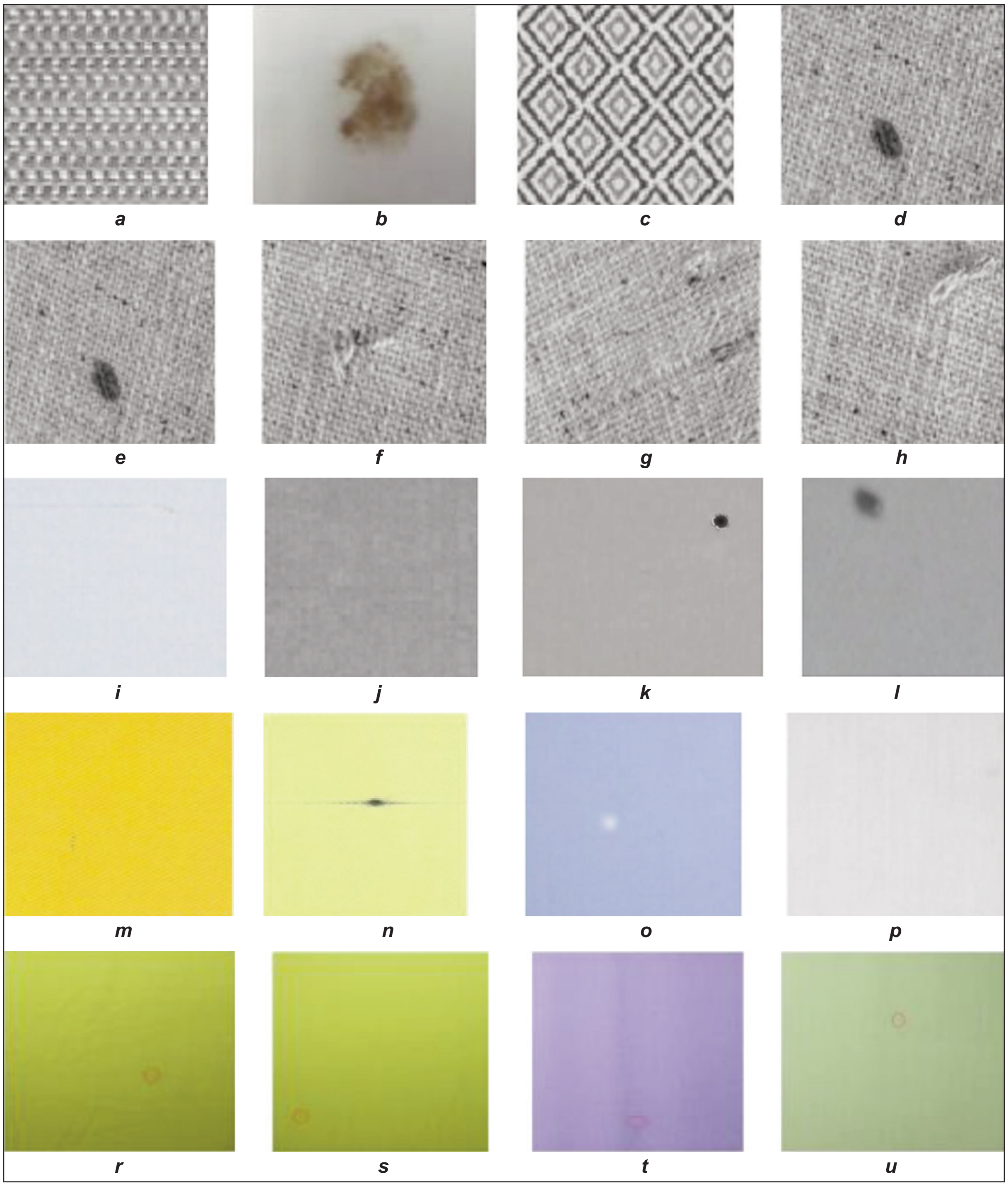


Fig. 2. Input images of: *a* – defect-free image; *b* – image with soil stain defect; *c* – defect-free image; *d* – image with oil stain defect; *e* – oilstain; *f* – double end; *g* – snarls; *h* – miss; *i* – horizontal stripes, *j* – lumpy; *k* – hole; *l* – dye spot; *m* – lumpy; *n* – horizontal stripes; *o* – fall out; *p* – hairiness; *r-u* – samples with tiny hole defects

Images of garments typically have noise following the scanning process. The clarity of the photos is impacted by this noise, which also distorts the textures and contours of the clothing. Common type of noise that affects the garment images are impulse noise, Gaussian noise and salt & pepper noise. It creates difficulties for the further garments' texture analysis and retrieval process. If noise is present, there is a chance for the misidentification of the noise as a defect. It affects the accuracy of the detection process. So, de-noising is one of the most important steps in the garment inspection process and computation. Noise is removed in this instance using contrast-limited adaptive histogram equalization. Channel-wise Feature Pyramid Network (CFPNet) is for extracting defects, and finally, the DBN algorithm is used for classification.

Contrast Limited Adaptive Histogram Equalization (CLALE)

The local contrast of an image can be improved via CLAHE (figure 3). It is an extension of histogram equalisation using both traditional and adaptive algorithms. Once the algorithm has divided each image into contextual zones, histogram equalisation is applied. This improves the visibility of the image's hidden information and evens out the distribution of the used grey values. The complete greyscale serves as the image. CLAHE is an improved version of AHE, or Adaptive Histogram Equalization, which was developed to address the shortcomings of conventional histogram equalisation.

Instead of processing the entire image, the traditional histogram, AHE method, only processes discrete data portions. (tiles). Because the contrast of each tile has been increased, the output region's histogram

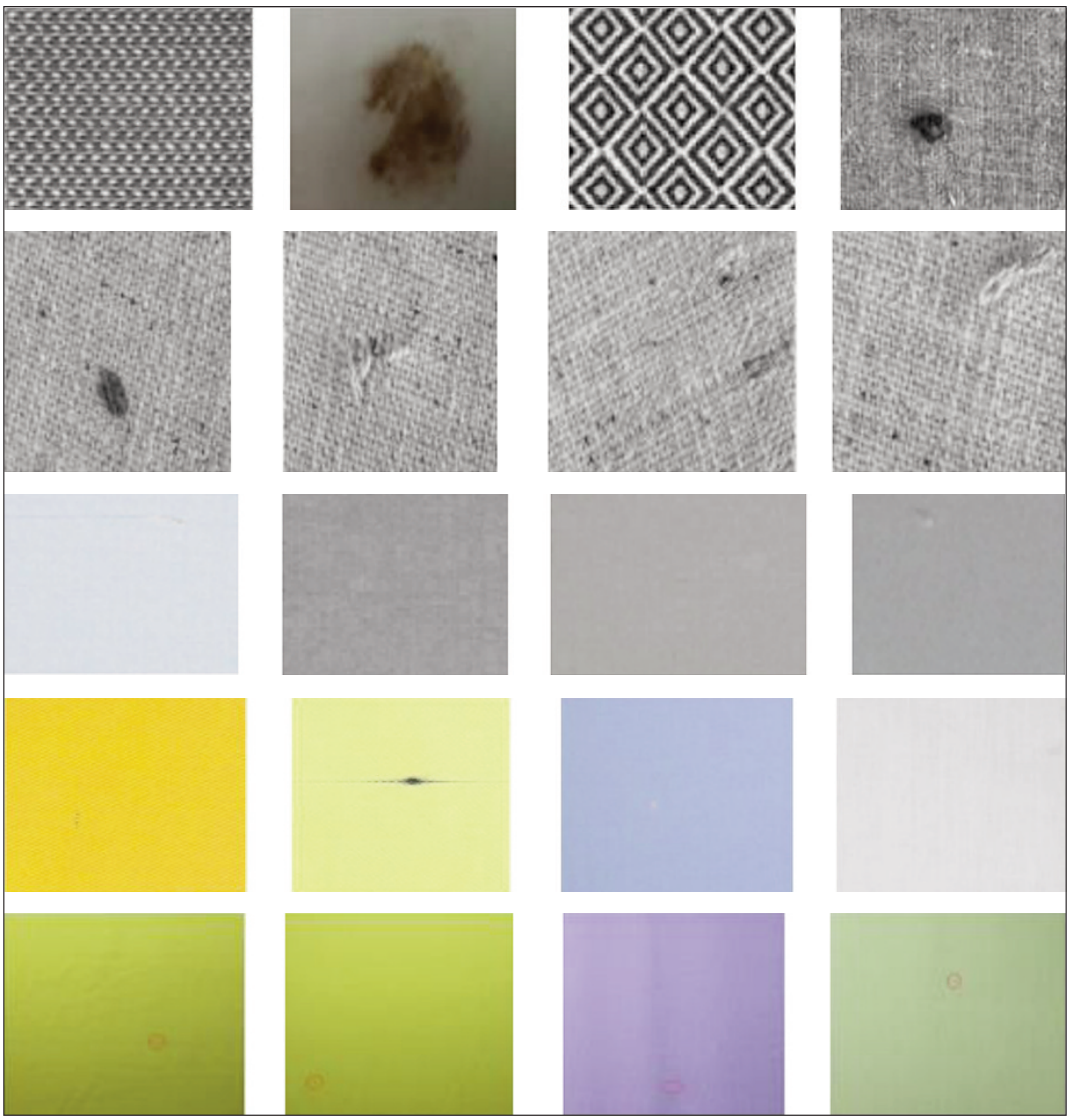


Fig. 3. CLAHE result of input images

roughly resembles the necessary histogram. Next, adjacent tiles are combined using bilinear interpolation to remove artificially created boundaries. Reducing the contrast will prevent the possible noise in the image from increasing, particularly in areas of homogeneity [16].

This algorithm's temporal complexity is $O(M \times N \times W^2 + n)$, where $M \times N$ represents the image's entire pixel count. The window size is W, and there are n bins. The AHE algorithm's temporal complexity rises with window size. So, it is important to choose the window size carefully. A small window lets in noise, whereas a large window lets in artifacts.

CLAHE was introduced to address this AHE issue. Contrast enhancement is the slope of the function that relates the input intensity to the output. According to the cumulative histogram equation 1 with histogram equalization, the mapping function $m(i)$ is proportional.

$$m(i) = (display\ range) * (cumulative\ histogram\ (i) / region\ size \quad (1)$$

Consequently, the derivative of $m(i)$ is related to the *histogram*(i). In CLAHE, the histogram is restricted, which restricts contrast enhancement. Below is a list of the CLAHE algorithm.

- Step 1: Acquire every input, such as the picture, the number of regions in the histograms showing the row and column directions, the number of bins for the histograms showing the dynamic range (also called the "dynamic range"), and the clip limit for contrast limiting. Normalized between 0 and 1.
- Step 2: Process the inputs first: Pad the image before region-based processing and, if needed, extrapolate the real clip limit from the normalized value.
- Step 3: By processing each contextual area (tile), grey level mappings are created: Extract a single region of the image using the number of bins that are provided, use the clip limit to clip the histogram, and then create a mapping (transformation function) for that region.
- Step 4: build the final CLAHE image by interpolating grey level mappings: Extraction of a group of four nearby mapping functions, processing of the portions of the image that partially encircle each mapping tile, extracting a single pixel, connecting four mappings to it, then breaking up the outcomes to get the output pixel; repeat across the picture.

Channel-Wise Feature Pyramid Network (CFPNet)

The Channel-wise Feature Pyramid Network (CFPNet) was created to collect production process parameters and determine how they relate to the final product's quality. The goal is to use the associations found to determine the proper manufacturing process settings to improve product quality.

Operating as the central nervous system of CFPNet, the channel-wise feature pyramid (CFP) module is a factorized convolution operator that splits a large kernel into smaller convolutions. Inception-v2 substitutes two 3 × 3 convolutional operators for the 5 × 5 size kernel that was employed in the original Inception module. Create a module using factorizations and multi-scale feature maps to handle a kernel size of up to 7 × 7. As with Inception-v2, swap out the 5 × 5 and 7 × 7 size kernels for two and three 3 × 3 convolution kernels, accordingly. Our real-time objectives cannot yet be met with this technique's size because of the complex procedure for saving the parameter up to 28% and 45%. To aggregate the convolution kernels into a single channel, only use the three 3 × 3 kernels. The Feature Pyramid (FP) channel was then created by asymmetrically transforming the conventional convolution [17]. Create a multiscale feature map by utilizing a skip connection to merge the recovered data from every asymmetric convolution block. Even with the same receptive field size, the FP channel can save an additional 67% of parameters as compared to the implementation of Inception-v2. Since every asymmetric convolution block has concatenating properties, reorder the filter numbers for each asymmetric block so that the input and output have the same dimension. The first and second blocks of the 3 × 3 and 5 × 5 convolutions, respectively, should be assigned N/4 if the input dimension is N. Pull out the large weighted significant features from the 7 by 7 kernel of the third block using N/2 filters.

Network architecture: To create a shallow network with both light and effective properties, as shown in figure 4. Table 1 also displays the architecture's characteristics. The initial feature extractor starts with three 3 × 3 convolutions. Next, the same down sampling method was used with the ENet [18] model, which comprises a 2 × 2 max pooling, a stride 2 convolution, and a 3 × 3 convolution. The output dimensions are one-eighth the size of the input after these three downsampling repetitions. Before the first and second max pooling layers and the final 1 × 1 convolution, use skip connections to inject decreased input

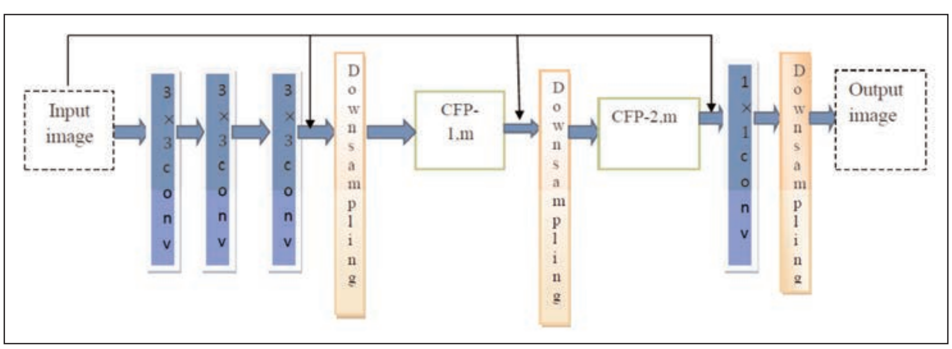


Fig. 4. Architecture of proposed CFPNet

images to provide the segmentation network additional information. Finally, pick the CFP module's repeat intervals of n = 2 and m = 6 using the dilation rates $r_{KCFP}-1$ = [2,2] and $r_{KCFP}-2$ = [4,4,8,8,16,16] for the CFP-1 and CFP-2 clusters, respectively.
The final feature map is activated using a 1 × 1 convolution after the segmentation masks are constructed using a straightforward decoder and bilinear interpolation. After each of those convolutions, the PTeLU activation function and batch normalization are performed. Because studies have already shown that, in a shallow network, PTeLU outperforms TeLU. Each feature contains or represents a key attribute or

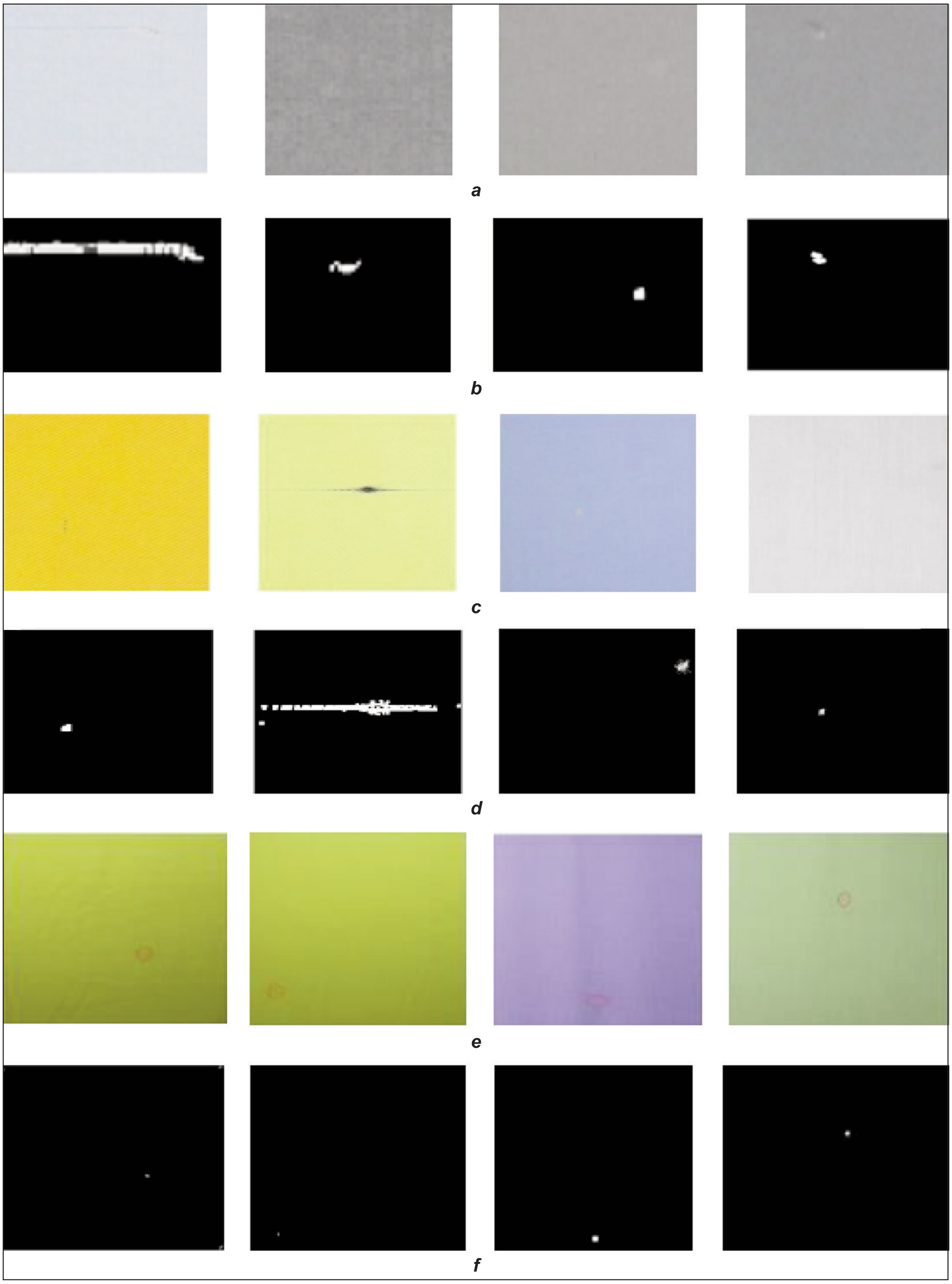


Fig. 5. Results of the proposed method: *a, c, e* – input images with defects; *b, d, f* – detection results of input images

Table 1

ARCHITECTURE DETAILS OF CFPNet			
No.	**Layer**	**Mode**	**Value**
1	3 × 3conv	Stride 2	32
2	3 × 3conv	Stride 1	32
3	3 × 3conv	Stride 1	32
4	Down sampling		64
5-6	2 × *CFP*	$r_k = 2$	64
7	Down sampling		128
8-9	2 × *CFP*	$r_k = 4$	128
10-11	2 × *CFP*	$r_k = 8$	128
12-13	2 × *CFP*	$r_k = 16$	128
14	3 × 3conv	Stride 1	19
15	Bilinear interpolation	× 8	19

set of characteristics from the source image. Hidden neuron's j, k^{th} output in equation 2:

$$\sigma(\rho + \Sigma_{i=0}^{n} W_l, \Sigma_{m=0}^{m} a_j + 1, k + m) \qquad (2)$$

where, σ – Neural activation function, ρ – Shared bias value, W_l, m – Shared Weights ($n \times n$ array), J, k – hidden neurons and $a_{x,y}$ – Activation inputs at x, y.

The output of the convolutional layer is of size $(N - m + 1) \times (Nm + 1)$, where the $N \times N$ input neuron layer is convoluted with a $M \times M$ filter. Through the neural activation function, non-linearity was implemented. The analytic function represents a smooth approximation to the rectifier.

In the convolutional layer, $N \times N$ input neuron layer is convoluted with $M \times M$ filter, then the convolutional layer output will be of size $(N - m + 1) \times (Nm + 1)$. It applied non-linearity through neural activation function. A smooth approximation to the rectifier is the analytic function in equation 3:

$$f(x) = \ln(1 + e^x) \qquad (3)$$

The sparsity in the hidden units is induced by this activation function. It has also been shown that deep neural networks can be trained more efficiently than sigmoid and logistic regression activation functions. Quality control is a crucial aspect of the textile business. Traditional human inspection might result in inaccurate findings, increased costs, and sluggish production. As a result, several researchers employed SVMs to identify flaws in clothing and fabric (including yarn, woven fabric, knit fabric, and dyeing flaws) (i.e., cutting, sewing, and accessories defects). Yet, it never yields a precise result. The most popular kind of DBN is utilized in this study for flaw identification and quality control.

Deep belief network

In increasingly complex setups, deep belief networks can replace deep feed-forward networks or even convolutional neural networks. They gain from having far higher resistance to the vanishing gradients problem and lower computational cost. Deep belief networks include significant restrictions on their weight connections, making them significantly less expressive than deep neural networks, which perform better on jobs for which sufficient input data is available. Even in their prime, deep belief networks were rarely directly applied. Instead, they were used as a pretraining phase to define and train a deep belief network that shared a similar deep neural network's general design. A suitable deep neural network is then built using its weights, modified, and then utilized. Sequentially connected, bounded Boltzmann machines make up a deep belief network. Every Boltzmann machine has an "output" layer that is trained to convergence, frozen, and then used as input by the machine in the chain following it. This process continues until the entire network is trained in equations 4 and 5 [19]:

$$oup = \begin{cases} 1 & \text{with } 1 - Bnz_{prb}(\lambda) \\ 0 & \text{with } 1 - Bnz_{prb}(\lambda) \end{cases} \qquad (4)$$

$$Bnz_{prb}(\lambda) = \frac{1}{1 + e^{-\lambda / pte}} \qquad (5)$$

where pte stands for the pseudo temperature parameter, which supports the probability's noise level. A representation of the stochastic system in equation 6:

$$\lim_{pte \to 0} Bnz_{prb}(\lambda) = \lim_{pte \to 0} \frac{1}{1 + e^{-\lambda / pte}} =$$

$$= \begin{cases} 0 & \text{for } \lambda < 0 \\ 1/2 & \text{for } \lambda = 0 \\ 1 & \text{for } \lambda > 0 \end{cases} \qquad (6)$$

We modify the Boltzmann system depending on the Boltzmann distribution to precisely mimic the input patterns in equation 7.

The joint probability distribution is represented by the energy function given by equation 8, which is derived from the Gibbs distribution and computed using equation 9, where h_n and x_m might have values in the set [0,1], and $\xi_{n,m}$, β_m, γ_n are real valued weights.

$$\max_{\xi} \Pi_{x \in X}\, p(X) \qquad (7)$$

$$E(x,h) = \Sigma_{n=1}^{N} \Sigma_{m=1}^{M} \xi_{n,m} h_n x_m - \Sigma_{m=1}^{M} \beta_m x_m - \Sigma_{n=1}^{N} \gamma_n h_n \qquad (8)$$

$$p(x,h) = \frac{1}{\Sigma_x \Sigma_h e^{-E(x,h)}} e^{-E(x,h)} \qquad (9)$$

Deep networks are initially learned using unsupervised learning, and then supervised learning is applied to improve the model with tagged data. This method nearly always outperforms networks learned without pre-training since pre-training acts as a regularizer and aid for the supervised optimisation problem. The greatest energy that results from tying the network weights is equivalent to the energy found in the directed model, and it is upper bounded by equation 11. For the directed model, one may estimate this energy using equation 10. The derivative equals in equation 12 at equality, which is utilized to resolve the maximization problem, which is now easier to understand.

$$E(x^o,h^0) = -\left(\log p(h^0)\right) + \left(\log p\left(x^o / h^0\right)\right) \quad (10)$$

$$\log p(h^0) \geq \Sigma_{\forall h^0}\, p\left(h^0 / x^o\right) \log p(h^0) + \log p\left(x^o / h^0\right) -$$
$$- \Sigma_{\forall h^0}\, Q\left(h^0 / x^o\right) \log Q\left(h^0 / x^o\right) \quad (11)$$

$$\frac{\partial \log p(x^o)}{\partial \xi_{n,m}} = \Sigma_{\forall h^0}\, p\left(h^0 / x^o\right) \log p(h^0) \quad (12)$$

Figure 6 shows the outcomes of categorization and detection. When the proposed work is applied to the garment photos that have problems, the quality is improved, and the defects are accurately detected.

COMPARATIVE ANALYSIS

In this section, the suggested models are contrasted. MATLAB 2018 is used to implement the proposed task. Two CPUs and 14 GB of RAM and four CPUs

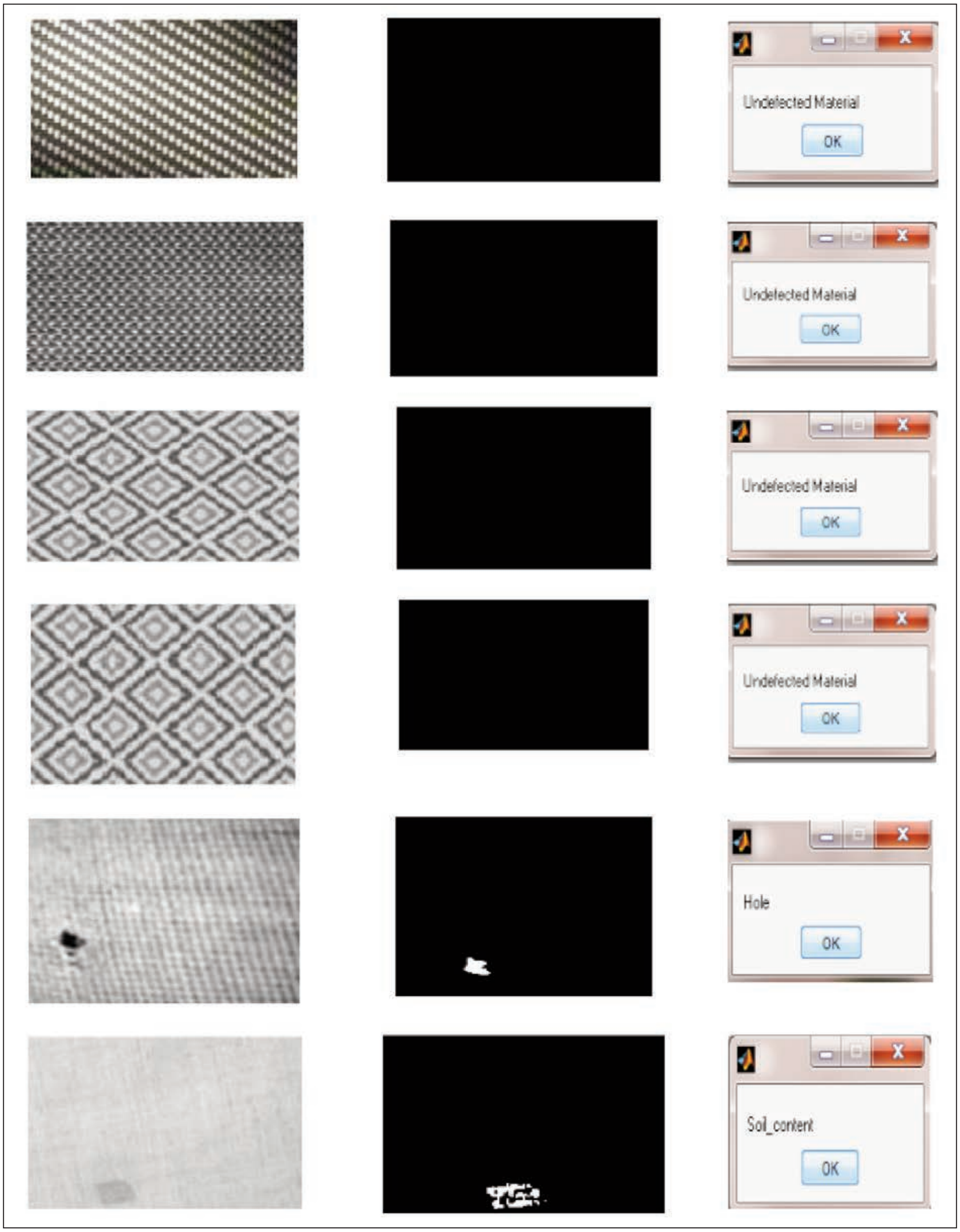


Fig. 6. Results of classification

Table 2

COMPARISON OF ENTROPY, CONTRAST AND EME VALUES WITH EXISTING METHODS				
Sl.No	**Algorithm**	**Entropy**	**Contrast**	**Effective measure of enhancement**
1	Gabor filter	6.991	0.773	52.38
2	Morphological filter	7.210	0.712	31.44
3	Histogram equalization	7.210	0.711	37.75
4	Adaptive Histogram equalization	6.181	0.771	47.52
5	Proposed	7.398	0.792	62.50

and 17 GB of RAM each were used in the computations on the Kaggle kernel. The comparison of the proposed models is followed by the presentation of the evaluations. By computing accuracy, precision, recall, f1-score, quadratic weighted kappa indices, detection rate, TPR, FPR, and confusion matrix, this paper assessed the accuracy, sensitivity, specificity, precision, recall, f1-score, and FPR applied to the DBN methodology used in this instance.

By gathering data on entropy, contrast, effective measure of enhancement, and average computing time, the performance of the proposed task is assessed. Table 2 summarizes performance metrics. Entropy is attained at 7.398, contrast is at 0.792, and EME is at 62.50 in the proposed work. When compared to previous enhancement techniques, the proposed work's entropy is practically identical to that of the original image. As a result, the original image's information content is kept more. Comparing this work to previous enhancement techniques, the average entropy of the suggested work is more similar to the input image.

The performance metrics are displayed in table 3. The proposed work has better precision, sensitivity, specificity, and accuracy than existing approaches, according to a comparison with existing models. When it comes to fabric inspection computation costs, AlexNet – the most popular traditional method – performs better than other conventional works. The most recent developments, GAN and CNN, which are commonly used detection methods, may identify and highlight many kinds of flaws. Evaluations are conducted in the same environment using real clothes samples. This method effectively detects impacts in garments because it applies convolutional layers in both the horizontal and vertical orientations to extract defect features. Since this model relies on the information retrieved from the flaws and the spatial domain approach, its sensitivity would not be satisfied when the defects' contours are vague and confused with the texture of regular clothing. This makes it impossible for this model to correctly represent the entire contour of the faults. Only fault types can be accurately detected by the CFPNet detection model with 97.3% accuracy.

Table 4 displays the suggested work's classification accuracy with other performance metrics. Scanned photos from a fabric guide and photographs from the classification data set were used. The following 12 default categories were chosen: hole, excessive margin, ink stain, crack, stain, ripped, drop stitch, broken end, defect free, and incorrect stitch balance. Photos of garments with holes and no imperfections are categorized more accurately than photos of other defects.

Table 5 shows that the performance metric accuracy is compared with the existing methods for defect-free garment images. The proposed work achieves a high accuracy value of 97.33%, and the image decomposition method provides a low accuracy value of 83.3%. The table compares performance metric accuracy with existing classifiers for the garments image with hole defect. The proposed work achieves a high accuracy value of 97.16%, and the artificial neural network method provides a low accuracy value of 82.33%. The comparison of performance metric accuracy with existing classifiers for the garments image with stain defect is shown in the above table. The proposed work achieves a high accuracy value of 95.85%, and the BPN method provides a low accuracy value of 83.33%. The dye spot values are also shown in the above table.

Table 3

PERFORMANCE COMPARISON TABLE OF PROPOSED AND CONVENTIONAL METHODS					
Classes	**Wavelet transform**	**AlexNet**	**Improved GAN**	**Modified CNN**	**Proposed**
Sensitivity	93.33	90	88.89	84.84	92.5
Specificity	92.85	89.58	96.22	94.12	93.7
Precision	90.32	91.52	96.48	94.73	97.23
Recall	91.2	87.75	90.68	91	93.5
F1-score	89	90	92	91	94
Accuracy	90.16	89.91	92.82	93.56	97.3

Table 4

CLASSIFICATION RESULTS OF GARMENT DEFECTS						
Types of effects	**Accuracy**	**Sensitivity**	**Specificity**	**Precision**	**Recall**	**F1-score**
Defect free	97.33	78.94	98.73	95.85	92	83
Soil stain	95.85	83	98.15	91.32	91.7	91.5
Oil stain	91.32	91.5	98.20	92.2	90.8	92
Double end	92.2	92	98.73	90	98.20	83
Snarls	90	91.7	98.15	92.16	92	98.73
Miss	92.16	90.8	98.73	83	91.7	98.15
Horizontal stripes	93.33	98.20	98.15	91.5	98.73	98.20
Lumpy	94.85	98.73	83	92	98.15	98.73
Dye spot	94.32	98.15	91.5	91.7	93.33	98.15
Fall out	90.2	98.20	92	90.8	94.85	98.73
Hairiness	96	98.73	91.7	98.20	94.32	92
Tiny hole	97.16	98.15	90.8	83	93.33	91.7

Table 5

PERFORMANCE COMPARISON TABLE OF PROPOSED AND CONVENTIONAL WORK FOR THE IMAGE WITH NO DEFECT, HOLE DEFECT AND STAIN DEFECT		
Defects	**Methods**	**Accuracy**
No defect	BPN	83.3
	Modified Elman neural network	84.85
	VGG	90.32
	CNN	91.2
	Proposed	97.33
Tiny hole defect	BPN	82.33
	Modified Elman neural network	84.85
	VGG	92.32
	CNN	91.2
	Proposed	97.16
Stain defect	BPN	83.33
	odified Elman neural network	89.85
	VGG	90.32
	CNN	91.2
	Proposed	95.85
Dye spot	BPN	83
	Modified Elman neural network	87.6
	VGG	85.2
	CNN	89.7
	Proposed	94.32

CONCLUSIONS

The intelligent inspection method for identifying and categorizing garment defects was created and introduced in the current study. For the automatic inspection of apparel products, the method was primarily used and proposed in the textile industry. It was employed to make up for the shortcomings of manual inspection in detecting flaws with accuracy, consistency, and efficiency. As a result of worker exhaustion or ennui, inspection results were frequently unreliable, ambiguous, and prejudiced. To categorise garment flaws in the apparel business, a CFPNet model and DBN neural network were presented in this study. A CLAHE with an enhancement approach was first introduced. A Segmented Approach A faulty picture was created using CFPNet, and the collected photos were then input into a DBN classifier to carry out recognition operations. 12 different types of fabric defects can be categorized, including holes, excessive margins, stains, cracks, poor stitch balancing, needle breaks, ink stains, tears, drop stitches, broken ends, defect-free, and soil content images. The suggested method obtains a 95.85% stain defect detection rate, a 97.33% defect-free garment recognition rate, and a 97.16% hole defect recognition rate. The outcomes of the experiment demonstrate the viability and applicability of the strategy established in this study.

REFERENCES

[1] Ren, M., Liu, Y., Ma, X., *Research on the application status of image recognition technology in the textile and clothing field*, In: SHS Web of Conferences, 2023, 155, 03021, https://doi.org/10.1051/shsconf/202315503021

[2] Ashiba, H.I., Ashiba, M.I., *Novel proposed technique for automatic fabric defect detection*, Multimedia Tools and Applications, 2023, 82, 20, 30783–30806, https://doi.org/10.1007/s11042-023-14368-3

[3] Paulauskaite-Taraseviciene, A., Noreika, E., Purtokas, R., Lagzdinyte-Budnike, I., Daniulaitis, V., Salickaite-Zukauskiene, R., *An intelligent solution for automatic garment measurement using image recognition technologies*, In: Applied Sciences, 2022, 12, 9, 4470. https://doi.org/10.3390/app12094470

[4] Shahrabadi, S., Castilla, Y., Guevara, M., Magalhães, L.G., Gonzalez, D., Adão, T., *Defect detection in the textile industry using image-based machine learning methods: a brief review,* In: Journal of Physics: Conference Series, 2022, 2224, 1, 012010, https://doi.org/10.1088/1742-6596/2224/1/012010

[5] Kim, H., Jung, W.K., Park, Y.C., Lee, J. W., Ahn, S.H., *Broken stitch detection method for sewing operation using CNN feature map and image-processing techniques,* In: Expert Systems with Applications, 2022, 188, 116014, https://doi.org/10.1016/j.eswa.2021.116014

[6] Peng, Z., Gong, X., Lu, Z., Xu, X., Wei, B., Prasad, M., *A novel fabric defect detection network based on attention mechanism and multi-task fusion,* In: 7th IEEE International Conference on Network Intelligence and Digital Content (IC-NIDC), 2021, 484–488, https://doi.org/10.1109/IC-NIDC54101.2021.9660399

[7] Zhu, D., Pan, R., Gao, W., Zhang, J., *Yarn-dyed fabric defect detection based on autocorrelation function and GLCM,* In: Autex Research Journal, 2015, 15, 3, 226–232, https://doi.org/10.1515/aut-2015-0001

[8] Li, Y., Zhao, W., Pan, J., *Deformable patterned fabric defect detection with fisher criterion-based deep learning,* In: IEEE Transactions on Automation Science and Engineering, 2016, 14, 2, 1256–1264, https://doi.org/10.1109/TASE.2016.2520955

[9] Tong, L., Wong, W.K., Kwong, C.K., *Differential evolution-based optimal Gabor filter model for fabric inspection,* In: Neurocomputing, 2016, 173, 1386–1401, https://doi.org/10.1016/j.neucom.2015.09.011

[10] Chittilappilly, A.J., Subramaniam, K., *SVM based defect detection for industrial applications,* In: 4th International Conference on Advanced Computing and Communication Systems (ICACCS), 2017, 1–5, https://doi.org/10.1109/ICACCS.2017.8014696

[11] Li, C., Gao, G., Liu, Z., Yu, M., Huang, D., *Fabric defect detection based on biological vision modeling*, In: IEEE Access, 2018, 6, 27659–27670, https://doi.org/10.1109/ACCESS.2018.2841055

[12] Patil, M., Patil, S.R., *Fabric defect detection using discrete wavelet transform*, In: Int. Res. J. Eng. Technol., 2019, 6, 06

[13] Johnson, J.M., Chen, Z., Varley, J.B., Jackson, C.M., Farzana, E., Zhang, Z., Hwang, J., *Unusual formation of point-defect complexes in the ultrawide-band-gap semiconductor β-Ga 2 O 3*, In: Physical Review X, 2019, 9, 4, 041027, https://doi.org/10.1103/PhysRevX.9.041027

[14] Cao, H., Ji, X., *Prediction of garment production cycle time based on a neural network*, In: Fibres & Textiles in Eastern Europe, 2021, 1, 145, 8–12, https://doi.org/10.5604/01.3001.0014.5036

[15] Kim, H., Jung, W.K., Park, Y.C., Lee, J.W., Ahn, S.H., *Broken stitch detection method for sewing operation using CNN feature map and image-processing techniques*, In: Expert Systems with Applications, 2022, 188, 116014, https://doi.org/10.1016/j.eswa.2021.116014

[16] Kumar, K.S., Bai, M.R., *LSTM based texture classification and defect detection in a fabric*, In: Measurement: Sensors, 2023, 26, 100603, https://doi.org/10.1016/j.measen.2022.100603

[17] Oosterom, E.B., Baytar, F., Akdemir, D., Kalaoglu, F., *Predicting consumers' garment fit satisfactions by using machine learning*, In: AUTEX Research Journal, 2024, 24, 1, 20230016, https://doi.org/10.1515/aut-2023-0016

Authors:

DENNISE MATHEW, N.C. BRINTHA

Kalasalingam Academy of Research and Education, Department of Computer Science and Engineering, Krishnankoil, Srivilliputhur, Tamil Nadu 626126, India

Corresponding author:

DENNISE MATHEW
e-mail: dennisemathew@gmail.com

Predictive power of newfangled GARCH models in assessing stock price volatility of Indian textile companies

DOI: 10.35530/IT.076.02.2023138

BHARAT KUMAR MEHER
SANTOSH KUMAR
ZABHISHEK ANAND
RAMONA BIRAU
VIRGIL POPESCU
SUNIL KUMAR
PETRE VALERIU NINULESCU
MUHAMMAD AWAIS-E-YAZDAN

ABSTRACT – REZUMAT

Predictive power of newfangled GARCH models in assessing stock price volatility of Indian textile companies

This research endeavours to contribute to the existing body of knowledge by assessing the predictive power of various GARCH models in the specific context of Indian textile companies listed on stock exchanges. The GARCH family encompasses several models, each designed to address specific aspects of volatility dynamics. By evaluating the performance of these models against historical stock price data, we aim to shed light on their efficacy in forecasting volatility patterns and enhancing risk management strategies for investors in the Indian textile sector by applying symmetric and asymmetric models, namely: FIGARCH, FIEGARCH, GJR-GACRH, EGARCH and GARCH (1.1). The object of the study includes quantitative analysis, estimation and forecasting of daily volatility with Normal, Students-t distributions and generalized error distribution constructs of various Indian textile market i.e. KPR Mill Limited (NLKPRM), The Trident Group (NLTRIE), Page industry limited (NLPAGE), Welspun India Limited (NLWLSP) and, Alok Industries Limited (NLALOK). The objective is to discern the impact of the global financial crisis on the linkages across these textile markets. The sample data spans a long period from April 2013 to May 2023 and includes the COVID-19 pandemic, the war between Russia and Ukraine, Current conflicts in the Middle East and climate risk.

Keywords: *textile industry in India, volatility, GARCH models, long memory, leverage effect, COVID-19 pandemic*

Puterea predictivă a modelelor GARCH de ultimă generație în evaluarea volatilității prețului acțiunilor companiilor textile din India

Acest studiu încearcă să contribuie la ansamblul de cunoștințe existente prin evaluarea puterii de predicție a diferitelor modele GARCH în contextul specific al societăților textile indiene cotate la bursă. Familia GARCH cuprinde mai multe modele, fiecare conceput pentru a aborda aspecte specifice ale dinamicii volatilității. Prin evaluarea performanței acestor modele în raport cu datele istorice privind prețurile acțiunilor, ne propunem să determinăm eficacitatea lor în prognozarea modelelor de volatilitate și îmbunătățirea strategiilor de gestionare a riscurilor pentru investitorii din sectorul textil din India, prin aplicarea modelelor simetrice și asimetrice, și anume: FIGARCH, FIEGARCH, GJR-GACRH, EGARCH și GARCH (1.1). Obiectul studiului include analiza cantitativă, estimarea și prognoza volatilității zilnice cu distribuții normale, Students-t și distribuții generalizate ale erorilor pe diferite piețe textile din India, și anume KPR Mill Limited (NLKPRM), The Trident Group (NLTRIE), Page industry limited (NLPAGE), Welspun India Limited (NLWLSP) și Alok Industries Limited (NLALOK). Obiectivul este de a discerne impactul crizei financiare globale asupra legăturilor dintre aceste piețe textile. Datele eșantionului se întind pe o perioadă lungă de timp, din aprilie 2013 până în mai 2023, și includ pandemia COVID-19, războiul dintre Rusia și Ucraina, conflictele actuale din Orientul Mijlociu și riscul climatic.

Cuvinte-cheie: *industria textilă din India, volatilitate, modele GARCH, memorie de lungă durată, efect de pârghie, pandemie COVID-19*

INTRODUCTION

In the dynamic environment of financial markets, the ability to accurately forecast and manage stock price volatility is crucial for investors, financial analysts, and policymakers alike [1–4]. Volatility, a measure of the degree of variation of a trading price series over time, plays a pivotal role in rational investment decisions and risk management strategies [5–9]. This research paper explores the realm of stock price volatility within the context of the Indian textile industry, employing advanced financial modelling techniques known as the Generalized Autoregressive Conditional Heteroskedasticity (GARCH) family models.

The textile industry in India, a cornerstone of the nation's economy, has witnessed substantial growth and transformation over the years [10–13]. As listed textile companies navigate through the complexities of global markets [14–17], understanding and effectively managing stock price volatility becomes imperative for sustaining competitiveness and ensuring financial stability. The GARCH family models, known for their efficacy in capturing time-varying volatility patterns, provide a robust framework for analysing and predicting the inherent uncertainty in stock prices [18–23]. This research endeavours to contribute to the existing body of knowledge by assessing the predictive power of various GARCH models in the specific context of Indian textile companies listed on stock exchanges. The GARCH family encompasses several models, each designed to address specific aspects of volatility dynamics [24–27] by evaluating the performance of these models against historical stock price data, we aim to shed light on their efficacy in forecasting volatility patterns and enhancing risk management strategies for investors in the Indian textile sector. The motivation behind this research stems from the critical need for accurate and reliable volatility forecasts in financial decision-making processes. Investors and financial institutions often rely on volatility estimates to make informed investment decisions, design optimal hedging strategies, and assess risk exposures. The unique characteristics of the Indian textile industry, influenced by both domestic and global factors, provide an intriguing backdrop for exploring the applicability and effectiveness of GARCH models in this particular economic context.

REVIEW OF LITERATURE

GARCH [28–30] family models are widely used in finance to forecast and analyse volatility in stock prices [31]. A study compared three GARCH models (Symmetric GARCH, GJR-GARCH, and E-GARCH) and found that the E-GARCH model was accepted for predicting and forecasting market volatility. These models take into account the uncertainty in stock returns, prices, and unexpected events [32]. They are important for risk management and portfolio optimization [31]. Another study compared seven GARCH-family models and found that the standard GARCH model provided the best one-step-ahead forecasts of daily conditional variance [33]. Different factors influence the performance of GARCH models, such as the sample window period, forecasting horizon, financial period, and underlying distribution of log returns [31]. The AR(1)-GARCH (1,1) model was found to be the best fit for estimating parameters, predicting share prices, and forecasting volatility [34]. Realized GARCH variants, such as log-linear RealGARCH, RealEGARCH, and GARCH@CARR, have been proposed for volatility forecasting.

A study comparing these variants found that the GARCH@CARR model outperformed the others in terms of forecasting efficiency [35].

Stock price volatilities are assessed using GARCH models by analysing historical data and estimating parameters based on closing prices, as well as other information such as daily minimum and maximum prices [36]. These models help in understanding the behaviour of stock returns and the risk associated with them [37]. Different types of GARCH models are used to assess stock price volatility. Some commonly used models include Symmetric GARCH, GJR-GARCH, E-GARCH, and TGARCH [38]. The choice of model depends on factors such as the sample window period, forecasting horizon, financial period, and underlying distribution of log returns [31].

Assessing stock price volatility is significant for Indian textile companies as it helps investors and market participants make informed investment decisions [39–41]. Volatility provides opportunities for risk-seeking investors to earn unexpected profits, but it also raises concerns for risk-averse investors.

Understanding and predicting volatility can help companies manage their risk exposure and optimize their financial strategies [32, 42].

GARCH family models are used to assess stock price volatility in Indian textile companies. These models help in understanding and predicting volatility, which is significant for investors and companies in managing risk and making informed decisions. Different types of GARCH models are used based on various factors, and they take into account the uncertainty and unexpected events in stock returns and prices.

Research gap

Despite the extensive use of GARCH models in financial research, a noticeable research gap exists in the context of Indian textile companies. No studies have specifically investigated the predictive power of GARCH models in assessing stock price volatility within this industry. Given the unique dynamics of the Indian textile sector, characterized by diverse factors such as raw material fluctuations, global market dependencies, and policy influences, there is a dearth of comprehensive analyses. This research aims to fill this gap by providing an in-depth examination of the applicability and effectiveness of GARCH models in forecasting stock price volatility for Indian textile companies, contributing valuable insights to both academic literature and financial practitioners.

Need of the study

This research aspires to contribute valuable insights to both academic and practitioner communities by exploring the predictive power of GARCH family models in assessing stock price volatility within the unique context of the Indian textile industry. As financial markets continue to evolve, the ability to navigate and mitigate risks associated with stock price fluctuations remains paramount, making this investigation particularly timely and relevant. The findings from this study can empower investors, financial institutions, and policymakers to make informed decisions regarding investments in Indian textile companies. By assessing the predictive capabilities of GARCH models, the research contributes to enhancing market efficiency, enabling more transparent and rational decision-making. Investors can benefit from improved risk assessments, adjusting their portfolios to navigate the dynamic landscape of stock price movements. Furthermore, the study's outcomes may have broader implications for economic stability, influencing regulatory measures and strategies to promote financial health. This research not only advances academic knowledge in the field but also has practical applications that extend to investor education, industry competitiveness, and the overall economic growth of society at large.

Limitations of the study

- External Factors and Market Shocks: GARCH models primarily focus on endogenous factors to explain volatility, neglecting important exogenous variables and unforeseen events that can significantly impact stock prices. External factors such as macroeconomic changes, geopolitical events, or sudden market shocks may not be adequately captured by the GARCH model. Consequently, the model's predictive power may be limited in situations where these external factors play a crucial role in driving volatility.
- Parameter Sensitivity and Model Calibration: GARCH models involve the estimation of various parameters, and the results can be sensitive to the chosen model specifications and calibration techniques. Different researchers might use different parameter values, leading to divergent conclusions. Sensitivity to parameter choices can undermine the robustness of the findings and make it challenging to generalize the results across different studies or periods.

RESEARCH METHODOLOGY

India is one of the most successful countries in the textile industry, along with China. In today's competitive world, the textile manufacturing industry in India has made a global splash in garment manufacturing using advanced technology. India's top textile companies have been working to create a competitive product range and increase the number of innovative clients. Companies are constantly working to improve product quality and stay in the global market. The textile industry is one of the most important industries in the history of India. The textile industry is a field which has a strange connection between agriculture and industry. The cultivation of cotton, the cultivation of silk – the outcome of which depends largely on the textile industry. India is currently emerging as one of the brightest places in the world economy for textile companies. This country is currently the most attractive investment destination in the world. This research paper examines changes in volatility parameters as well as the movement behaviour of selected Indian textile industries market (i.e. KPR Mill Limited (NLKPRM), The Trident Group (NLTRIE), Page industry limited (NLPAGE), Welspun India Limited (NLWLSP) and Alok Industries Limited (NLALOK). They were selected based on their market capitalization as listed on the money control website, accessed on September 2023. For this purpose, we collected the daily opening price, closing price, high price, and low price of the various textile industries (figure 1 and table 1).

Steps of analysing the data

Step-1: Variables Description and Data Sources
Step-2: Calculation of Log Returns
Step-3: Unit Root Test
Step-4: Visualization of Volatility Clustering
Step-5: ARCH effect Diagnosis.
Step-6: Different GARCH Model formulation.
Step-7: Selection of Suitable GARCH Model using the statistics like LLH, AIC and SIC.

This paper's primary goal is to examine the method for estimating the influence of long-term volatility on the Analysis of Volatility of selected sample using Generalized Autoregressive Conditional Heteroscedasticity (GARCH) class models; GARCH (1, 1) model, EGARCH model, GJR-GARCH, PGARCH, FIGARCH and FIEGARCH model to estimate the presence of leverage effect. Traditional heteroskedastic models either specify the conditional variance as in Bollerslev [28] or describe the conditional standard deviation directly as in Taylor [43]. ADF and PP test statistics) have been used to determine whether the data is stationary to apply various

Table 1

DESCRIPTION AND SOURCE OF DATA RELATED TO INDIAN TEXTILE INDUSTRIES		
Name of the company	**Source of data collection**	**Observations**
KPR Mill Limited (LKPRM)	https://finance.yahoo.com	2610
The Trident Group (NLTRIE)	https://finance.yahoo.com	2610
Page industry limited (NLPAGE)	https://finance.yahoo.com	2610
Welspun India Limited (NLWLSP)	https://finance.yahoo.com	2610
Alok Industries Limited (NLALOK)	https://finance.yahoo.com	2610

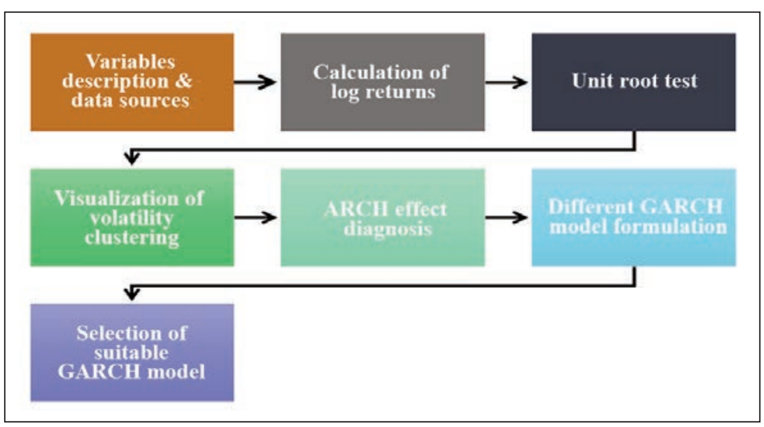


Fig. 1. Flow chart depicting the process of analysing the data

GARCH family models. To choose the most appropriate asymmetric volatility model for stock markets, numerous criteria have been used to examine the results of the models after they had been created using different distributions. E-Views 12 has been applied to the creation of models for certain stock indexes.

ANALYSIS, RESULTS AND DISCUSSION

There are various models in the GARCH Family. A brief of each kind of GARCH model is mentioned below.

EGARCH model

"The log of the variance distinguishes the EGARCH model from the GARCH variance structure" [44]. The EGARCH model is represented by equation 1.

$$\log(\sigma_t^2) = \omega + \sum_{j-i}^{p} \beta\, i \log(\sigma_{t-i}^2) + \\ + \sum_{j-1}^{q} \alpha\, i \langle \frac{\varepsilon\, i-t}{\sigma_{i-t}} \left| \frac{-\sqrt{2}}{n} \right| - yi \frac{\varepsilon\, i-t}{\sigma\, i-t} \rangle \quad (1)$$

GJR-GARCH

The model proposed by Glosten et al. [45] is a variation of the GARCH model that considers the asymmetry of returns. It is denoted by GJR-GARCH and defined by equation 2:

$$\sigma_t = \omega + \alpha\iota\,[\varepsilon_{t=1} \geq 0]\,\varepsilon_{t=1} + \gamma\iota\,[\varepsilon_{t=1} < 0]\,\varepsilon_{t=1} \beta\, \alpha_{t-1} \quad (2)$$

The impulse of unfavourable shocks ($\alpha + \gamma$) is greater than the impulse of favourable shocks (α), indicating asymmetry.

PGARCH models

The variance in a PGARCH model (general) is written as:

$$\sigma_t^{\delta} = \omega + \sum_{i=1}^{p} (\alpha_i\,|y_{t-i}| - y_i y_{t-i})^{\delta} + \sum_{j=1}^{q} \beta_j\, \sigma_{t-j}^{\delta} \quad (3)$$

This is an essential prerequisite for the positive variance. In the financial data series, higher values of the α_i coefficient show a greater volatility response to market shocks, whereas larger coefficients of the β_j coefficient shows the presence of market shocks [46, 47].

FEGARCH

FEGARCH, or Fractionally Integrated Exponential Generalized Autoregressive Conditional Heteroscedasticity, is a statistical model used in financial econometrics and time series analysis to model and forecast volatility in financial data. It is an extension of the more commonly known GARCH model [48].

Mathematically, the FEGARCH (p, d, and q) model can be represented as follows:

$$r_t = \sigma_y\, \varepsilon_t$$

$$\sigma_t^2 = \alpha_0 + \Sigma_{i=1} \alpha_i (|\varepsilon_{t-1}| - \gamma\,|\varepsilon_{t-1}|)\, \Sigma_{j=1} \beta_j\, \sigma_{t-j}^2 + \\ + \Sigma_{k=1} \theta_k (|\epsilon_{t-k}| - \gamma\,|\epsilon_{t-k}|) \quad (4)$$

FIEGARCH model

The FIEGARCH model was proposed by Bollerslev and Mikkelsen [28, 49]. In its simplest form, the FIEGARCH model is given by:

$$\gamma_t = \sigma_y\, \varepsilon_t\,(1 - \varphi L)(1 - L)^d \log\sigma_t^2 = \omega + g(\varepsilon_t - 1) \quad (5)$$

where $g(\varepsilon_t) = \alpha\left(|\varepsilon_t| - \sqrt{\frac{2}{\pi}}\right) + \gamma\varepsilon_t$ and ε_t is the Gaussian white noise with variance 1. The parameter y measures the leverage effect, as before d in the long memory parameter.

Empirical results and findings

We begin with a descriptive statistics study to understand the value of investor return in chosen textile market indexes from April 2013 to March 2023. Table 2 summarizes the profitability statistics of five textile industries' prices. When compared to another sample, the mean return of NLKPRM (0.001522) is greater than other samples, followed by NLPAGE (0.000931) and NLTRIE (0.000468). The standard deviation of NLTRIE (0.054654) and NLWLSP (0.053083) was higher as compared to other samples, followed by NLALOK (0.035647). This means that while textile industries deliver bigger returns, their volatility (risk) is also higher. The skewness of NLTRIE and NLWLSP is negative, and all industries' prices are leptokurtic since the kurtosis value is greater than three. The presence of leptokurtic influence on the series returns is shown by the aberrant pattern of kurtosis.

All the selected samples of Indian textile industries contain a significant number of normal volatility rates and quantifiable anomalous scales. Investors, academics, and researchers should pay close attention to the post-financial crisis scale and positive return ratios. It indicates unambiguously how seriously investors take long-term investing.

Log returns for financial data series, such as the NLPAGE, NLKPRM, NLTRIE, NLWLSP, and NLALOK have been determined for the eight asymmetric GARCH Models, GARCH (1, 1), EGARCH, GJR-GARCH, PGARCH, FIGARCH and FIEGARCH. The unit root test, or the Augmented Dickey-Fuller Test, was used to assess the stationarity of the sample data of Indian textile industries, which contains the test equations Intercept, Trend, and Intercept, and None. The sample data were discovered to be stationary since the probability values are significant at <0.01 (lower part of table 2). In the following table 3, the group unit root test of all selected samples from Indian textile industries has been highlighted. The group's sample data were also discovered to be stationary since the probability values are significant at <0.01 (table 3).

The Johansen cointegration test is a statistical method used in econometrics to assess whether there is a long-run relationship, or cointegration, between two or more time series variables. This test is particularly useful when dealing with non-stationary time series data, where the variables may have trends and exhibit stochastic behaviour. Results indicated

Table 2

DESCRIPTIVE STATISTICS					
Variables	**NLPAGE**	**NLKPRM**	**NLTRIE**	**NLWLSP**	**NLALOK**
$\bar{x}$	0.000931	0.001522	0.000468	$-1.51 \cdot 10^{-5}$	0.000104
σ	0.0197	0.023645	0.054654	0.0530 83	0.035647
x~	–0.00027	0.000000	–0.000977	–0.00093	0.000000
Skew	0.343168	0.372254	–27.99227	–30.39278	0.918334
β2	6.528163	8.784051	1181.382	1303.335	7.054886
Max.	0.145081	0.134037	0.182322	0.164303	0.257189
Min.	–0.108278	–0.195999	–2.288696	–2.278659	–0.150481
Jarque-Bera	1404.402	3697.121	1.51E+08	$1.84 \cdot 10^{8}$	2154.105
Sum Sq. Dev.	1.012113	1.458104	7.790358	7.348835	3.314042
Numbers	2609	2609	2609	2609	2609
Probability	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
ADF test	–48.57012 (< 0.01)	–48.94204 (< 0.01)	–48.81558 (< 0.01)	–49.82232 (< 0.01)	–27.84377 (< 0.01)
PP test	–48.51221 (< 0.01)	–49.02635 (< 0.01)	–48.79528 (< 0.01)	–49.82361 (< 0.01)	–41.35911 (< 0.01)

Notes: The table presents the main statistics (the max (Max.) and minimum (Max.), the mean ($\bar{x}$), standard deviation (σ), skewness (Skew.), and kurtosis (Kurt.)) for the selected textile industries prices considering the value of log returns. Sample period: April 2013 – March 2023. Number of observations: 2610 for each sample.

Table 3

GROUP UNIT ROOT TEST				
Group unit root test: Summary				
Series: NLPAGE, NLKPRM, NLTRIE, NLWLSP, NLALOK				
Automatic lag length selection based on SIC: 0 to 1				
Newey-West automatic bandwidth selection and Bartlett kernel				
Method	Statistic	Prob.**	Cross-sections	Obs
Null: Unit root (assumes common unit root process)				
Levin, Lin & Chu t*	–134.714	< 0.0001	5	13039
Null: Unit root (assumes individual unit root process)				
Im, Pesaran and Shin W-stat	–112.696	< 0.0001	5	13039
ADF – Fisher Chi-square	285.148	< 0.0001	5	13039
PP – Fisher Chi-square	123.293	< 0.0001	5	13040

Notes: ** Probabilities for Fisher tests are computed using an asymptotic Chi-square distribution. All other tests assume asymptotic normality.

that the all the selected index are cointegrated as we can see that the value of the trace statistics and max-Eigen statistics is greater than the value of the 0.06 critical value.

The following sections are built on evaluating the relevant hypotheses needed to create the various GARCH family models. Figure 1 shows graphs with the log returns of the selected Indian textile industries market displayed to show the presence of volatility clustering (figures 2 and 3). Movement style of the Stationary Series for NLPAGE, NLKPRM, NLTRIE, NLWLSP, and NLALOK. Figure 2 shows graphs with the log returns of the selected indexes of the top five countries' stock markets displayed to show the presence of volatility clustering.

The property of figure 2 indicates there are different clusters in this diagram because we can see that in the Line graphs in figure 2, sometimes volatility is high and sometimes volatility is less. In figure 3, we represent the comparative volatility sketches of all selected indices.

After examining the log return graphs of selected financial data series in figures 2 and 3, it is clear that the data exhibits volatility clustering. These significant changes during 2008 and 2020 are a blatant sign that the pandemic is having a leveraging impact on market values, and asymmetric GARCH models would be suitable for simulating the volatility of the stock prices of a chosen index.

Implementation of GARCH Models for Alok Industries Limited of India

Alok Industries Limited is an Indian textile company that operates in various segments of the textile industry.

Table 4

JOHNSON COINTEGRATION TEST AND CORRELATION MATRIX						
Series: NLPAGE NLKPRM NLTRIE NLWLSP NLALOK						
Hypothesized No. of CE(s)	**Eigenvalue**	**Trace Statistic**	**0.05 Critical Value**	**Max-Eigen Statistics**	**0.05 Critical value**	**Prob.****
None *	0.191857	2284.355	69.81889	554.6933	33.87687	0.0000
At most 1 *	0.171755	1729.662	47.85613	490.7147	27.58434	0.0000
At most 2 *	0.166832	1238.947	29.79707	475.2809	21.13162	0.0000
At most 3 *	0.162685	763.6662	15.49471	462.3529	14.26460	0.0000
At most 4 *	0.109268	301.3134	3.841465	301.3134	3.841465	0.0000
Correlation	**NLPAGE**	**NLKPRM**	**NLTRIE**	**NLWLSP**	**NLALOK**	-
NLPAGE	1	-	-	-	-	-
NLKPRM	0.1647	1	-	-	-	-
NLTRIE	0.0598	0.1502	1	-	-	-
NLWLSP	0.0919	0.1308	0.0778	1	-	-
NLALOK	0.0889	0.1742	0.1358	0.0977	1	-

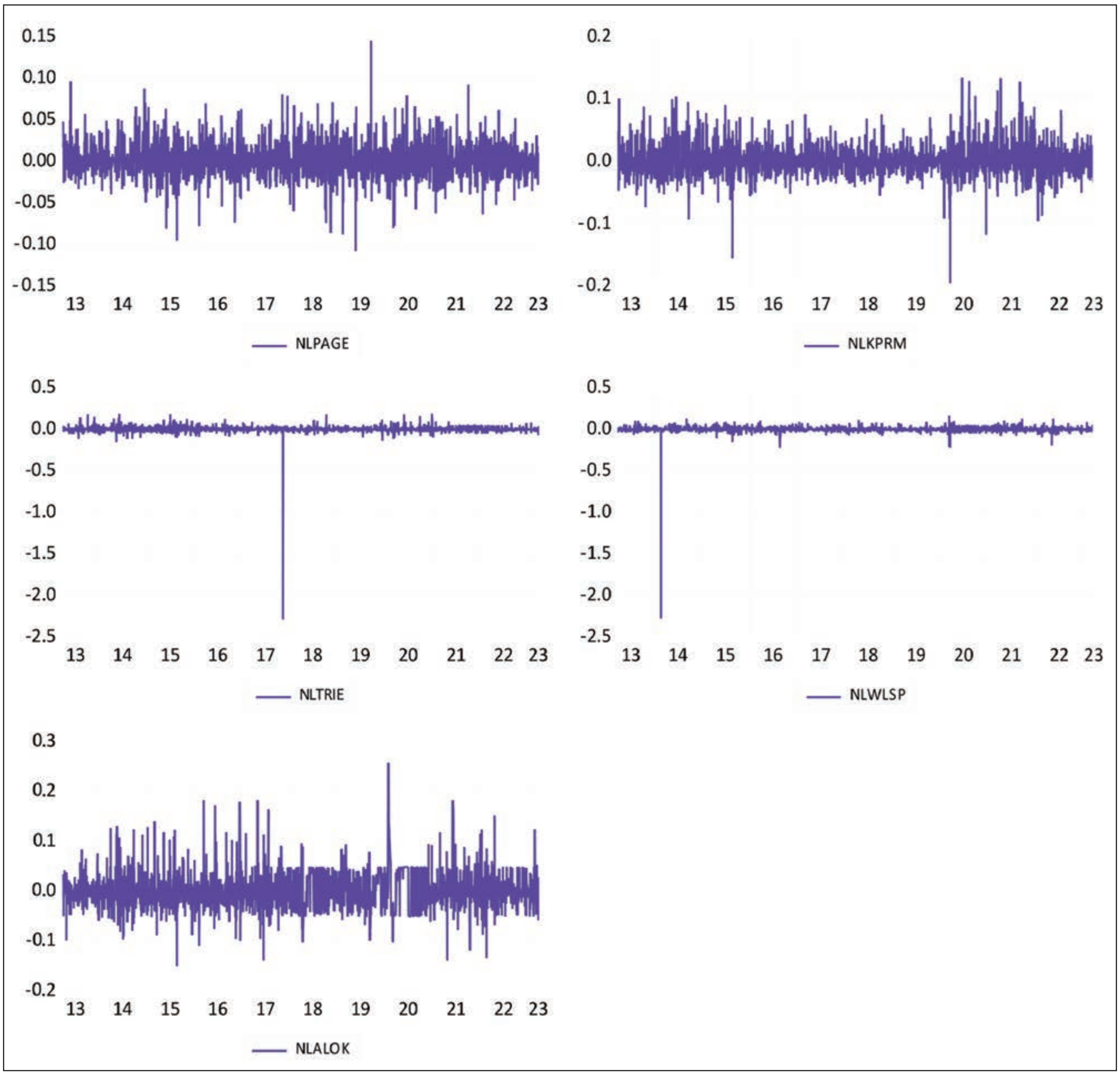


Fig. 2. Movement pattern of selected variables of Indian textile industries

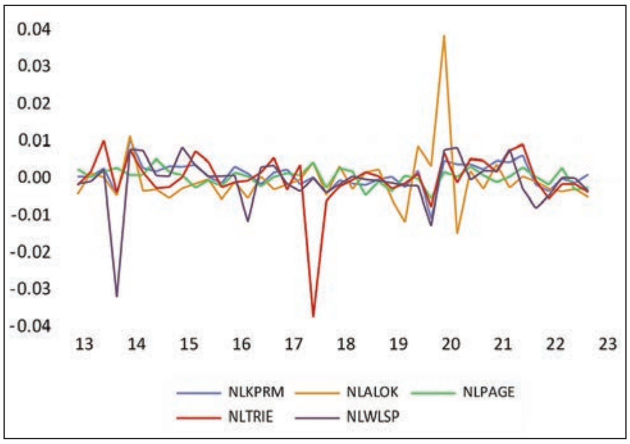


Fig. 3. Comparative volatility sketches of Indian textile industries

It is engaged in the manufacturing of a wide range of textile products, including cotton yarn, synthetic yarn, fabric, and garments. The company's products cater to both domestic and international markets. The company serves a diverse customer base, supplying textiles and garments to various sectors, including apparel brands, retailers, and institutional buyers. Alok Industries has a significant focus on exports and is known for its global reach. The company exports its products to several countries around the world. Alok Industries has a significant focus on exports and is known for its global reach. The company exports its products to several countries around the world.

All of the asymmetric GARCH models reflect the asymmetric volatility effect for Alok Industries Limited of India (table 5). The study discovered that the PGARCH under Student-t distribution is the best to explain asymmetric volatility of selected textile stocks returns, as the Adjusted R2 and Log likelihood values are high with significant coefficient and Arch effect. As a result, the PGARCH model is thought to be the best one. The table below lists the outcomes of the

Table 5

CHOOSING AN APPROPRIATE GARCH MODEL: ALOK INDUSTRIES LIMITED OF INDIA			
GARCH models	**LLH**	**AIC**	**SIC**
ARCH	5365.980	–4.111181	–4.099934
GARCH (11)	5388.013	–4.127311	–4.113815
GJR-GARCH	5388.039	–4.126564	–4.110818
EGARCH	5396.816	–4.133294	–4.117549
PGARCH	**5409.652**	**–4.142371**	**–4.124377**
FIGARCH	5396.333	–4.132924	–4.117178
FIEGARCH	5207.914	–3.987664	–3.969669

chosen PGARCH Model for Alok Industries Limited of India.

Alok Industries Limited of India is represented in the above table as the output of the PGARCH (1, 1, 1) model using students' distribution constructed as a best model. The constant (mu) in the primary equation is significant because their probabilities are less than 0.05. As their probability values are all less than 0.05, every coefficient in the variance equation is considered significant. Focus should be placed on the fact that the coefficient of the asymmetric term Alpha /ARCH) is negative, or –0.016212. This suggests that there is a leverage effect on the Alok industries' price volatility, and it also indicates that negative news has a greater impact on this volatility.

Implementation of GARCH Models for KPR Mill Limited of India

KPR Mill Limited is an Indian company operating in the textile industry. It is one of the largest vertically integrated textile manufacturers in India and is involved in various segments of the textile value chain, including yarn, fabric, and garments. KPR Mill is known for its vertical integration, which means it is involved in multiple stages of the textile value chain,

Table 6

RESULTS OF VARIOUS GARCH MODELS: ALOK INDUSTRIES LIMITED OF INDIA							
GARCH models	**Constant (mu)**	**Unconditional variance (ω)**	**Alpha (ARCH)**	**Beta (GARCH)**	$\alpha+\beta$	γ	
ARCH	–0.002615	**0.250341**	0.640816	-	-	-	
GARCH (11)	–0.002258*	0.246620*	0.504361*	0.325076*	0.82	-	
TGARCH	–0.002284*	0.246161*	0.497540*	0.325606*	**0.81**	**0.018754 (0.8660)**	
EGARCH	–0.002219*	0.262543*	0.555596*	0.710309*	1.26	–0.013929 (0.7084)	
PGARCH	**–0.002964***	**0.211929***	**0.326823***	**0.486898***	**0.80**	**–0.016212 (0.8284)**	
		OMEGA	ALPHA	BETA	THETA1	THETA2	D
FIGARCH	–0.002379*	0.231829*	0.568524*	0.361573 (0.0035)			0.263816 (0.0201)
FIEGARCH	–0.000538	0.000000	0.0009*	0.0480*	0.0000	0.1586	0.0000

Note: * means p value is < 0.05.

from spinning yarn to producing fabrics and ready-made garments. This integration allows the company to have better control over the quality and efficiency of its products. KPR Mill has its headquarters in Coimbatore, Tamil Nadu, India. The company's product range includes a wide variety of yarns, fabrics, and ready-made garments, catering to both domestic and international markets. KPR Mill is known for its high-quality products and has earned a reputation as a reliable supplier in the textile industry. Additionally, the company places a strong emphasis on sustainability and eco-friendly practices. It has implemented various measures to reduce its environmental impact and promote responsible manufacturing. The empirical results show that our approach is statistically superior to other models and represents a valuable methodology that can be used by risk managers, investors, and policymakers to assess the effects of the pandemic on spillover effects in energy markets.

Table 7

CHOOSING AN APPROPRIATE GARCH MODEL: KPR MILL LIMITED OF INDIA			
GARCH models	**LLH**	**AIC**	**SIC**
ARCH	6110.482	–4.682885	–4.673888
GARCH (11)	6189.956	–4.743064	–4.731818
GJR-GARCH	6190.988	–4.743089	–4.729592
EGARCH	6200.343	–4.750263	–4.736767
PGARCH	6198.873	–4.748369	–4.732623
FIGARCH	6202.560	–4.751963	–4.738467
FIEGARCH	**6206.828**	**–4.753702**	**–4.735707**

The aforementioned table shows that in all six GARCH family models with normal, student t's distribution and Generalized error construct, it was determined that FIEGARCH with student's distribution parameter has the lowest AIC (–4.753702) and SIC (–4.735) when compared to the other models when the AIC and SIC of all the aforementioned other models are compared. Aside from that, the FIEGARCH model has the highest Log Likelihood (6206.828). As a result, this model is thought to be the best one. The table below lists the outcomes of the chosen FIEGARCH Model for the KPR Mill Limited of India.

KPR Mill Limited of India is represented in the following table as the output of the FIEGARCH model using the student's distribution parameter. Focus should be placed on the fact that the coefficient of the asymmetric term is negative, or –0.028 (table 8), and statistically significant. This suggests that there is a leverage effect on the KPRM stock price volatility, and it also suggests that negative news has a greater impact on this volatility. According to the FIEGARCH estimation results in table 8, for the KPR Mill Limited of India, the estimated coefficient is significant. Results also revealed that the value of Beta is negative, showing that negative shocks are associated with more volatility than positive shocks.

Implementation of GARCH Models for Page industry limited of India

Page Industries is a value-driven, fully integrated manufacturing, marketing, distribution and Retail Company dedicated to building world-class brands. Page Industries Limited is a well-known Indian company that operates in the textile industry. It is primarily engaged in the manufacturing, distribution, and marketing of innerwear, loungewear, and other related products. The company is known for being the exclusive licensee of Jockey International Inc. USA for the manufacturing, distribution, and marketing of Jockey brand products in India, Sri Lanka, Bangladesh, Nepal, and the UAE. Page Industries Limited was founded in 1995 and has its headquarters in Bengaluru, Karnataka, India. Over the years, the company has achieved significant growth and

Table 8

RESULTS OF APPROPRIATE GARCH MODEL: KPR MILL LIMITED OF INDIA							
GARCH models	**Constant (mu)**	**Unconditional variance (ω)**	**Alpha (ARCH)**	**Beta (GARCH)**	$\alpha+\beta$	γ	
ARCH	0.00129*	0.076004*	0.18248*	NA	NA	NA	
GARCH	0.00125*	0.044533*	0.06921*	0.90035*	0.96	-	
GJR-GARCH	0.001179 (<0.05)	0.045962 (0.0228)	0.062383 (<0.05)	0.898848 (<0.05)	0.95	0.020899 (0.0260)	
EGARCH	0.001098 (0.0091)	0.043727 (0.0277)	0.178673 (<0.05)	0.956912 (<0.05)	1.12	–0.00708 (0.3737)	
PGARCH	0.001103 (0.0088)	0.041319 (0.0327)	0.092630 (<0.05)	0.893657 (<0.05)	0.98	0.036183 (0.4750)	
		OMEGA	**ALPHA**	**BETA**	**THETA1**	**THETA2**	**D**
FIGARCH	0.001181 (0.0044)	0.041013 (0.0601)	0.329594 (<0.05)	0.461237 (<0.05)	NA	NA	0.234017
FIEGARCH	0.001161 (0.0047)	–6.623230 (<0.05)	0.836007 (0.0013)	–0.31422 (0.2032)	–0. 0.247 (<0.05)	–0.02848 (0.0185)	0.079849 (0.5061)

Note: * means p value is < 0.05.

Table 9

CHOOSING AN APPROPRIATE MODEL: PAGE INDUSTRY LIMITED OF INDIA			
GARCH models	**LLH**	**AIC**	**SIC**
ARCH	6582.605	–5.044942	–5.035945
GARCH (11)	6610.454	–5.065532	–5.054285
TGARCH	6611.678	–5.065704	–5.052208
EGARCH	6617.956	–5.070518	–5.057022
PGARCH	6616.332	–5.068506	–5.052761
FIGARCH	6614.146	–5.067596	–5.054100
FIEGARCH	**6622.369**	**–5.072368**	**–5.054374**

market presence, establishing itself as a leading player in the innerwear segment in the Indian market. The aforementioned table shows that in all six GARCH family models with normal, student t's distribution and Generalized error construct, it was determined that FIEGARCH with student's distribution parameter has the lowest AIC (–5.072) and SIC (–5.054) when compared to the other models when the AIC and SIC of all the aforementioned other models are compared. Aside from that, the FIEGARCH model has the highest Log Likelihood (6222.37). As a result, this model is thought to be the best one. The table below lists the outcomes of the chosen FIEGARCH Model for the KPR Mill Limited of India.

Results of the various GARCH models for Page industry limited of India is represented in the above table 10 as the output of the FIEGARCH model using student's distribution parameter considered as the best models. Focus should be placed on the fact that the coefficient of the theta 2 term is negative, or –00.105 (table 10), and statistically significant. This suggests that there is a leverage effect on the page industries' stock price volatility, and it also suggests that negative news has a greater impact on this volatility. According to the FIEGARCH estimation results in table 10, for the textile stock index, i.e. Page industry limited of India, the estimated coefficient is also significant. Results also revealed that the value of Alpha, beta and theta 1 is also significant.

Implementation of GARCH Models for the Trident Group

The Trident Group is an Indian business conglomerate with diversified interests across various industries. It is primarily known for its presence in the textile and paper sectors. Apart from textiles and paper, the Trident Group has diversified its operations into other sectors, such as energy, chemicals, and agriculture. The Trident Group has a widespread international presence, with its products being exported to numerous countries across the world. The company has implemented various sustainability initiatives to

Table 11

CHOOSING AN APPROPRIATE GARCH MODEL: THE TRIDENT GROUP			
GARCH models	**LLH**	**AIC**	**SIC**
ARCH	4786.024	–3.667196	–3.658199
GARCH	5716.618	–4.379309	–4.365812
GJR-GARCH	5636.794	–4.317326	–4.301581
EGARCH	5694.356	–4.361469	–4.345724
PGARCH	**5728.262**	**–4.386704**	**–4.368709**
FIGARCH	3550.589	–2.718243	–2.704747
FIEGARCH	3552.489	–2.727436	–2.724754

Table 10

RESULTS OF VARIOUS GARCH MODELS: PAGE INDUSTRY LIMITED OF INDIA							
GARCH models	**Constant (mu)**	**Unconditional variance (ω)**	**Alpha (ARCH)**	**Beta (GARCH)**	**α+β**	**γ**	
ARCH	0.000892 (0.0123)	0.066533 (0.0017)	0.197670 (<0.05)	NA	NA	NA	
GARCH (11)	0.000191 (0.0071)	0.061848 (0.0047)	0.142541 (<0.05)	0.646401 (<0.05)	0.79	NA	
GJR-GARCH	0.000908 (0.0161)	0.061564 (0.0047)	0.122183 (<0.05)	0.633587 (<0.05)	0.75	0.052228 (0.0047)	
EGARCH	0.000853 (0.0137)	0.073356 (0.0008)	0.302104 (<0.05)	0.770460 (<0.05)	1.07	–0.01698 (0.2956)	
PGARCH	0.000831 (0.0168)	0.073937 (0.0006)	0.167971 (<0.05)	0.622654 (<0.05)	0.79	0.062461 (0.2704)	
		OMEGA	**ALPHA**	**BETA**	**THETA1**	**THETA2**	**D**
FIGARCH	0.001006 (0.0073)	0.064620 (0.0040)	0.720028 (<0.05)	0.658809 (<0.05)	NA	NA	0.105013
FIEGARCH	0.000849 (0.0141)	–7.64267 (<0.05)	0.629240 (<0.05)	0.081839 (<0.05)	0.281126 (<0.05)	–0.010463 (<0.05)	–0.77940

Source: Author's calculation.

Table 12

RESULTS OF VARIOUS GARCH MODELS: TRIDENTS GROUPS							
GARCH models	**Constant (mu)**	**Unconditional variance (ω)**	**Alpha (ARCH)**	**Beta (GARCH)**	**α+β**	**γ**	
ARCH	–0.00194 (<0.05)	0.000521 (<0.05)	2.346774 (<0.05)	NA	NA	NA	
GARCH	–0.00125 (0.0036)	0.090502 (<0.05)	0.555549 (<0.05)	0.321263 (<0.05)	0.88	NA	
GJR-GARCH	–0.00128 (0.0002)	0.000324 (<0.05)	0.592112 (<0.05)	0.302868 (<0.05)	0.89	–0.00922 (0.9519)	
EGARCH	–0.00092 (0.0439)	0.099669 (<0.05)	0.488416 (<0.05)	0.637322 (<0.05)	1.080	0.119755	
PGARCH	–0.00157	0.017504 (0.0471)	0.359679 (<0.05)	0.478377 (<0.05)	0.82	–0.05290 (0.4527)	
		OMEGA	**ALPHA**	**BETA**	**THETA1**	**THETA2**	**D**
FIGARCH	–0.00870 (0.0041)	0.002695 (<0.05)	0.492288 (<0.05)	0.546367 (<0.05)	NA	NA	1.076363
FIEGARCH	–0.00077 (0.0911)	–7.165940 (<0.05)	–0.92831 (<0.05)	0.849409 (<0.05)	0.444586 (<0.05)	0.199228 (<0.05)	0.131969

Table 13

CHOOSING AN APPROPRIATE GARCH MODEL: WELSPUN INDIA LIMITED			
GARCH models	**LLH**	**AIC**	**SIC**
ARCH	5864.066	–4.493149	–4.481902
GARCH	5877.234	–4.502480	–4.488984
GJR-GARCH	5877.345	–4.501798	–4.486053
EGARCH	5857.100	–4.486273	–4.470528
PGARCH	5889.753	–4.510547	–4.492552
FIGARCH	3711.462	–2.841612	–2.828115
FIEGARCH	5861.556	–4.488156	–4.467912

reduce its environmental impact and promote responsible business practices. It has undertaken measures for resource conservation and waste management.

All of the asymmetric GARCH models reflect the asymmetric volatility effect for the Trident Group returns. The study discovered that the power GARCH is the best to explain asymmetric volatility of Trident groups stocks return (table 11), and of Welspun India Limited (table 13) as the Adjusted R2 and Log likelihood values are high. As a result, this model is thought to be the best one. The table below lists the outcomes of the chosen PGARCH Model for the Tridents groups (table 12) and for the Welspun India Limited in table 14.

Table 14

RESULTS OF VARIOUS GARCH MODELS: WELSPUN INDIA LIMITED							
GARCH models	**Constant (mu)**	**Unconditional variance (ω)**	**Alpha (ARCH)**	**Beta (GARCH)**	**α+β**	**γ**	
ARCH	–0.00078 0.0660	**0.094603**	0.442317	NA	**NA**	**NA**	
GARCH	–0.00075 (0.0719)	0.338497 (<0.05)	0.457337 (<0.05)	0.333126 (<0.05)	0.78	NA	
GJR-GARCH	–0.00079 (0.0614)	0.325641 (<0.05)	0.453510 (<0.05)	0.341256 (<0.05)	0.79	0.038946 (0.6476)	
EGARCH	–0.00056 (0.1957)	–1.106721 (<0.05)	0.176080 (<0.05)	0.860271 (<0.05)	1.03	0.101091	
PGARCH	–0.00083 (0.0455)	0.009075 (<0.05)	0.158672 (<0.05)	0.661826 (<0.05)	0.81	0.040122 (0.6255)	
		OMEGA	**ALPHA**	**BETA**	**THETA1**	**THETA2**	**D**
FIGARCH	–0.01017 (<0.05)	0.001820 (<0.05)	0.253912 (0.2458)	0.024251 (0.8477)	NA	NA	0.570301
FIEGARCH	–0.00069 (0.1121)	–7.20603 (<0.05)	0.998189 (<0.05)	–0.91018 (<0.05)	0.264719 (<0.05)	0.145994 (<0.05)	–0.40431

Implementation of GARCH Models for Welspun India Limited

Welspun India Limited is one of the leading textile companies based in India. It is primarily engaged in the manufacturing of various textile products, including home textiles, terry towels, bedsheets, rugs, and bathrobes. The company is known for its quality products and has a strong presence in both the domestic and international markets. It is a globally recognized brand and exports its textile products to countries all over the world. It has a strong customer base and distribution network in several countries. Welspun India is primarily known for its textiles business, the company has diversified its operations into other areas as well, including renewable energy and infrastructure. It also invests in research and development to introduce new products and technologies that meet the evolving demands of the market.

Trident group's stocks return and that of Welspun India Limited are represented in the above table (tables 12 and 14 respectively) as the output of the PGARCH (1, 1, 1) model using students' distribution Construct. The outcomes come in two sections. Results revealed that the constant (C) and unconditional variance in the primary equation are significant because their probabilities are less than 0.05 in both stock returns. In the case of stock returns of the tridents groups on India, the coefficient of the asymmetric term (y) is negative, or –0.05290 (table 12). This suggests that there is a leverage effect on the stock price volatility, and it also suggests that negative news has a greater impact on this volatility. While outcomes of the PARCH models for the Welspun India Limited, the value of y is positive. This suggests that there is a leverage effect on the stock price volatility. It indicates that the series have strong volatility presence and have a strong impact on listed textile stocks.

CONCLUSION

The empirical data and findings indicate that the chosen Indian textile industry displays different degrees of profitability and volatility. The descriptive statistics presented in table 2 provide a comprehensive overview of the mean returns, standard deviations, skewness, kurtosis, and other relevant measures for five textile industries – NLPAGE, NLKPRM, NLTRIE, NLWLSP, and NLALO – over the period from April 2013 to March 2023. The mean return of NLKPRM is notably higher than other samples, followed by NLPAGE and NLTRIE. However, this higher return is associated with increased volatility, as evidenced by the higher standard deviations of NLTRIE and NLWLSP. The negative skewness of NLTRIE and NLWLSP indicates a distribution with a longer left tail, suggesting occasional extreme negative returns. Moreover, the leptokurtic nature of all industry prices, as indicated by kurtosis values greater than three, highlights the presence of heavy tails and potential outliers in the return distributions. This finding is supported by the Jarque-Bera test results, which reject normality assumptions for all textile industry prices. The stationarity of the log returns is confirmed through unit root tests, providing a foundation for subsequent analyses. The Johansen cointegration test further indicates a long-run relationship among the selected index series, emphasizing the interconnectedness of the textile market variables. The volatility clustering observed in log return graphs (figure 2) and the comparative volatility sketches (figure 3) further support the need for sophisticated modelling techniques to capture the dynamic nature of stock price volatility, particularly during significant events such as the 2008 financial crisis and the COVID-19 pandemic. The implementation of various GARCH models for Alok Industries Limited, KPR Mill Limited, Page Industries Limited, Trident Group, and Welspun India Limited reveals the significance of asymmetric volatility effects in these companies' stock returns. The PGARCH model is identified as the most suitable for simulating volatility in Alok Industries Limited, while the FIEGARCH model is preferred for KPR Mill Limited, Page Industries Limited, Trident Group, and Welspun India Limited. The results of these models emphasize the importance of considering asymmetric effects, especially negative news impacting stock price volatility. For instance, in the case of Alok Industries Limited, the negative coefficient of the asymmetric term (Alpha/ARCH) suggests a leverage effect, indicating that negative news has a more pronounced impact on volatility. In conclusion, the findings of this research underscore the necessity of employing advanced modelling techniques, particularly asymmetric GARCH models, to effectively capture and predict stock price volatility in the Indian textile industry. The insights provided can be valuable for investors, researchers, and policymakers seeking a deeper understanding of the dynamics and risks associated with investing in these companies.

Again, utilizing Normal and Student-t density functions, along with various GARCH family models, including FIGARCH, FIEGARCH, GJR-GARCH, and EGARCH, the study revealed asymmetric behaviour in the conditional volatility of the selected stocks. Notably, the Exponential model with Student-t distribution exhibited superior performance in capturing asymmetric volatility effects across all six index classes. The presence of leverage effects (asymmetry) in financial series was substantiated by significant results from multiple GARCH family models, suggesting that negative shocks (volatility) tend to persist for an extended duration. In literature, there were previously conducted several research studies that examined the stock market behaviour using GARCH family models [50–53]. The findings underscore the importance of volatility projections in risk management, security valuation, portfolio diversification, and monetary policymaking. However, it is acknowledged that the study's scope was limited to the textile industry, and future research could enhance its comprehensiveness by including diverse financial assets such as Gold, Crude oils, Agriculture commodities, and investment funds.

Methodologically, extending the analysis to incorporate additional forecasting models, like CGARCH, COGARCH, Copula GARCH, EVT-GARCH, F-ARCH, FIAPARCH, DCC models, and GRS-GARCH, could further contribute to a nuanced understanding of daily volatility in investment funds. Additionally, exploring the impact of various risk indices, such as geopolitical risk and climate risk, on the textile industry would be a valuable avenue for future research investigations.

REFERENCES

[1] Poon, S.-H., Granger, C.W.J., *Forecasting Volatility in Financial Markets: A Review*, In: Journal of Economic Literature, 2003, 41, 2, 478–539, https://doi.org/10.1257/002205103765762743

[2] Al Janabi, M.A.M., Hatemi-J, A., Irandoust, M., *An empirical investigation of the informational efficiency of the GCC equity markets: Evidence from bootstrap simulation*, In: International Review of Financial Analysis, 2010, 19, 1, 47–54, https://doi.org/10.1016/j.irfa.2009.11.002

[3] Deng, C., Huang, Y., Hasan, N., Bao, Y., *Multi-step-ahead stock price index forecasting using long short-term memory model with multivariate empirical mode decomposition*, In: Information Sciences, 2022, 607, 297–321, https://doi.org/10.1016/j.ins.2022.05.088

[4] Li, D., Zhang, L., Li, L., *Forecasting stock volatility with economic policy uncertainty: A smooth transition GARCH-MIDAS model*, In: International Review of Financial Analysis, 2023, 88, 102708, https://doi.org/10.1016/j.irfa.2023.102708

[5] Lettau, M., Ludvigson, S.C., *Chapter 11. Measuring and Modeling Variation in the Risk-Return Trade-off*, In: Y. Aït-sahalia L. P. Hansen (Eds.), Handbook of Financial Econometrics: Tools and Techniques North-Holland, 2010, 1, 617–690, https://doi.org/10.1016/B978-0-444-50897-3.50014-6

[6] Kissell, R., *Chapter 6. Price Volatility*, In: R. Kissell (Ed.), The Science of Algorithmic Trading and Portfolio Management, Academic Press, 2014, 193–234, https://doi.org/10.1016/B978-0-12-401689-7.00006-4

[7] Villar-Rubio, E., Huete-Morales, M.-D., Galán-Valdivieso, F., *Using EGARCH models to predict volatility in unconsolidated financial markets: The case of European carbon allowances*, In: Journal of Environmental Studies and Sciences, 2023, 13, 3, 500–509, https://doi.org/10.1007/s13412-023-00838-5

[8] Andersen, T.G., Su, T., Todorov, V., Zhang, Z., *Intraday Periodic Volatility Curves*, In: Journal of the American Statistical Association, 2023, 0, 0, 1–11, https://doi.org/10.1080/01621459.2023.2177546

[9] Di-Giorgi, G., Salas, R., Avaria, R., Ubal, C., Rosas, H., Torres, R., *Volatility forecasting using deep recurrent neural networks as GARCH models*, In: Computational Statistics, 2023, https://doi.org/10.1007/s00180-023-01349-1

[10] Teli, M.D., *Textile coloration industry in India*, In: Coloration Technology, 2008, 124, 1, 1–13, https://doi.org/10.1111/j.1478-4408.2007.00114.x

[11] Prakash, Y., Charwak, B., Kumar, P.V., *Textile industry in new India: Challenges and opportunities*, In: International Journal of Indian Culture and Business Management, 2020, 21, 4, 435-458, https://doi.org/10.1504/IJICBM.2020.111349

[12] Pulicherla, K.K., Adapa, V., Ghosh, M., Ingle, P., *Current efforts on sustainable green growth in the manufacturing sector to complement "make in India" for making "self-reliant India",* In: Environmental Research, 2022, 206, 112263, https://doi.org/10.1016/j.envres.2021.112263

[13] Nepal, M., Deb, R., *Board Characteristics and Firm Performance: Indian Textiles Sector Panorama*, In: Management and Labour Studies, 2022, 47, 1, 74–96, https://doi.org/10.1177/0258042X211026148

[14] Masson, R., Iosif, L., MacKerron, G., Fernie, J., *Managing complexity in agile global fashion industry supply chains*, In: The International Journal of Logistics Management, 2007, 18, 2, 238–254, https://doi.org/10.1108/09574090710816959

[15] Alam, M.A.A., Biswas, M.K., Mahiat, T., Chowdhury, R.B., Biswas, K.F., Hossain, M.M., Sujauddin, M., *Taking stock of the share of global environmental burden of knitwear production in Bangladesh: Constructing the life cycle inventory*, In: Journal of Cleaner Production, 2023, 412, 137376, https://doi.org/10.1016/j.jclepro.2023.137376

[16] Mukherjee, D., Kumar, S., Pandey, N., Lahiri, S., *Is offshoring dead? A multidisciplinary review and future directions*, In: Journal of International Management, 2023, 29, 3, 101017, https://doi.org/10.1016/j.intman.2023.101017

[17] Pandey, A., Saxena, N., Paliwal, U., *Perceptions of the textile industry stakeholders on a multi-slab goods and services tax system in India*, In: Research Journal of Textile and Apparel, 2023, https://doi.org/10.1108/RJTA-04-2023-0046

[18] Herwartz, H., *Stock return prediction under GARCH – An empirical assessment*, In: International Journal of Forecasting, 2017, 33, 3, 569–580, https://doi.org/10.1016/j.ijforecast.2017.01.002

[19] Song, Y., Tang, X., Wang, H., Ma, Z., *Volatility forecasting for stock market incorporating macroeconomic variables based on GARCH-MIDAS and deep learning models*, In: Journal of Forecasting, 2023, 42, 1, 51–59, https://doi.org/10.1002/for.2899

[20] Rubio, L., Palacio Pinedo, A., MejíaCastaño, A., Ramos, F., *Forecasting volatility by using wavelet transform, ARIMA and GARCH models*, In: Eurasian Economic Review, 2023, 13, 3, 803–830, https://doi.org/10.1007/s40822-023-00243-x

[21] Chen, C.W.S., Watanabe, T., Lin, E.M.H., *Bayesian estimation of realized GARCH-type models with application to financial tail risk management*, In: Econometrics and Statistics, 2023, 28, 30–46, https://doi.org/10.1016/j.ecosta.2021.03.006

[22] Salisu, A.A., Gupta, R., Bouri, E., *Testing the forecasting power of global economic conditions for the volatility of international REITs using a GARCH-MIDAS approach*, In: The Quarterly Review of Economics and Finance, 2023, 88, 303–314, https://doi.org/10.1016/j.qref.2023.02.004

[23] Kumar, S., Anand, A., Birau, R., Meher, B.K., Kumar, S., Ion, F., *Temporal Analysis of Mexico Stock Market Index Volatility using GJR-GARCH model*, In: Revista de Științe Politice. Revue des Sciences Politiques, 2023, 79, 46–56

[24] Diebold, F.X., Lopez, J.A., *Modeling Volatility Dynamics*, In: K.D. Hoover (Ed.), Macroeconometrics: Developments, Tensions, and Prospects, Springer Netherlands, 1995, 427–472, https://doi.org/10.1007/978-94-011-0669-6_11

[25] So, M.K.P., Chu, A.M.Y., Lo, C.C.Y., Ip, C.Y., *Volatility and dynamic dependence modeling: Review, applications, and financial risk management*, In: WIREs Computational Statistics, 2022, 14, 5, e1567, https://doi.org/10.1002/wics.1567

[26] Kumar, S., Meher, B.K., Birau, R., Anand, A., Simion, M.L., *Investigating Volatility Dynamics of the Portugal Stock Market using FIGARCH Models*, In: Annals of "Dunarea de Jos" University of Galati Fascicle I. Economics and Applied Informatics, 2023, 3, 39–45, https://doi.org/10.35219/eai15840409360

[27] Rapach, D., Zhou, G., *Chapter 6. Forecasting Stock Returns*, In: G. Elliott & A. Timmermann (Eds.), Handbook of Economic Forecasting, Elsevier, 2013, 2, 328–383, https://doi.org/10.1016/B978-0-444-53683-9.00006-2

[28] Bollerslev, T., *Generalized autoregressive conditional heteroskedasticity*, In: Journal of Econometrics, 1986, 31, 3, 307–327, https://doi.org/10.1016/0304-4076(86)90063-1

[29] Glosten, L.R., Jagannathan, R., Runkle, D.E., *On the Relation between the Expected Value and the Volatility of the Nominal Excess Return on Stocks*, In: The Journal of Finance, 1993, 48, 5, 1779–1801, https://doi.org/10.1111/j.1540-6261.1993.tb05128.x

[30] Ding, Z., Granger, C.W.J., Engle, R.F., *A long memory property of stock market returns and a new model*, In: Journal of Empirical Finance, 1993, 1, 1, 83–106, https://doi.org/10.1016/0927-5398(93)90006-D

[31] Viljoen, H., Conradie, W.J., Britz, M.-M., *The influence of different financial market regimes on the dynamic estimation of GARCH volatility model parameters and volatility forecasting*, In: Studies in Economics and Econometrics, 2022, 46, 3, 169–184, https://doi.org/10.1080/03796205.2022.2143881

[32] Dixit, J.K., Agrawal, V., Agarwal, S., *Measuring stock market volatility – A study in India's perspective*, In: International Journal of Economic Policy in Emerging Economies, 2022, 16, 1, 1–13, https://doi.org/10.1504/IJEPEE.2022.124655

[33] Sharma, P., Vipul, *Forecasting stock market volatility using Realized GARCH model: International evidence*, In: The Quarterly Review of Economics and Finance, 2016, 59, 222–230, https://doi.org/10.1016/j.qref.2015.07.005

[34] Virginia, E., Ginting, J., Elfaki, F.A.M., *Application of GARCH Model to Forecast Data and Volatility of Share Price of Energy (Study on Adaro Energy Tbk, LQ45)*, In: International Journal of Energy Economics and Policy, 2018, 8, 3, Article 3, https://www.econjournals.com/index.php/ijeep/article/view/6352

[35] Xie, H., Yu, C., *Realized GARCH models: Simpler is better*, In: Finance Research Letters, 2020, 33, 101221, https://doi.org/10.1016/j.frl.2019.06.019

[36] Fiszeder, P., Perczak, G., *Low and high prices can improve volatility forecasts during periods of turmoil*, In: International Journal of Forecasting, 2016, 32, 2, 398–410, https://doi.org/10.1016/j.ijforecast.2015.07.003

[37] Kazungu, K., Mboya, J.R., *Volatility of Stock Prices in Tanzania: Application of Garch Models to Dar Es Salaam Stock Exchange*, In: Asian Journal of Economic Modelling, 2021, 9, 1, 15–28, https://doi.org/10.18488/journal.8.2021.91.15.28

[38] Namugaya, J., Weke, P.G.O., Charles, W.M., *Modelling stock returns volatility on Uganda securities exchange,* In: Applied Mathematical Sciences, 2014, 8, 5173–5184, https://doi.org/10.12988/ams.2014.46394

[39] Tripathy, T., Gil-Alana, L.A., *Modelling time-varying volatility in the Indian stock returns: Some empirical evidence*, In: Review of Development Finance, 2015, 5, 2, 91–97, https://doi.org/10.1016/j.rdf.2015.04.002

[40] Ahmad, N., Raheem Ahmed, R., Vveinhardt, J., Streimikiene, D., *Empirical analysis of stock returns and volatility: Evidence from Asian stock markets*, In: Technological and Economic Development of Economy, 2016, 22, 6, 808–829, https://doi.org/10.3846/20294913.2016.1213204

[41] Ali, F., Suri, P., Kaur, T., Bisht, D., *Modelling time-varying volatility using GARCH models: Evidence from the Indian stock market*, In: F1000Research, 2022, 11, 1098, https://doi.org/10.12688/f1000research.124998.2

[42] Muthukamu, M., Amudha, R., *The Rollout of GST and its Impact on the Auto Sector Stocks of National Stock Exchange*, In: Indian Journal of Finance, 2020, 14, 12, Article 12, https://doi.org/10.17010/ijf/2020/v14i12/156482

[43] Taylor, S.J., *Forecasting the volatility of currency exchange rates,* In: International Journal of Forecasting, Elsevier, 1987, v, 3, 1, 159–170, https://ideas.repec.org/a/eee/intfor/v3y1987i1p159-170.html

[44] Dhamija, A.K., Bhalla, V.K., *Financial Time Series Forecasting: Comparison of Neutral Networks and ARCH Models,* In: International Research Journal of Finance of Management, 2010, 49, 1, 159–172

[45] Glosten, L.R., Jagannathan, R., Runkle, D.E., *On the Relation between the Expected Value and the Volatility of the Nominal Excess Return on Stocks*, In: The Journal of Finance, 1993, 48, 5, 1779–1801, https://doi.org/10.1111/j.1540-6261.1993.tb05128.x

[46] Alsharkasi, A., Crane, M., Ruskin, H., *Evaluating the Volatility Behaviour in Irish ISEQ Overall Index Using GARCH Models*, In: British Journal of Economics, Management & Trade, 2016, 13, 1, 1–13, https://doi.org/10.9734/BJEMT/2016/24632

[47] Salamat, S., Lixia, N., Naseem, S., Mohsin, M., Zia-ur-Rehman, M., Baig, S., *Modeling Cryptocurrencies Volatility Using Garch Models: A Comparison Based on Normal and Student's T-Error Distribution*, In: Entrepreneurship and Sustainability, 2019, 7, 3, 1580–1596, https://doi.org/10.9770/jesi.2020.7.3(11)

[48] Zhao, L.-T., Liu, K., Duan, X.-L., Li, M.-F., *Oil price risk evaluation using a novel hybrid model based on time-varying long memory*, In: Energy Economics, 2019, 81, 70–78, https://doi.org/10.1016/j.eneco.2019.03.019

[49] Christensen, B.J., Nielsen, M.Ø., Zhu, J., *Long memory in stock market volatility and the volatility-in-mean effect: The FIEGARCH-M Model*, In: Journal of Empirical Finance, 2010, 17, 3, 460–470, https://doi.org/10.1016/j.jempfin.2009.09.008

[50] Trivedi, J., Birau, R., *Investigating co-movements between emerging and developed stock markets and forecasting transmission pattern dimensions*, In: NAUN International Journal of Economics and Statistics, 2013, 4, 1, 191–199, ISSN: 2309-0685

[51] Kumar, S., Abhishek, A., Birau, R., Meher, B.K., Kumar, S., Florescu, I., *Temporal Analysis of Mexico Stock Market Index Volatility using GJR-GARCH model*, In: Revista de Științe Politice. Revue des Sciences Politiques, 2023, 79, 46–56

[52] Spulbar, C., Birau, R., Trivedi, J., Iacob (Troto), A.I., Florescu, I., Baid, R., *Investigating volatility patterns for a cluster of developed stock markets including Austria, France, Germany and Spain by using GARCH models*, In: Revista de Științe Politice. Revue des Sciences Politiques, 2023, 77, 41–48

[53] Meher, B.K., Kumari, P., Birau, R., Spulbar, C., Anand, A., Florescu, I., *Forecasting Volatility Spillovers Using Advanced GARCH Models: Empirical Evidence for Developed Stock Markets from Austria and USA*, In: Annals of "Dunarea de Jos" University of Galati, Fascicle I. Economics and Applied Informatics, 2024, 1, 16–29, ISSN-L 1584-0409, ISSN-Online 2344-441X, https://doi.org/10.35219 /eai15840409383

Authors:

BHARAT KUMAR MEHER[1], SANTOSH KUMAR[2], ABHISHEK ANAND[3], RAMONA BIRAU[4],
VIRGIL POPESCU[5], SUNIL KUMAR[6], PETRE VALERIU NINULESCU[7], MUHAMMAD AWAIS-E-YAZDAN[8]

[1]PG Department of Commerce, Purnea University, Purnia, Bihar, 854301, India
e-mail: bharatraja008@gmail.com, abhi2eco@gmail.com

[2]Department of Commerce, D. S. College, Katihar, Bihar, 854105, India
e-mail: krsant1994@gmail.com

[3]PG Department of Economics, Purnea University, Purnia, Bihar, 854301, India
e-mail: abhi2eco@gmail.com

[4]Faculty of Economic Science, University Constantin Brancusi, Tg-Jiu, Romania

[5]University of Craiova, Faculty of Economics and Business Administration, Craiova, Romania
e-mail: virgil.popescu@vilaro.ro

[6]Department of Economics, Purnea College, Purnia, Bihar, 854301, India
e-mail: sunil197779@gmail.com

[7]University of Craiova, "Eugeniu Carada" Doctoral School of Economic Sciences, Craiova, Romania
e-mail: petre.pregi@yahoo.it

[8]Department of Occupational Health & Safety, School of Public Health, Walailak University, ThaSala,
Nakhon Si Thammarat 80161, Thailand
e-mail: awais.yazdan@gmail.com

Corresponding author:

RAMONA BIRAU
e-mail: ramona.f.birau@gmail.com

Does supplier development matter for procurement performance in the textile industry? The moderating role of contract management difficulty

DOI: 10.35530/IT.076.02.202438

JORGE ALBERTO ESPONDA PÉREZ
REYNA ESPERANZA ZEA GORDILLO
ELIZABETH CÉSPEDES OCHOA
SARMAD EJAZ
KOMAL KAMRAN
MD BILLAL HOSSAIN
LÁSZLÓ VASA

ABSTRACT – REZUMAT

Does supplier development matter for procurement performance in the textile industry? The moderating role of contract management difficulty

The research aims to examine the impact of supplier development on procurement performance, taking into consideration contract management difficulties as a moderating variable. The research method section of the study employs a cross-sectional research design. In this survey technique, a questionnaire is employed to collect primary data from 220 respondents from the purchasing department via Google Forms through an adopted questionnaire. The initial step in our analysis was to clean and analyse the data using SPSS and SmartPLS 3 software, then incorporate structural equation modelling (SEM) to conduct our analysis. The findings confirmed that supplier development affects procurement performance. In addition to this, the contract management difficulties suggested a negative and significant impact on procurement performance. Furthermore, the relationship between supplier development and procurement performance is moderated by contract management difficulty. These unique findings highlight the importance of supplier development and effective contract management in improving procurement performance in the textile industry. The work's implementation of transaction cost theory to analyse how supplier development impacts sourcing capability is recognized as the primary theoretical contribution.

Keywords: *supplier development, contract management difficulty, procurement performance*

Dezvoltarea furnizorilor influențează performanța achizițiilor în industria textilă? Rolul moderator al dificultății de gestionare a contractelor

Studiul își propune să examineze impactul dezvoltării furnizorilor asupra performanței achizițiilor, luând în considerare dificultățile de gestionare a contractelor ca variabilă moderatoare. Secțiunea privind metoda de cercetare a studiului utilizează un design de cercetare transversală. În această tehnică de sondaj, se folosește un chestionar pentru a colecta date primare de la 220 de respondenți din departamentul de achiziții prin intermediul Google Forms printr-un formular adoptat. Pasul inițial al analizei noastre a fost curățarea și analiza datelor folosind software-ul SPSS și SmartPLS 3, apoi încorporarea modelării ecuațiilor structurale (SEM). Constatările au confirmat că dezvoltarea furnizorilor afectează performanța achizițiilor. În plus, dificultățile de gestionare a contractelor au sugerat un impact negativ și semnificativ asupra performanței achizițiilor. În plus, relația dintre dezvoltarea furnizorilor și performanța achizițiilor este moderată de dificultatea de gestionare a contractelor. Aceste constatări unice evidențiază importanța dezvoltării furnizorilor și a gestionării eficiente a contractelor în îmbunătățirea performanței achizițiilor în industria textilă. Implementarea teoriei costurilor de tranzacționare pentru a analiza modul în care dezvoltarea furnizorilor are impact asupra capacității de aprovizionare este recunoscută drept principala contribuție teoretică.

Cuvinte-cheie*: dezvoltarea furnizorilor, dificultăți în gestionarea contractelor, performanța achizițiilor*

INTRODUCTION

Recent indigenous empirical studies point to the fact that the competitiveness of procurement activities is largely reliant on the quality of supplier relations. The various studies showed that the quality of employee relations can make a huge difference in the advantages obtained through the procurement department during operations. With the purpose of cutting expenses, boosting quality and delivery, and promoting innovations, the suppliers of procurement teams should emphasize building sound relationships. Besides supplies like raw materials, products, and services, there are certain other values that, including the experience, knowledge, and assistance from the suppliers, are essential. By nurturing harmonious relationships with their suppliers, firms can get leverage in tapping the value of their supplier network and achieving their business objectives [1]. In the course of performing supplier management tasks, there is a need to think over and introduce the process of supplier development. The term supplier development involves practices such as working with suppliers to increase their capacities, structures, and operational performance [2]. In addition to this, corporations can do so by spending on what is referred to as supplier development, which aims at improving the quality and reliability of the supply chain and generating long-term value for the companies and the suppliers to which they extend their services. However, the company's investment in setting up and maintaining the institution shows its dedication to its suppliers, which may eventually develop loyalty and trust. Strategic alliances and mutually beneficial terms for both parties may evolve from that in the long run.

The industry requires a supplier for wide range, including the supplies and services obtained to support the textile industry, which includes supplier development, which is a highly crucial factor [3]. To make sure that they buy good and excellent materials at affordable prices, the industry should work closely with their suppliers. Also, supplier development could be the way to develop the textile sector and keep this sector as a partner for textile sector receivers. Therefore, an entity that deals with an industry can resourcefully evaluate its suppliers' effectiveness and efficiency. This can contribute to the process of supplier development programs and also determine the region that needs progress.

Similarly, the industry will develop partnerships with vendors that are based on mutual respect and trust and survive for a long time. Changing "Industry will develop partnerships with vendors that are based on mutual respect and trust and survives for a long time" to "Industry will create relationships with vendors that are built on respect and trust, which will last long". Several other options, like favourable prices and favourable terms, could be experienced, and we can lower the conveyance costs of a product in the case where it is sourced from local suppliers. The industry would also have to ensure the suppliers follow the quality and security standards by having a watchful eye on the performance of the latter. These possible aids acknowledge any issues and produce ways to improve. While the buyer gets the best experience, the providers should also create an environment which pushes the suppliers to thrive. Lastly, industries can foster better supplier performance, encourage innovation, develop long-term relationships, and reinforce supply chain stability by developing interventions related to suppliers' development [4].

Numerous studies have been conducted related to supplier development in procurement performance regarding the service sector [5, 6]. A recent study showed how a particular vendor development programme affected the supply chain resilience and the organization's performance [7]. Supplier development in various forms might strengthen the supply chain medium and enhance workers' integrity. The impact of supplier development on productivity in the Bangladeshi apparel industry was similarly conducted by Afshan and Motwani [8]. The findings of these studies confirmed that, among others, it is possible to enhance the productivity of supply with the help of supplier development programmes, which also yield beneficial effects along the whole supply chain. Encouraged by the conceptual model [9], the paper proceeded to explore the reasons and consequences of positive supplier development. Research indicates that some factors have a higher focus than others; these include the way the supplier is resourced, how strong the relationship between the supplier and the buyer is, and the supplier development plan structure. Aside from this, the researchers also looked at whether the involvement of suppliers in the development process had impacted the supply chain performance and whether or not the type of suppliers mattered. The studies showed that supplier development has both positive and negative effects on the supply chain [10, 11]. Besides, the effect is greater for strategic suppliers, and this one is more noticeable than that for transactional suppliers. In the Malaysian automotive sector, particular emphasis is given to how certain strategies, such as supplier development, can result in higher supplier performance and broader customer satisfaction. Supplier development as a strategy has been a key issue, especially when supplier performance needs to be enhanced. This also improves both buyer and supplier satisfaction.

A study conducted recently traces the imbalance in supplier development and procurement performance among service industries, particularly in countries with economies faced with the challenge of development. To confirm if client-supplier management affected buying performance, the researchers surveyed purchasing managers. They suggested that we should explore the faces of purchasing managers of these industries and other developing country respondents who will support our assertions [12]. Therefore, this study aims to examine the direct effect of supplier development on procurement performance in Pakistan's textile industry. However, the moderating role of contract management difficulties has not yet to previously worked together regarding the textile industry of Pakistan.

THEORETICAL FRAMEWORK AND HYPOTHESES DEVELOPMENT

Theoretical framework

As transaction cost economics (TCE) states, firms factor the minimization of transaction costs into decision-making [13]. In particular, supplier development can be a synonym for a buying company putting much effort towards transaction cost reduction, concerned with the suppliers' low performance, low-quality products or delay in delivery. The problem of contract management, providing a moderating variable, describes the supplier development effectiveness by changing the difficulty of the buyer-supplier relationship management [14]. In contrast, the moderating variable describes the effectiveness of supplier development efforts by changing the complexity of buyer-supplier relationship management.

Furthermore, the resource-based view (RBV) postulated that those companies that are able to gain a competitive advantage are those that harness their special resources and put them into practice [15]. In this sense, supplier development can be treated as one of the beneficial resources for the buyers, which contributes to their capability by improving strategic procurement components such as supplier selection, relationship management, and knowledge sharing. Moderating the relationship between supplier development and procurement performance, no less than the contract management difficulty, affects the purchaser's capability of implementing well and capitalizing on the developed suppliers' resources. Secondly, the origin of agency theory is when a party is delegated to act on behalf of another within a principal-agent relationship wherein there is potential for information asymmetry and opportunistic behaviour [16]. Supplier development, on the other hand, can be regarded as an instrument that helps to fill some gaps between the interests of the buyer and supplier, reduces information asymmetry, and cuts conflict of interest. In addition to this, contract management difficulty, as a moderating factor, standing between the success of supplier development and the clarity of term contract structure, accountability by monitoring mechanism, and the buyer's choice to ensure performance are the reasons.

Nevertheless, Transaction Cost Economics (TCE) is the guiding theory for this particular work because it applies in cases, has a transaction cost perspective, provides practical implications and now has an empirical basis in procurement practice [17]. The TCE theory establishes how the elements of expertise, receptivity, and opportunity may be used in practitioners' procurement actions. Moreover, it connects the buyer and the seller. It refers to the costs related to this transaction, which is parallel to what we have recorded in the paragraph mentioned above. TCE relies heavily on the concept of transaction costs as the tool through which the economic activity is structured. From a purchase perspective, the transaction costs are not only monetary ones but also include costs of deficient information, opportunistic behaviour of the parties and sunk costs for the relationship-specific investments [18]. This research considers the transaction cost point of view from the purchaser and supplier sides. It thus investigates how supplier development and contract management difficulty influence this transaction cost and then change procurement performance.

Literature review & Hypothesis development

Supplier development

Supplier development programs, as already proven, have been showing a positive realm of performance indicators like punctual delivery, product quality, and process efficiency. For instance, according to a recent study by Gu et al. [19], supplier development initiatives served as capacity building and as a training tool for suppliers and have resulted in higher quality and reliability of delivery. Similarly, the development of supplier programs is characterized by enhanced relationships and effective communication between buyers and suppliers, which cause an internal level of collaboration, trust and mutual understanding [20]. This can lead to better communication, working together and homogeneous relations; thus, the relationship can be elevated to a fulfilling satisfaction level. Furthermore, supplier development is one tool that can be used to address transaction costs by turning uncertainties into regular operations, in some cases into transparency, and minimal opportunistic behaviours. A recent study confirmed that through getting together with their suppliers, developing their skills and setting common goals, buyers are good at decreasing the transaction costs resulting from erroneous supplier performance or interruptions [21]. In addition to this, the implementation of the supplier development programs is associated with the use of the investors' time, effort, and resources from both buyers and suppliers. In enhancement, regarding cost in some cases, it covers training, technology transfer, process improvements and monitoring.

Nevertheless, with the need for more resources to divert and the capacity to execute these strategies, the organizers might find themselves in a complex situation [22]. Besides, some suppliers are flexible, and they are eager and able to contribute to supplier development programs. Differently, small- and medium-sized suppliers may need more means, resources, or abilities to get involved in these activities. This can limit the potential impact of supplier development on procurement performance, especially when the supplier base is diverse. Finally, as another aspect, passing on the benefits of the supplier development programs over time might be a difficult task as well [23]. Suppliers could need help maintaining the newly attained high-performance level even though they seek a trade-off. Hence, alteration of the market conditions, competitive dynamics, or buyer-supplier relationships turn into factors that influence the lengthy-term survival of gains from supplier development. Thus, the following alternative hypothesis is suggested:

H1: SD is positively related to PP.

Moderating role contract management difficulty

Proper contract management invariably brings about a good understanding of duties and responsibilities that make possible improved compliance with contracting conditions [24]. While contracts with clear layouts and meanings get concluded, the performance of the procurement process would probably increase. Existing research has revealed that when it comes to contract clarity, the better it is, the higher procurement performance increases. This increase is visible in such factors as cost savings and supplier performance. In addition to this, risk management for procurement activities can only be performed effectively while contract management is advancing [25]. Since contracts are usually intricate documents that contain various terms, including insufficient risk allocation, unclear performance metrics or too much uncertainty, the parties may face disputes, delays and quality issues, to name a few problems during the implementation of the projects.

Similarly, through efficient contract administration, we can avoid undue performance and integrity issues [26].

The same can be said about contract management's difficulty in obtaining a supplier's report on their performance. When the situations in which contracts are complicated or hard to yield are imposed, it then becomes a task to get the ground of the suppliers and their performance around established metrics. Furthermore, useful contract management practices provide a mechanism for monitoring, and therefore, it makes it easier for buyers to see and act swiftly if implementation deviations occur [27].

However, the managing of contract relaxations on determined activities, such as lengthy documentation, approval processes, and legal aspects, could be more manageable and bureaucratic for procurement staffers [28]. This may be stealing time from strategic efforts, having them focus on noncore activities, and thus dipping procurement performance below the set targets. It has been noticed that organizations are required to strike a balance between contract management, which is effective in their operations, and the minimalizing of the administrative roles. The high level of the rightness of the contract may be a problem if it does not prosper due to the required flexibility to adjust to the complexities and changes in the market, technological development, or unknown incidents arising. This is not possible because the stability of contractual terms could be detrimental to decision-making, and procurement is rigid and cannot be changed in time when conditions or tenders change. A balance of contract difficulty with the need for flexibility is fundamental and invaluable in the optimization of procurement [29]. Similarly, the complexity of the contract administrations will make the buyer-supplier relationship even more difficult. Lastly, technical complicacy and ambiguities of contracts may result in a lack of clarity, loss of faith and frustration with collaboration. Thus, the following alternative hypothesis is suggested:

H2: CMD is negatively related to PP.

H3: CMD moderates the relationship between SD and PP.

METHODOLOGY

Data collection procedure and sample size

In the present study, 220 employees were working in the purchasing departments of various textile industries in Pakistan. The research used a survey methodology, and the primary data were asked using an adopted questionnaire that was made available on the internet instead of using the paper and pen approach (online). We used a questionnaire, and its validity and reliability were tested through a pretest. Besides, it had questions based on the earlier research. Responses were collected during four weeks, and a space was made up for each week as a whole to complete the questionnaire. The data were scraped for garbage to discard any inaccurate or unavailable data. The reliability and consistency were ensured during the data cleaning stage when the appropriateness of the questions was checked and reviewed. For our first effort, we imported the data into the SPSS and then ran descriptive statistics to compile our findings. The first step was the development of a research hypothesis, which was then tested by analyzing the data of the experimental group separately from the control group using the SmartPLS 3 programme. The received data was processed through structural equation modelling (SEM) by adopting a path analysis approach to demonstrate the results. With the help of the indicators, which are reflective and formative, the research hypotheses were tested, and the model structure and measurement method were confirmed.

Research instrument

The independent variable supplier development was taken from the studies of [14, 30] and research items are "We suggest improvement targets to our suppliers, we provide feedback about performance evaluation to our suppliers, the allocated personnel in managing suppliers enhance suppliers' and Our firm has taken supplier development with supplier X through setting improvement targets".

The moderating variable contract management difficulty is used in the study, and we have adopted this study [14]. Items are "The time and efforts put into developing formal contracts with our suppliers are significant, the costs associated with developing and maintaining formal agreements with our suppliers are significant and ensuring that our contracts adequately represent our evolving relationships with our suppliers requires substantial resources".

The dependent variable procurement performance is taken from the research of Wachiuri [14]. Research items are "We are very satisfied with our suppliers, our complaints to engaged suppliers have reduced significantly if we had to start all over again, we would still choose the same suppliers and we respond to user departments' orders in time".

Tool for data analysis

A standard tool for an assessment of the key dimensions in the structural equation modelling (SEM) approach is the SmartPLS 3 software. Researchers from a variety of departments, such as the social sciences, management, marketing and economics, are using SmartPLS [31]. SmartPLS 3 software offers class features, including the possibility to run very complicated models with high dimensionality, latent variable path models, formative and reflective measurement models, a variety of statistics and latent variable path models.

RESULTS AND DISCUSSION

Common biased method

Cooper et al. [32] argue that the CMV may introduce errors in the measure of study outcomes by using participant-reported data techniques or a single source [32]. However, the likelihood of the reported data showing certain biases is very high, so it could be socially desired bias, response bias or acquiescence bias – which explains the same. With the help of CMV, a researcher can examine and account for the possible bias related to a specific technology/data source that may have influenced the findings. Therefore, this study may get more authenticity if scientists statistically adjust (=control for) CNNM. Researchers claim that the factor parts of ANOVA will make up at most 50% of the variance [33]. The range is less than 0.45% or less than 0.47% of the current research.

Reliability and validity (Questionnaire)

There needs to be a clear understanding of which data is gathered correctly and which hypotheses are correctly tested; thus, reliability and validity must be ensured [34]. Errors existing in the hypothesis testing may discard the likely facts, while the testing of no reliable and legal data could result in the conclusion of the wrong idea. Hence, a gathering of characteristics, improving the measure of accuracy and precision, should be checked before the faculty of the hypothesizing is accepted. Cronbach's alpha and composite reliability are indicators that are considered to be very reliable for research reliability assessment. For the current research, perfectly determining the reliability of Cronbach's alpha or composite reliability is typically recommended at a threshold value of 0.70 or more [35]. It is thus evident that the homogeneity value provides a tangible indicator of a scale's or item's internal consistency and reliability, as the difference in the response patterns can be unattributed to the measured phenomenon.

Conclusively, this value physicalizes the construct as the phenomenon underlying the occasions of measurement. In this research, all the Cronbach's alpha and composite reliability scores were higher than 0.70, which indicates that the internal consistency and reliability of the measurement scales were appropriate for each construct being examined. Table 1 and figure 1 show the data.

Table 1

RELIABILITY AND VALIDITY (QUESTIONNAIRE)

Factors	Item SPSS coding	Items loading	Cronbach alpha value	Composite reliability	Average Variance Extraction (AVE)
Supplier development	SD1	0.800	0.903	0.933	0.778
	SD2	0.930			
	SD3	0.910			
	SD4	0.882			
Contract management difficulty	CMD1	0.867	0.844	0.906	0.763
	CMD2	0.879			
	CMD3	0.873			
Procurement performance	PP1	0.872	0.903	0.932	0.774
	PP2	0.885			
	PP3	0.849			
	PP4	0.913			

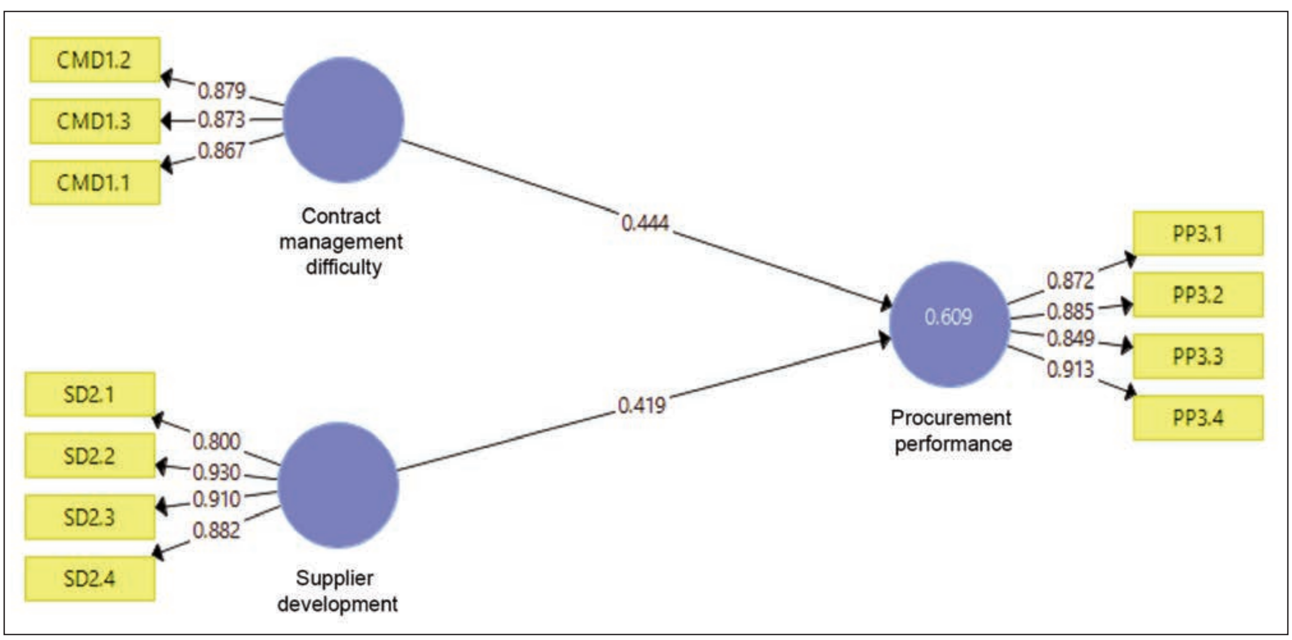


Fig. 1. Model fitness

In structural equation modelling (SEM), average variance extracted (AVE) is a prominent statistic for the estimation of the convergent validity of a measurement model. What we do is take the squaring of the correlation between the indicators of the construct to obtain a squared correlation and then average the squared correlations of the overall indicators of the construct, and the AVE is computed. The range of the AVE Index equals or above 0.5, which means that the indicators explain about half of the variance for the concept. Employing the average variance extracted (AVE) techniques for this study, we can see that the items measuring each of the constructs have AVE values that are higher than 0.50, meaning that the indicators used for each construct can explain at least 50% of the entire construct's variability [36]. The measurement model has convergent validity to a great extent, as the measurement error does not influence the variance of each construct but has a great relationship with its indicator (table 1 and figure 1).

Testing of hypothesis – Supplier development

The data was confirmed with a beta value of 0.391 and a t-value of 5.536. This indicates that supplier development clearly showed a positive and significant impact on procurement performance. The higher value showed more surveys, the result will be statistically significant, and if there is more t-value, it means more impact on beta. Thus, supplier improvement has played a crucial role in helping enhance procurement (table 2 and figure 2).

The moderating effect of contract management difficulty

However, the report hypotheses H2 and H3, focusing on earlier research, explore the moderating influence of contract management difficulty in Pakistan's textile industry. Looking at the results, we got a t-value of 4.265 and a negative beta value of (–) 0.097, which was significant. This, therefore, means that the contract management difficulty negatively supports the performance of buyer-supplier development as well as procurement (table 2 and figure 2).

Discussion on results

H1, the empirical result reveals that there exists a strong and meaningful link between supplier development and procurement performance ($\beta = 0.391$, $p < 0.001$). This implies that as companies are involved in supplier development activities like training, capability building, and working partnerships, procurement results will get better. The positive sign showed that supplier development is stronger in preference, which leads to improved procurement performance. This outcome, in the same way as other research, shows how supplier development has financial benefits through the improvement of performance,

Table 2

MODERATING EFFECT			
Paths	**Value of Beta**	**T-Value**	**Remarks**
Supplier Development -> Procurement Performance	0.391	5.536	Supported
Contract Management Difficulty -> Procurement Performance	0.403	6.805	Supported
Moderating Effect 1 (Supplier Development* Contract Management Difficulty)	–0.097	4.265	Supported

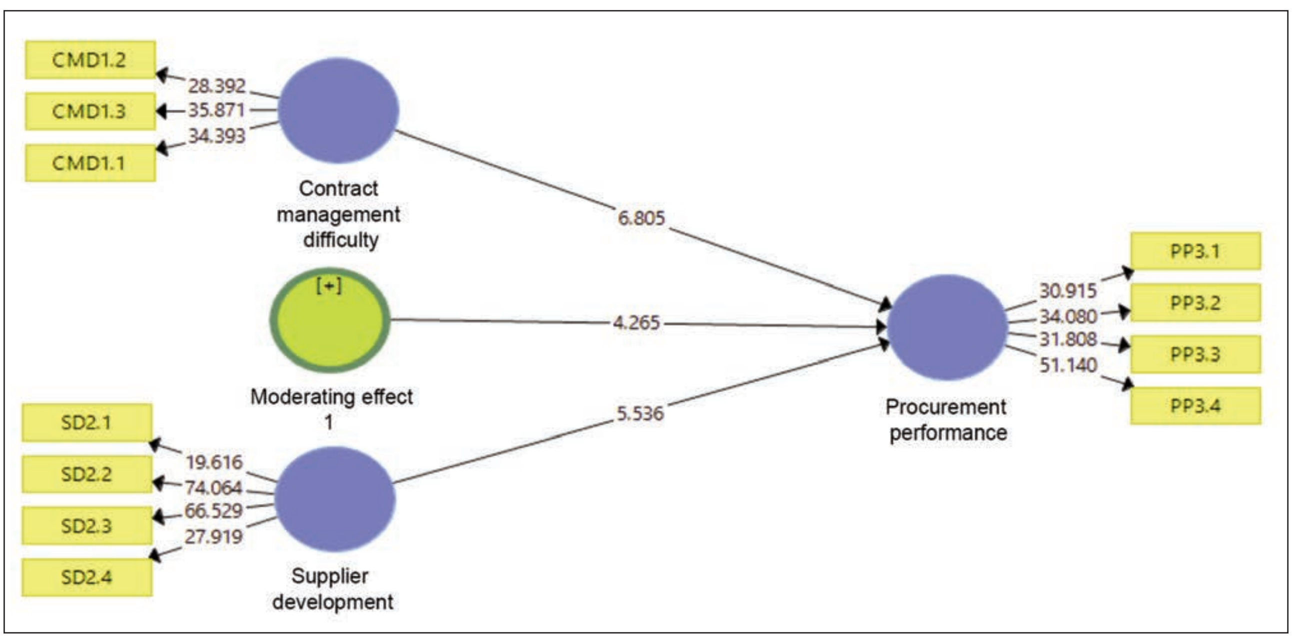


Fig. 2. Moderating effect of contract management difficulty

the enrichment of relationships and the reduction of transaction costs [37, 19]. The evidence points towards the direction of manufacturing companies in the textile industry in that they can attain good procurement results by actively partaking in supplier development programs.

H2, the correlation analysis shows that contract management difficulty and procurement performance are negatively correlated ($\beta = -0.0403$, $p < 0.001$). Thus, we can deduce that procurement performance worsens with an increase in the complexity of contract management. The minus sign indicates that contract management issues, such as complexity, vagueness, and extra-administrative burden, hinder procurement performance. The result confirms the previous studies that explain every one of the contract management categories, which are the mitigation of risks to the organisations, enforcement of compliance and performance evaluation [14, 38]. Furthermore, assessment has brought the realization that there is a need for organisations to put contract management practices in place for more enhanced procurement performance.

H3, the analysis showed that contract management difficulty performs a moderating effect on the supplier development – procurement performance relationship ($\beta = -0.097$, $p < 0.001$). Quite obviously, the level of contract management difficulty used is a determinant of how supplier development interacts with and affects procurement performance. It is the negative correlation which implies that the better the supplier development efforts get, the more difficult the contract management is. Lastly, it implies that the supply development gain becomes less apparent when commercial management becomes more difficult [39]. This showed that enterprises must bear the responsibility of mitigating suppliers' intricacies to reap full supplier development harvests [40].

CONCLUSION

Through the analysis of the textile industry's primary data, this paper studied the relationship between supplier development, contract management difficulty and procurement performance. Three hypotheses were introduced, and data was analyzed to test them. The conducted analysis came up with a well-ordered tendency link between the development of suppliers and procurement results. In addition to this, the result thus provides an empirical confirmation of the claim that supplier development is positively and respectively linked to procurement performance. Every analysis, in this case, focused on supplier development and contract management's difficult interaction in procurement performance. The findings proved that the results were noticeably moderating role. The result is also evidence which adds up to the assumptions that supplier development will become less effective under a condition where contract management difficulty is present.

The study findings suggest that supplier development positively influences procurement performance in the textile industry. Additionally, higher contract management difficulty is associated with lower procurement performance. Furthermore, contract management difficulty moderates the relationship between supplier development and procurement performance. These unique findings highlight the importance of supplier development and effective contract management in improving procurement performance in Pakistan's textile industry.

Limitations and future research directions

These are some limitations, and they will be addressed as well. The data was filtered from only one data source, with small limitations on how widely we can adapt the results to different textile companies. As for future research, investigators could be encouraged to gather data from multiple sources to improve the validity of this data. In one breath, the fact that the study was conducted in a developing country raises a concern that the results may not be generalised to other nations since other factors may have contributed. For future studies, other countries or different locations would also like to do the same research to obtain similar results. In terms of the approach, it is vital to consider that the type of data utilized was cross-sectional, making it difficult for scholars to identify the cause and effect. The functional relationship between supplier development, contract management and procurement outcomes can be confirmed through the employment of longitudinal or experimental approaches in research. Lastly, the research focused on the textile sector. Researchers might conduct a similar study for service areas, such as education, hotels, and financial industries, to discover how the outcome of such studies fits in varied circumstances.

REFERENCES

[1] Shukor, A.A.A., Newaz, M.S., Rahman, M.K., Taha, A.Z., *Supply chain integration and its impact on supply chain agility and organizational flexibility in manufacturing firms*,In: Int. J. Emerg. Mark., 2021, 16, 8, 1721–1744

[2] Subramaniam, P.L., Iranmanesh, M., Kumar, K.M., Foroughi, B., *The impact of multinational corporations' socially responsible supplier development practices on their corporate reputation and financial performance*, In: Int. J. Phys. Distrib. Logist. Manag., 2020, 50, 1, 3–25

[3] Aldrighetti, R., Zennaro, I., Finco, S., Battini, D., *Healthcare supply chain simulation with disruption considerations: A case study from Northern Italy*, In: Glob. J. Flex. Syst. Manag., 2019, 20, Suppl 1, 81–102

[4] Espino-Rodríguez, T.F., Taha, M.G., *Supplier innovativeness in supply chain integration and sustainable performance in the hotel industry*, In: Int. J. Hosp. Manag., 2022, 100, 103103

[5] Ağan, Y., Kuzey, C., Acar, M.F., Açıkgöz, A., *The relationships between corporate social responsibility, environmental supplier development, and firm performance*, In: J. Clean. Prod., 2016, 112, 1872–1881
[6] Yawar, S.A., Kauppi, K., *Understanding the adoption of socially responsible supplier development practices using institutional theory: Dairy supply chains in India*, In: J. Purch. Supply Manag., 2018, 24, 2, 164–176
[7] Wieteska, G., *The impact of supplier involvement in product development on supply chain risks and supply chain resilience*, In: Oper. Supply Chain Manag. An Int. J., 2020, 13, 4, 359–374
[8] Debnath, B., et al.., *A grey approach to assess the challenges to adopting sustainable production practices in the apparel manufacturing industry: Implications for sustainability*, In: Results Eng., 2024, 22, 102006
[9] Afshan, N., Motwani, J., A*n investigation of antecedents and consequences of supplier integration: a study in Indian context*, In: Meas. Bus. Excell., 2021, 25, 2, 138–151
[10] Fan, D., Xiao, C., Zhang, X., Guo, Y., *Gaining customer satisfaction through sustainable supplier development: The role of firm reputation and marketing communication*, In: Transp. Res. Part E Logist. Transp. Rev., 2021, 154, 102453
[11] Lo, S.M., Zhang, S., Wang, Z., Zhao, X., *The impact of relationship quality and supplier development on green supply chain integration: A mediation and moderation analysis*, In: J. Clean. Prod., 2018, 202, 524–535
[12] Armoh, M.B., Agyei, P.M., Bossman, A., Gonu, E., Asare-Larbi, M., *Effect of supplier appraisal on firm performance in Ghana: views of employees of selected manufacturing firms*, In: Sci. African, 2023, 21, e01829
[13] Cuypers, I.R.P., Hennart, J.-F., Silverman, B.S., Ertug, G., *Transaction cost theory: Past progress, current challenges, and suggestions for the future*, In: Acad. Manag. Ann., 2021, 15, 1, 111–150
[14] Changalima, I.A., Mchopa, A.D., Ismail, I.J., *Supplier development and public procurement performance: does contract management difficulty matter?*, In: Cogent Bus. Manag., 2022, 9, 1, 2108224
[15] Zahra, S.A., *The resource-based view, resourcefulness, and resource management in startup firms: A proposed research agenda*, In: J. Manage., 2021, 47, 7, 1841–1860
[16] Parker, D.W., Dressel, U., Chevers, D., Zeppetella, L., *Agency theory perspective on public-private-partnerships: International development project*, In: Int. J. Product. Perform. Manag., 2018, 67, 2, 239–259
[17] Canıtez, F., Çelebi, D., *Transaction cost economics of procurement models in public transport: An institutional perspective*, In: Res. Transp. Econ., 2018, 69, 116–125
[18] Celtekligil, K., *Transaction cost theory*, Strateg. Priorities Compet. Environ. Multidimens. Approaches Bus. Success, 2020, 141–154
[19] Gu, V.C., Zhou, B., Cao, Q., Adams, J., *Exploring the relationship between supplier development, big data analytics capability, and firm performance*, In: Ann. Oper. Res., 2021, 302, 151–172
[20] Ganguly, K.K., Roy, S., *Supplier satisfaction in buyer–supplier relationships: Assessment from supplier perspective*, In: J. Business-to-bus. Mark., 2021, 28, 3, 247–264
[21] Alghababsheh, M., Gallear, D., *Socially sustainable supply chain management and suppliers' social performance: The role of social capital*, In: J. Bus. Ethics, 2021, 173, 4, 855–875
[22] Demerouti, E., Bakker, A.B., *Job demands-resources theory in times of crises: New propositions*, In: Organ. Psychol. Rev., 2023, 13, 3, 209–236
[23] Charpin, R., Powell, E.E., Roth, A.V., *The influence of perceived host country political risk on foreign subunits' supplier development strategies*, In: J. Oper. Manag., 2021, 67, 3, 329–359
[24] Briggs, I.T.F., *Contract management and performance of infrastructural projects in Rivers State*, In: Diam. Bridg. Econ. Bus. J., 2022, 2, 2
[25] Huma, S., Ahmed, W., Najmi, A., *Understanding the impact of supply-side decisions and practices on supply risk management*, In: Benchmarking An Int. J., 2020, 27, 5, 1769–1792
[26] Panya, K.O., Awuor, E., *Public procurement reforms in Africa: challenges, constraints and improvement opportunities*, In: Strateg. J. Bus. Chang. Manag., 2023, 10, 2, 1435–1456
[27] Zhang, T., Feng, T., Cui, M., *Smart contract design and process optimization of carbon trading based on blockchain: The case of China's electric power sector*, In: J. Clean. Prod., 2023, 397, 136509
[28] Atkinson, C.L., *Competence in bureaucracy*, Global encyclopedia of public administration, public policy, and governance, Springer, 2023, 2244–2248
[29] Xu, J., Gürbüz, M.C., Feng, Y., Chen, S., *Optimal spot trading integrated with quantity flexibility contracts*, In: Prod. Oper. Manag., 2020, 29, 6, 1532–1549
[30] Rajput, A., Gulzar, S., Shafi, K., *Impact of supplier development on supplier performance: Mediating role of trust*, In: Bus. Econ. Rev., 2019, 11, 2, 45–66
[31] Kamis, A., Saibon, R.A., Yunus, F.M., Rahim, B., Herrera, L.M., Montenegro, P., *The SmartPLS analyzes approach in validity and reliability of graduate marketability instrument*, In: Soc. Psychol. Educ., 2020, 57, 8, 987–1001
[32] Cooper, B., Eva, N., Fazlelahi, F.Z., Newman, A., Lee, A., Obschonka, M., *Addressing common method variance and endogeneity in vocational behavior research: A review of the literature and suggestions for future research,* In: J. Vocat. Behav., 2020, 121, 103472
[33] Chin, W.W., *Commentary: Issues and opinion on structural equation modeling*, In: MIS quarterly, JSTOR, 1998, vii–xvi
[34] Pandey, P., Pandey, M.M., *Research methodology tools and techniques*, Bridge Center, 2021
[35] Shrestha, N., *Factor analysis as a tool for survey analysis*, In: Am. J. Appl. Math. Stat., 2021, 9, 1, 4–11
[36] Hair Jr, J.F., et al., *Evaluation of reflective measurement models*, Partial Least Squares Struct. Equ. Model. Using R A Workb., 2021, 75–90

[37] Pradhan, S.K., Routroy, S., *Improving supply chain performance by Supplier Development program through enhanced visibility*, In: Mater. Today Proc., 2018, 5, 2, 3629–3638
[38] Wacker, J.G., Yang, C., Sheu, C., *A transaction cost economics model for estimating performance effectiveness of relational and contractual governance: Theory and statistical results*, In: Int. J. Oper. Prod. Manag., 2016, 36, 11, 1551–1575
[39] Johnson, F., Leenders, M.R., Flynn, A.E., *Purchasing and supply management*, McGraw-Hill Companies, Inc, 2021
[40] Sheffi, Y., *The new (ab) normal: Reshaping business and supply chain strategy beyond Covid-19*, MIT CTL Media, 2020

Authors:

JORGE ALBERTO ESPONDA PÉREZ[1], REYNA ESPERANZA ZEA GORDILLO[1], ELIZABETH CÉSPEDES OCHOA[1], SARMAD EJAZ[2], KOMAL KAMRAN[3], MD BILLAL HOSSAIN[4], LÁSZLÓ VASA[5]

[1]Universidad de Ciencias y Artes de Chiapas, Mexico
e-mail: reyna.zea@unicach.mx, elizabeth.cespedes@unicach.mx

[2]Department of Management Sciences, University of Okara, Pakistan
e-mail: sarmadejaz@uo.edu.pk

[3]FAST School of Management, FAST NUCES Lahore, Pakistan
e-mail: komal.kamran@nu.edu.pk

[4]Business Management and Marketing Department, School of Business and Economics, Westminster International University in Tashkent (WIUT), Tashkent 100047, Uzbekistan
e-mail: mbhossain@wiut.uz

[5]Faculty of Economics, Széchenyi Istvàn University, Győr, Hungary
e-mail: vasa.laszlo@sze.hu

Corresponding author:

JORGE ALBERTO ESPONDA PÉREZ1
e-mail: jorge.esponda@unicach.mx

Development of a fitting-ensured men's garment block pattern prediction model for people with convex belly (PWCB)

DOI: 10.35530/IT.076.02.202487

MENGSHU DING
TIANYU LUO
YAN HONG

ABSTRACT – REZUMAT

Development of a fitting-ensured men's garment block pattern prediction model for people with convex belly (PWCB)

The prevalence of People with a Convex Belly (PWCB) has been steadily increasing due to dietary and lifestyle changes. Standard garments available in the market are unsuitable for individuals with visible belly protrusion. While adapting patterns designed for individuals with normal morphology may be a potential solution, the design efficiency is currently inadequate. The purpose of this study is to propose the development of a Garment Block Pattern Prediction model to efficiently design fitting-ensured patterns for PWCB. This model aims to generate garment patterns that ensure a proper fit based on morphological data specific to PWCB. To achieve this objective, we simulate the mapping relationship between the body dimensions of PWCB and the dimensions of garment block patterns, which are adjusted to ensure a proper fit. Firstly, we identify key morphological dimensions of PWCB's bodies and determine the dimensions of garment block patterns using traditional garment pattern formulas. Secondly, we develop 130 fitting-ensured garment samples using CLO 3D software. Subsequently, we establish the mapping relationship using a linear regression model. The proposed prediction model in this study successfully enables the realization of personalized fitting-ensured garment block patterns for PWCB. This research significantly enhances the efficiency of pattern-making for PWCB and establishes a foundation for the automation and intelligence of garment pattern-making specifically tailored to PWCB's needs.

Keywords: *prediction model, convex belly, garment block pattern, pattern-making*

Dezvoltarea unui model de predicție a tiparelor de blocuri de îmbrăcăminte pentru bărbați cu ajustare garantată pentru persoanele cu abdomen proeminent (PWCB)

Prevalența persoanelor cu abdomen proeminent (PWCB) a crescut constant, ca urmare a schimbărilor alimentare și ale stilului de viață. Articolele de îmbrăcăminte standard disponibile pe piață sunt inadecvate pentru persoanele cu proeminențe vizibile ale abdomenului. Deși adaptarea modelelor concepute pentru persoanele cu morfologie normală poate fi o soluție potențială, eficiența designului este în prezent inadecvată. Scopul acestui studiu este de a propune dezvoltarea unui model de predicție a tiparelor de blocuri de îmbrăcăminte pentru a proiecta în mod eficient tipare care asigură potrivirea pentru PWCB. Acest model urmărește să genereze tipare de îmbrăcăminte care să asigure o potrivire corespunzătoare pe baza datelor morfologice specifice PWCB. Pentru a atinge acest obiectiv, a fost simulată relația de corespondență dintre dimensiunile corporale ale PWCB și dimensiunile modelelor blocurilor de îmbrăcăminte, care sunt ajustate pentru a asigura o potrivire corespunzătoare. În primul rând, au fost identificate dimensiunile morfologice cheie ale corpurilor PWCB și determinate dimensiunile tiparelor blocurilor de îmbrăcăminte utilizând formulele tiparelor de îmbrăcăminte convenționale. În al doilea rând, au fost dezvoltate 130 de eșantioane de îmbrăcăminte cu potrivire garantată utilizând software-ul CLO 3D. Ulterior, a fost stabilită relația de corespondență utilizând un model de regresie liniară. Modelul de predicție propus în acest studiu permite realizarea cu succes a tiparelor personalizate de blocuri de îmbrăcăminte cu potrivire garantată pentru PWCB. Acest studiu îmbunătățește semnificativ eficiența realizării tiparelor pentru PWCB și stabilește o bază pentru automatizarea și inteligența realizării tiparelor de îmbrăcăminte special adaptate nevoilor PWCB.

Cuvinte-cheie*: model de predicție, abdomen proeminent, tipar bloc de îmbrăcăminte, proiectarea tiparelor*

INTRODUCTION

During the recent years, obesity has increased in societies due to the reasons such as increasing stressful life, working long hours at desks and unhealthy nutrition [1]. The impact of trans fatty acids on the body's metabolism can result in fat accumulation, leading to a rising prevalence of the convex belly body type (PWCB) each year, which has become the most prevalent special body type [2]. The convex belly body type is characterized by a wider chest width compared to the back width, a longer front waist compared to the back waist length, a waist circumference that is close to or larger than the chest circumference, and a protruding belly [3–5].

Consequently, individuals with PWCB, particularly in the upper body region, do not fit into standard garment sizes available in stores, necessitating personalized products to cater to their unique needs in the consumer market [6].

In this particular scenario, the adaptation of ready-to-wear (RTW) garments to accommodate the morphology of PWCB is consistently required by this demographic. However, due to the complex geometric deformation of the body shape, the traditional 2D garment design process and associated design principles cannot be applied. The pattern-making phase, which plays a critical role in achieving proper garment fit, becomes a focal point for addressing convex belly-related issues [7, 8]. While straight lines can be determined using empirical formulas [9], the drawing of curves heavily relies on the expertise of pattern makers. Moreover, pattern makers encounter significant repetitive work during the pattern-making process, leading to time and energy wastage and diminished work efficiency. Currently, no efficient design solution catering specifically to PWCB is available in the market. In this context, the development of a prediction model capable of generating fitting-ensured garment patterns for individuals with convex bellies (PWCB) presents a potential solution.

In recent years, the field of garment pattern prediction has gained increasing attention from researchers. Liu et al. developed a system for the customization of jeans samples that utilizes both geometric and dimensional constraint parameters as inputs to generate the final product. The geometric constraints include the silhouette of the jeans, waist height, and trouser length, while the dimensional constraints encompass the individual's height, waist circumference, and hip circumference. This system features a sample modification process that facilitates interactive design and allows for real-time feedback [10]. In the realm of digital modeling, Abtew employed a technique to extract the body's surface contour by intersecting a cutting plane with the bust at its origin. This method involved the construction of a wireframe mesh, from which the volume of the breasts was determined using characteristic points on the mesh. This process enabled the simulation of a three-dimensional bra, which could subsequently be unfolded into a two-dimensional prototype [11]. Notable examples include Wang et al., who proposed a novel prediction model utilizing radial basis function (RBF) artificial neural networks (ANNs) to estimate body dimensions relevant to garment pattern-making [12]. Kolose et al.. employed a 3D body scanner to measure body dimensions from the New Zealand Defence Force Anthropometry Survey (NZDFAS) data and developed prediction models for shirt and trouser sizes using decision trees [13]. Additionally, Jin, SN et al. extracted human body sizes from body images and developed a system capable of automatically generating personalized patterns and style designs based on 2D human body images [14]. Numerous studies have demonstrated the existence of correlations between body dimensions and pattern dimensions, which can be effectively captured through prediction models. Such models have the potential to significantly enhance the efficiency of the garment pattern-making process. However, there is a dearth of research focusing on the prediction modeling of garment block patterns specifically tailored to PWCB. Thus, the objective of this paper is to develop a fitting-ensured garment block pattern prediction model for individuals with convex belly (PWCB), thereby improving the efficiency of pattern-making for this particular body type.

An effective garment pattern prediction model should align with classic pattern-making methods. Common methods include the proportion method, prototype method, and short-inch method, among others. The proportion method is suitable for simple garment styles, whereas the prototype method accommodates a broader range of garment styles. Therefore, in this study, the prototype method is adopted to establish the proposed prediction model. By employing the prototype method, diverse garment styles can be generated. To simplify the research problem, this study focuses solely on the garment block pattern. The garment block pattern serves as the foundation for pattern-making, representing the fundamental relationship between the garment and the morphology of the human body [15]. Various garment styles can be derived from garment block patterns. Hence, the key objective of realizing the proposed prediction model is to establish a matching relationship between morphological dimensions on the human body surface and garment block pattern dimensions under conditions that ensure a proper fit.

This study aims to investigate the relationship between garment block patterns and human body dimensions as a prediction model [16–18] to enhance the efficiency of garment pattern-making for PWCB. To achieve this objective, the following steps are undertaken. Firstly, a group of experienced pattern designers selects garment block patterns tailored to PWCB, considering key human body morphological dimensions. Secondly, a data set of 130 virtual PWCB with diverse morphology is created. In the virtual environment provided by CLO 3D, fitting-ensured garment block patterns are designed for each virtual PWCB. Subsequently, measurements of garment block dimensions and key human body morphological dimensions are obtained. These measurements serve as the basis for establishing their relationships using a linear regression model. Finally, an evaluation procedure is conducted to assess the accuracy and efficiency of the prediction model for clothing design, utilizing both virtual and physical fittings.

The study is structured into several chapters to address its research objectives comprehensively. 1st section provides an introduction to the background, purpose, and significance of the research topic and conducts a general review of the existing relevant literature. 2nd section outlines the methods and principles employed to derive the prediction model for this study. 3rd section constitutes the primary experiment of the research, employing appropriate methods and tools to obtain predictions of fitting garment block pattern dimensions based on key body dimensions. In the 4th section, the experimental results are rigorously validated and evaluated through both virtual fitting and physical fitting. 5th section encompasses the conclusion and outlook of the study, which summarizes the research findings, analyzes the innovative aspects, advantages, and limitations of the study, and suggests potential areas for future investigation.

GENERAL INFORMATION

The primary aim of the study delineated within this article is to conceptualize and develop an automated system for the generation of tailored suit samples specifically designed for male individuals with a prominent abdominal region. Consequently, the subsequent section will elucidate the methodology and underlying theoretical framework that inform the construction of the proposed model.

Principle of the proposed model

The objective of this study is to propose a prediction model for developing fit-ting-ensured garment block patterns using key human body morphological dimensions. The model's purpose is to facilitate the creation of a wider range of garment styles for individuals with a convex belly (PWCB). The proposed prediction model is constructed based on a digitalised convex belly body model within a virtual environment. It establishes a linkage between garment block patterns and the deformation of the human body surface. By leveraging key human body dimensions, the proposed model enables the efficient determination of fitting-ensured garment block pattern dimensions. As a result, the fitting-ensured garment block patterns can be effectively designed to accommodate a diverse selection of garment styles.

Related concepts and tools of the proposed model

CLO 3D software

In the pattern-making process of the experimental study, the virtual software CLO 3D is utilized to obtain the PWCB mannequins and their fit-ensured garment block patterns. This is because the manual measurement of the real human body dimensions takes time, and it can easily cause errors [19]. The 3D body scanning could be a solution, but the cost is high [20]. The adoption of CLO 3D offers significant advantages in terms of efficiency compared to real clothing production [21] while also enabling the generation of diverse human body shapes with regular distribution [22, 23]. Hence, this research employs CLO 3D, which emphasizes the utilization of virtual draping as an alternative to physical draping [24–26].

Linear regression model

In the field of fashion, it is well-established that garment patterns are composed of a collection of lines and curves, each of which corresponds to a specific feature on the human body's surface (e.g., the collar girth and its corresponding neck girth) [27]. These lines and curves on both the human body and the garment pattern represent key human body morphological dimensions and pattern feature line segments, respectively. Within mathematical theory, any continuous curve can be mathematically represented by an equation.

Fuzzy comprehensive evaluation method

In the evaluation part of this study, the paper uses the fuzzy comprehensive evaluation method, which can ensure the accuracy of the data. The evaluation using a five-level Likert scale with a rubric set of V = {very ill-fitting, relatively well-fitting, average, relatively well-fitting, very well-fitting} and its assigned values of γ = {1, 2, 3, 4, 5}, i.e., the values of *a, b, c, d*, and *e* are 1, 2, 3, 4, and 5, respectively. Experts evaluate the clothing fit according to the fitting degree judgment standard and the rubric set. Therefore, the affiliation function of this study is as in equations 1–5:

$$U_a(x,a,b) = \begin{cases} 1 & x \le 1 \\ (2-x)/(2-1) & 1 < x \le 2 \\ 0 & 2 < x \end{cases} \quad (1)$$

$$U_a(x,d,e) = \begin{cases} 0 & x \le 4 \\ (x-4)/(5-4) & 4 < x \le 5 \\ 1 & 5 < x \end{cases} \quad (2)$$

$$U_a(x,a,b,c) = \begin{cases} 0 & x \le 1 \\ (x-1)/(2-1) & 1 < x \le 2 \\ (3-x)/(3-2) & 2 < x \le 3 \\ 0 & 3 < x \end{cases} \quad (3)$$

$$U_a(x,b,c,d) = \begin{cases} 0 & x \le 2 \\ (x-2)/(3-2) & 2 < x \le 3 \\ (4-x)/(4-3) & 3 < x \le 4 \\ 0 & 4 < x \end{cases} \quad (4)$$

$$U_a(x,c,d,e) = \begin{cases} 0 & x \le 3 \\ (x-3)/(4-3) & 3 < x \le 4 \\ (5-x)/(5-4) & 4 < x \le 5 \\ 0 & 5 < x \end{cases} \quad (5)$$

EXPERIMENT

In this study, a prediction model is proposed based on the deformation of the human body surface, aiming to develop fitting-ensured garment block patterns with appropriate ease values, taking into consideration the individual characteristics of men with convex bellies. To achieve this objective, a series of experiments are designed, as illustrated in figure 1, which outlines the general framework consisting of three phases.

In the first phase, relevant knowledge regarding human body morphological characteristics, specifically on body and pattern dimensions, is extracted and quantified. In the second phase, this quantified knowledge serves as the foundation for establishing a mapping relationship between key body dimensions and detailed body dimensions for men with convex bellies. Through the utilization of a linear regression model, the mapping relationship between the detailed dimensions of men with convex bellies and the pattern dimensions of fitting garment block

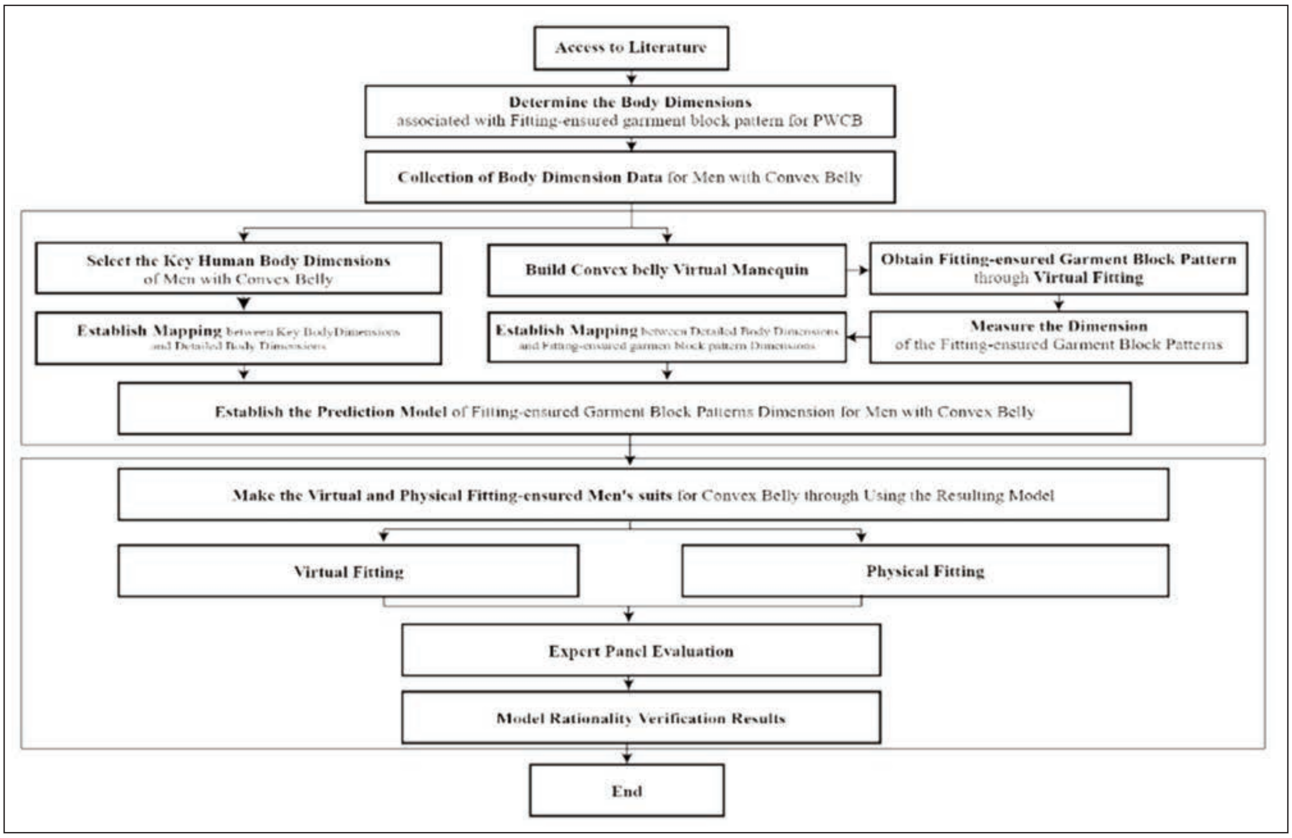


Fig. 1. General scheme for the development of a fitting-ensured men's garment block pattern prediction model

patterns is established. By combining these two relationships, a prediction model is derived for obtaining the pattern dimensions of fitting garment block patterns from key human body morphological dimensions. The prediction model is expressed through a set of linear regression equations. In the third phase, an evaluation is conducted, involving both virtual fitting and physical fitting methods [28]. This evaluation focuses on the fitting-ensured suits for individuals with convex bellies, aiming to validate the rationale behind the fitting-ensured Men's Garment Block Pattern Prediction Model for People with Convex Belly.

Experiment I: Selection of key human body morphological dimensions

Given the multitude of morphological dimensions present on the human body surface, it is crucial to identify the dimensions that are directly relevant to pattern making. To address this, a cohort of 130 virtual subjects with diverse morphology, representative of People with Convex Belly (PWCB), is created within the virtual environment facilitated by CLO 3D. It should be noted that while certain dimensions, such as hip circumference, hold significance in pattern making, they may not be relevant to upper body pattern creation. Consequently, the accuracy of dimension selection heavily relies on the expertise of pattern designers. To ensure a standardized and objective approach, a rigorous evaluation process is undertaken to assess the selection of human body morphological dimensions subjectively, as illustrated in figure 2.

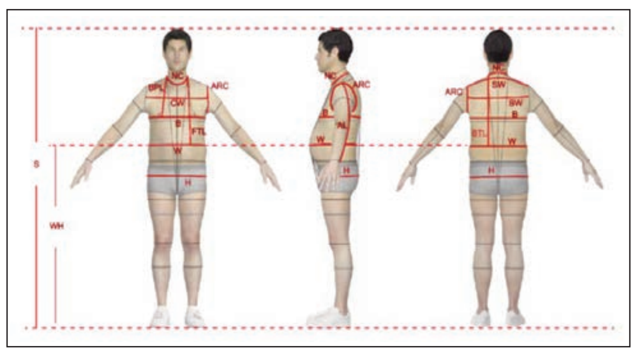


Fig. 2. Diagram of convex belly body anthropometric parts: Stature (S), Waist Height (WH), Back Length (BL), BP (Breast Point) Length (BPL), Arm Length (AL), Front Torso Length (FTL), Back Torso Length (BTL), Shoulder Width (SW), Chest Width (CW), Back Width (BW), Neck Circum-ference (NC), Arm Root Circumference (ARC), Bust (B), Waist (W), Hip (H)

We assembled a selection panel comprising ten experts in the pattern design field for this experiment. Before the selection process, the experts were provided with a comprehensive understanding of the experiment's objectives. Each panel member was tasked with compiling a list of human body morphological dimensions pertinent to their respective areas of expertise, encompassing factors such as height, length, width, and circumference of various body parts. The research object, namely the men's garment block pattern for individuals with convex bellies, was made available to the panelists as a point of reference during the selection process.

The panel engaged in detailed discussions to identify and eliminate redundant dimensions that lacked relevance to the pattern-making process specific to the men's garment block pattern for individuals with convex bellies. Employing a group decision-making approach, 14 human body morphological dimensions deemed integral to the men's garment block pattern for individuals with convex bellies were ultimately retained, which include Stature (S), Waist Height (WH), Back Length (BL), BP (Breast Point) Length (BPL), Arm Length (AL), Front Torso Length (FTL), Back Torso Length (BTL), Shoulder Width (SW), Chest Width (CW), Back Width (BW), Neck Circumference (NC), Arm Root Circumference (ARC), Bust (B), Waist (W), Hip (H).

Experiment II: Select the fitting pattern dimension date

Following the established research methodology, virtual fitting is conducted based on the acquired human body morphological dimensions. Subsequently, the fitting pattern is derived through expert perception evaluation.

Criteria for virtual fitting clothing fit assessment

To optimize cost, pattern adjustments are performed through virtual fitting [29, 30]. In this process, two key principles guide the evaluation of general clothing fit. Firstly, the clothing should exhibit a high degree of conformity to the human body, characterized by the absence of excess allowances and wrinkles. Secondly, considering the dynamic nature of the human body, the clothing should accommodate breathing and basic movement requirements while maintaining a certain degree of ease between the garment and the body surface.

In the experimental procedure, a panel of ten pattern design experts is assembled. The experts are provided with a clear explanation of the experiment's objectives. Each panelist is tasked with compiling a comprehensive list of garment fitting evaluation criteria based on their expertise. These criteria encompass the aspects influencing their assessment of the garment's fitting effect. Subsequently, all the proposed fitting evaluation criteria are presented to the panel for group discussion. Each panelist is then required to select the most suitable fitting evaluation criteria. As a result, two garment fitting evaluation criteria are identified: (1) "Overall" and (2) "Details". After that, similar processes are carried out to generate specific garment fitting evaluation positions for each garment fitting evaluation criterion. Finally, seven garment fitting evaluation positions are selected: Garment Length (GL), Bust Circumference (BC), Waist Circumference (WC), Hip circumference (HC), Collar Width (CW), Shoulder Width (SW), Armhole Depth (AD) and Back Collar Depth (BCD). For the "Overall" garment fitting evaluation criteria, "Garment Length", "Bust", "Waist", "Hip", and "Shoulder Width" are selected. For the "Details" garment fitting evaluation criteria, "Collar Width", "Back Collar Width", and "Armhole Depth" are selected. The criteria for determining the degree of the garment of men's tops with convex belly is as shown in table 1.

Principle of virtual fitting pattern adjustment

In this section, the initial step involves constructing a virtual human body model utilizing the available human body data, the flow is shown in figure 3. Subsequently, the initial garment block pattern is generated using traditional garment pattern formulas [31]. Following this, the garment block pattern is subjected to a try-on process, and the 2D pattern is adjusted based on the pressure, stress, and translucent diagrams observed in the 3D fitting analysis, as shown in figure 4 [32]. These adjustments continue until a consensus is reached among the expert panel. Ultimately, a modified garment block pattern is obtained, ensuring an appropriate fit.

To accommodate the adjustment of the garment block pattern for men's tops designed for individuals with a convex belly physique, several factors are considered. Firstly, the overall length of the garment is optimized to achieve proper fitting with the body surface. Emphasis is placed on achieving an ideal fit at the chest, shoulder blades, and shoulders.

Additionally, the front of the garment and the middle of the back should exhibit a flat and straight appearance. However, considering the protrusion of the convex belly, special attention is given to ensuring that the hem below the waist-line hangs vertically, remaining smooth and without any distortion. Moreover, sufficient breathing room is incorporated into the chest, waist, and hip areas of the garment. Lastly, when designing the collar arc and sleeve cagearc, care is taken to avoid tightness, allowing for adequate freedom of movement.

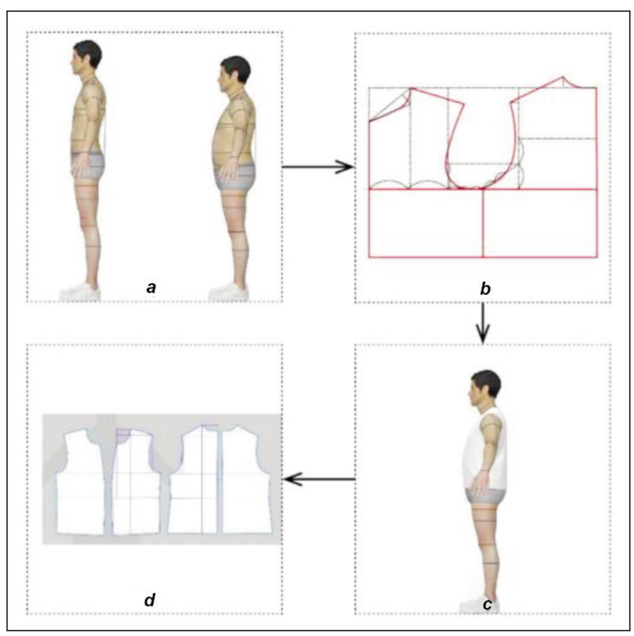


Fig. 3. Virtual fitting flowchart: *a* – adjustment of the standard body type virtual mannequin to a convex belly body mannequin; *b* – non-fit garment block pattern drawn according to the traditional formula; *c* – virtual fitting; *d* – obtaining a convex belly fitting garment block pattern

Table 1

CRITERIA FOR DETERMINING THE DEGREE OF FITTING OF THE GARMENT BLOCK PATTERN OF MEN'S TOPS WITH CONVEX BELLY		
Site		**Fitting criteria**
Overall	Garment length	**Try-on diagram:** The length of the garment is aligned with the hip line, with the front and back hems at the same level. The front and back exhibit a rounded, smooth, and flat appearance without any elevation in the front hem.
	Bust	**Try-on diagram:** The front piece of the garment fits the human chest without any excessive fabric, resulting in folds. It conforms to the contours of the chest and remains smooth at the shoulder blades of the back. **Perspective view:** Upon observation, the chest and back sections of the garment exhibit a close fit to the body, with approximately 2 to 3 cm of ease between the underarm area and the body surface. **Stress diagram:** The garment is predominantly displayed in green (indicating less stress) or blue (indicating very little stress), with white areas signifying no stress. However, the shoulder blade area, which bears stress due to gravity, is displayed in yellow (indicating more stress). If the stress reaches a significant level, it is indicated in red, suggesting a tight fit.
	Waist	**Try-on diagram:** The waist and upper belly areas of the front piece show no excess fabric folding. They conform to the body's waist and upper belly, while the back waist area slightly tapers inward and remains relatively flat. **Perspective view:** The waist and upper belly sections of the garment conform to the human body, with approximately 1–2 cm of ease between the side waist area and the body and approximately 3–5 cm of ease between the back waist area and the body surface. **Stress diagram:** The stress display for the waist area should predominantly show green, blue, or white colors. If the stress display appears red, it indicates a very tight fit, while yellow suggests a tighter fit.
	Hip	**Try-on diagram:** The garment exhibits no pleats formed by excessive fabric accumulation around the hips. It maintains a smooth and flattering appearance around the hip line, is neither tight nor flared, and remains as vertical to the ground as possible. **Perspective view:** The hip area of the garment fits the body's surface, with approximately 3–5 cm of ease between the lower belly section of the garment and the body. **Stress diagram:** The stress display for the hip area should predominantly show green, blue, or white colors. If the stress display appears red, it indicates a very tight fit, while yellow suggests a tighter fit.
	Shoulder width	**Try-on diagram:** The shoulder point of the garment is near the human shoulder point, ensuring a smooth and non-constricting shoulder line. **Perspective view:** There is approximately 1 cm of ease between the shoulder of the garment and the body surface. **Stress diagram:** As the shoulder serves as the primary load-bearing part of the garment, the stress in this area is ideally displayed in shades of yellow, green, blue, or white. If the stress area appears red, it indicates a very tight shoulder fit.
Details	Collar width	**Try-on diagram:** The collar width is slightly wider than the straight-line distance between the left and right neck points. **Stress diagram:** The stress display for the left and right neck points should predominantly show green, blue, or white colors. If the stress display appears red, it suggests a very tight collar circumference, while yellow suggests a tighter collar fit.
	Back collar depth	**Try-on diagram:** The depth of the back collar is near the back neck point. **Stress diagram:** The stress display for the back neck point should predominantly show green, blue, or white colors. If the stress display appears red, it indicates a very tight neckline, while yellow suggests a tighter neckline.
	Armhole depth	**Try-on diagram:** The armhole should not be excessively wide, and the curve of the armhole should follow a basic pattern along the shoulder point, front and rear axillary points, and the bottom point of the cage from the axillary point has the ease of about 5 to 6 cm. **Stress diagram:** The stress shown around the armhole should be green, blue or white. If the stress shows red, the armhole is very tight; if the stress shows yellow, the armhole is tighter.

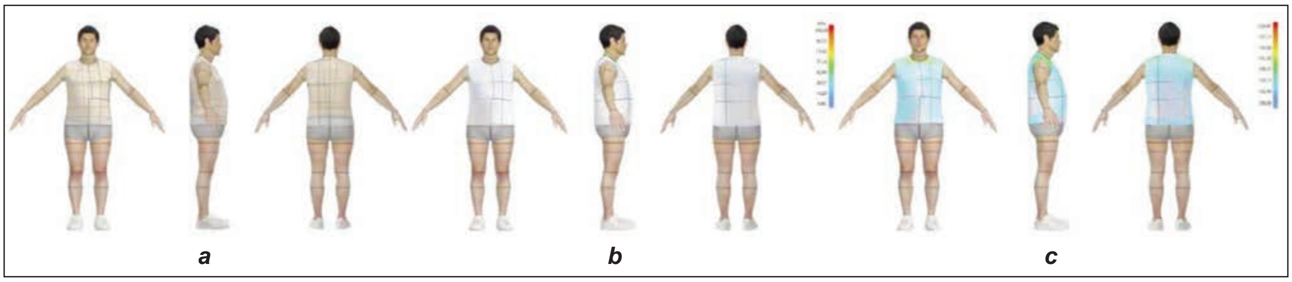


Fig. 4. Diagram of the adjustment details of the convex belly garment block pattern: *a* – perspective view (front, side, back); *b* – pressure diagram (front, side, back); *c* – stress diagram (front, side, back)

Fitting pattern data collection

Ten pattern design experts were invited to participate in a standardized subjective screening process aimed at identifying the pattern dimensions to be measured following the acquisition of fitting garment block patterns. The primary objective of the experiment was explained to the experts before their involvement. Subsequently, each panelist individually identified the characteristic lines that they deemed significant for pattern-making in men's garments designed for individuals with a convex belly physique. These characteristic lines encompassed the outlined line of the template, the structure line, and the auxiliary line. After the individual assessments, a group discussion was conducted to facilitate the selection of characteristic dimensions specifically tailored for men's garments intended for individuals with a convex belly physique. The convex belly fitting-ensured garment block pattern and diagram for measuring the characteristic dimensions of the convex belly fitting-ensured garment block pattern are as shown in figure 5.

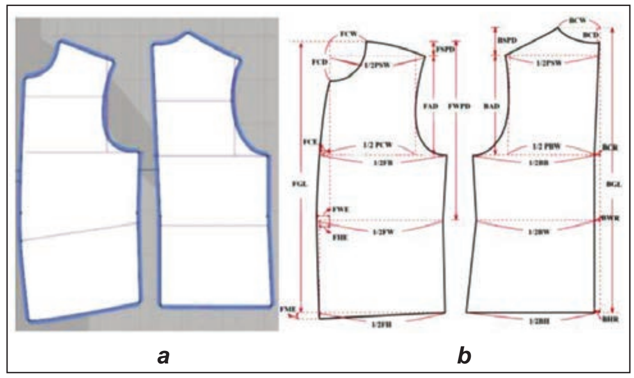


Fig. 5. The convex belly fitting-ensured garment block pattern and diagram for measuring the characteristic dimensions of the convex belly fitting-ensured garment block pattern: *a* – convex belly fitting-ensured garment block pattern obtained after virtual fitting, expert evaluation and adjustment; *b* – diagram for measuring the characteristic dimensions of the fitting-ensured garment block pattern of the convex belly

Mapping and modeling the relationship between body dimensions and pattern dimensions

Analysis of body dimensions data and extraction of key body dimensions

Based on the findings from previous anthropometry studies, it is evident that human body morphological dimensions exhibit certain correlations [33]. For instance, changes in human height are known to influence various body dimensions, while the degree

Table 2

CONVEX BELLY BODY TWO-BY-TWO DETAILED DIMENSIONS RELATED ANALYSIS RESULTS

	S	B	W	NC	ARC	H	SW	AL	BL	FTL	BTL	CW	BW	BPL	WH
S	1	0.316	0.292	0.460	0.527*	0.424	0.670*	0.842*	**0.737****	**0.748****	**0.741****	0.596*	0.560*	0.723*	**0.984****
B	0.316	1	0.860*	**0.937****	**0.927****	**0.924****	0.856*	0.289	0.370	0.586*	0.524*	**0.885****	**0.897****	0.682*	0.333
W	0.292	0.860*	1	0.807*	0.849*	0.857*	0.754*	0.278	0.267	0.406	0.392	0.696*	0.769*	0.762*	0.325
NC	0.460	**0.937****	0.807*	1	0.930*	0.898*	0.899*	0.402	0.462	0.665*	0.611*	0.895*	0.885*	0.769	0.469
ARC	0.527*	**0.927****	0.849*	0.930*	1	0.905*	0.914*	0.444	0.507*	0.668*	0.639*	0.882*	0.909*	0.813*	0.542*
H	0.424	**0.924****	0.857*	0.898*	0.905*	1	0.855*	0.377	0.410	0.619*	0.544*	0.854*	0.868*	0.752*	0.438
SW	0.670*	0.856*	0.754*	0.899*	0.914*	0.855*	1	0.572*	0.600*	0.740*	0.731*	0.925*	0.959*	**0.848****	0.673*
AL	0.842*	0.289	0.278	0.402	0.444	0.377	0.572*	1	0.635*	0.649*	0.634*	0.526*	0.497	0.621*	0.827*
BL	**0.737****	0.370	0.267	0.462	0.507*	0.410	0.600*	0.635*	1	0.814*	0.945*	0.506*	0.571*	0.539*	0.640*
FTL	**0.748****	0.586*	0.406	0.665*	0.668*	0.619*	0.740*	0.649	0.814*	1	0.841*	0.734*	0.677*	0.685*	0.670*
BTL	**0.741****	0.524*	0.392	0.611*	0.639*	0.544*	0.731*	0.634*	0.945*	0.841*	1	0.639*	0.698*	0.601*	0.658*
CW	0.596*	**0.885****	0.696*	0.895*	0.882*	0.854*	0.925*	0.526*	0.506*	0.734*	0.639*	1	0.907*	0.755*	0.605*
BW	0.560*	**0.897****	0.769*	0.885*	0.909*	0.868*	0.959*	0.497*	0.571*	0.677*	0.698*	0.907*	1	0.768*	0.568*
BPL	0.723*	0.682*	0.762*	0.769	0.813*	0.752*	**0.848****	0.621*	0.539*	0.685*	0.601*	0.755*	0.768*	1	0.724*
WH	**0.984****	0.333	0.325	0.469	0.542*	0.438	0.673*	0.827*	0.640*	0.670*	0.658*	0.605*	0.568*	0.724*	1

of human obesity is associated with alterations in circumference dimensions in different directions. Consequently, modifications in individual body part dimensions correspond to changes in the corresponding dimensions of the clothing worn.

Apart from general trends, more specific quantitative relationships may exist among the aforementioned data. To identify correlated data and establish precise quantitative relationships between relevant variables, the present study employs the data analysis software SPSS to conduct correlation and regression analyses. As presented in table 2, the strength of correlation between two body dimensions is indicated by the magnitude of the correlation coefficient, which falls within the range of 0 to 1. A correlation coefficient of 1 signifies that the two body dimensions are identical. In the table, an asterisk (*) is used to denote a stronger correlation between two groups of body dimensions. Based on the data provided in the table, ten pattern design experts analyze and screen the data, considering both the magnitude of the correlation coefficient and other factors such as representativeness in a single dimension and ease of measurement. The final selection of key dimensions includes Stature (S), Bust (B), Shoulder Width (SW), Waist (W), Arm Length (AL), and their respective detailed dimensions, as outlined in table 3. The correlation of these selected dimensions with other detailed dimensions is denoted by a double asterisk (**).

Based on the data presented in the table, it is evident that the correlation coefficient between certain screened key body dimensions and their corresponding detailed dimensions is not the highest. Notably, the measurement of height has been widely employed as an indicator of the longitudinal length of the human body in both scientific research and everyday life. Height is a well-recognized and easily measurable dimension, making it more representative. Therefore, height is deemed a crucial body dimension and is selected as one of the key dimensions.

Linear regression model for body dimension data

As depicted in table 4, a linear regression analysis is conducted on the two sets of data, considering the relationship between the screened key body dimensions and the corresponding detailed body dimensions. The R-square value signifies the extent to which the selected independent variable can explain the dependent variable. A higher R-square value, closer to 1, indicates a stronger explanatory power of

Table 3

TABLE OF CORRELATION COEFFICIENTS OF SCREENED KEY BODY DIMENSION AND THE DETAILIED BODY DIMENSIONS THEY REPRESENT

Key body dimensions	Detailed body dimensions	Correlation coefficient
Stature (S)	Back Length (BL)	0.737
	Front Torso Length (FTL)	0.748
	Back Torso Length (BTL)	0.741
	Waist Height (WH)	0.984
Bust (B)	Neck Circumference (NC)	0.937
	Hip (H)	0.924
	Arm root circumference (ARC)	0.927
	Chest Width (CW)	0.885
	Back Width (BW)	0.897
Shoulder width (SW)	Breast Point Length (BPL)	0.848
Waist (W)	-	-
Arm length (AL)	-	-

the independent variable over the dependent variable. The coefficients and constants of the linear regression model for back length and height are presented in table 5 as 0.225 and 7.351, respectively, with significance levels of 0.022 and 0.000 ($P<0.05$), thereby indicating the statistical significance of the linear regression analysis results. Figure 6, *a* illustrates that the independent variable (height) in the regression model approximates a normal distribution. The quality of the linear regression model fit can be assessed by examining the proximity of scattered points in the standardized residual normal *P-P* plot (figure 6, *b*) to the straight line, and the scatter and regularity of points in the scatter plot (figure 6, *c*).

Utilizing the aforementioned analyses, the linear regression equation is derived from the linear regression model, with the screened key body dimensions serving as the independent variable and the remaining detailed dimensions as the dependent variable. The obtained linear regression equation is presented in table 6. With this linear regression equation, it

Table 4

SUMMARY TABLE OF HEIGHT-BACK LENGTH LINEAR REGRESSION ANALYSIS MODEL

Model	R	R-Squared	Adjusted R2	Error in standard estimation	Change statistics					Durbin-Watson
					R-squared change amount	F change amount	Freedom 1	Freedom 2	Significance F amount of change	
1	0.737[a]	0.544	0.540	1.1342	0.544	152.581	1	128	0.000	1.892

Note: a – predictive variables: (Constant), Height; b – dependent variable: Back length.

Table 5

TABLE OF COEFFICIENTS OF HEIGHT-BACK LENGTH LINEAR REGRESSION ANALYSIS								
Model	**Unstandardized coefficient**		**Standardized coefficient**		**T**	**Significance**	**Covariance statistics**	
	B		**Standard Error**	**Beta**			**Tolerances**	**VIF**
1	(Constant)	7.351	3.163	/	2.324	0.022	/	/
	Height	0.225	0.018	0.737	12.352	0.000	1.000	1.000

Note: a – dependent variable: Back length.

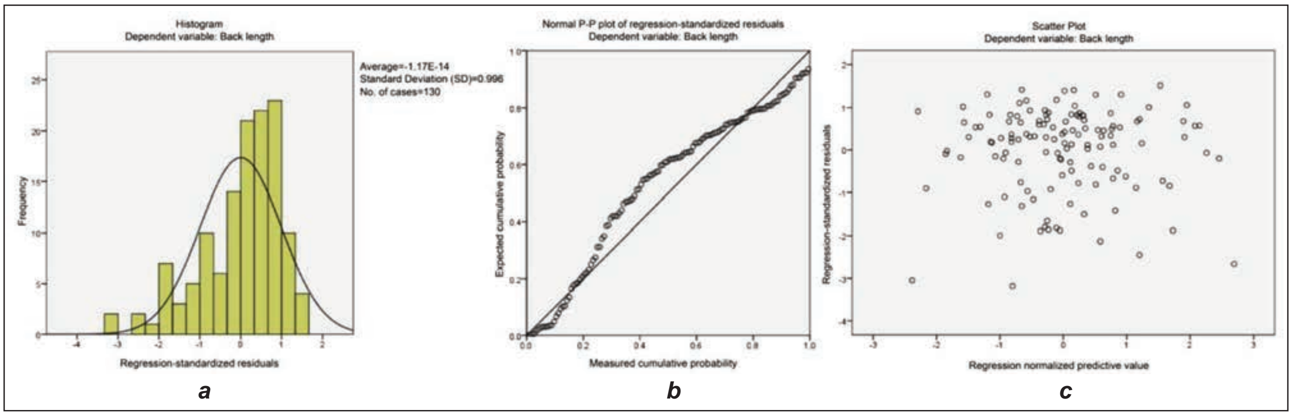


Fig. 6. Linear regression model for body dimension data: *a* – histogram of standardized residuals from height-back length regression; *b* – normal P-P plot of regression-standardized residuals; *c* – height-back length regression standardized predictive scatter plot

Table 6

CONVEX BELLY KEY DIMENSION-DETAILED DIMENSION LINEAR REGRESSION EQUATION	
Detailed dimension	**Linear regression equation**
Back length (BL)	BL = 0.225S + 7.351 (S: height)
Front Torso Length (FTL)	FTL = 0.242S + 5.208 (S: height)
Back Torso Length (BTL)	BTL = 0.263S + 3.436 (S: height)
Waist Height (WH)	WH = 0.708S – 15.830 (S: height)
Chest Width (CW)	CW = 0.189B + 20.117 (B: bust)
Back Width (BW)	BW = 0.216B + 16.594 (B: bust)
Neck Circumference (NC)	NC = 0.279B + 13.120 (B: bust)
Hip (H)	H = 0.791B + 19.956 (B: bust)
Arm root circumference (ARC)	ARC = 0.542B – 7.985 (B: bust)
Breast Point Length (BPL)	BPL = 0.478SW + 6.834SW: shoulder width)

becomes feasible to predict other detailed body dimensions based on the screened key body dimensions.

Linear regression model of body dimension data and pattern dimension data

In the case of the sleeve pattern, the traditional pattern formula is employed due to the minimal difference observed between the arm portion of individuals with convex belly body type and those with normal body type. By establishing a correlation between human data and pattern data, the necessary human detail dimensions required for constructing the regression analysis model of human data – pattern data can be obtained. The detailed dimensions encompass chest width (CW), back width (BW), neck circumference (NC), and waist height (WH). The regression models illustrating the relationships between these body-detailed dimensions and the key body dimensions are presented in table 7.

In this study, a comprehensive linear regression analysis is performed to investigate the relationship between human body dimensions and garment pattern dimensions. To illustrate this relationship, the linear regression model of human chest circumference and sample chest dimension is utilized as an exemplar. The model summary table (table 8) reveals an R-squared value approaching unity, indicating a strong ability of the independent variable (human chest circumference) to account for the variability observed in the dependent variable (pattern chest

Table 7

LINEAR REGRESSION MODEL OF BODY DIMENSION DATA AND PATTERN DIMENSION DATA	
Body dimension	**Linear regression equation**
Chest Width (CW)	CW = 0.189B + 20.117
Back Width (BW)	BW = 0.216B + 16.594
Neck Circumference (NC)	NC = 0.279B + 13.120
Waist Height (WH)	WH = 0.708S – 15.830

circumference). Examining the coefficient table (table 9), we find that the coefficients of the independent variables, namely bust and constant, are estimated to be 0.455 and 7.022, respectively. Moreover, their corresponding significance levels are determined to be 0.000, indicating statistical significance (P<0.05).

Figure 7, *a* exhibits a histogram representing the bust measurements, which demonstrates a favorable fit to the normal distribution curve. This observation suggests that the bust distribution among the experimental cases aligns closely with a normal distribution. Additionally, the regression normalized residuals normal P-P plot (figure 7, *b*) displays a satisfactory correspondence between the predicted accumulation probability and the observed accumulation probability, further indicating a normal distribution pattern within the pattern data. Furthermore, the scatter plot (figure 7, *c*) displays a random and irregular distribution of points, signifying a robust fit of the regression model.

According to the results presented in table 10, the linear regression analysis has enabled the determination of the final linear regression equation. This equation establishes the relationship between the independent variable of detailed body dimensions and the dependent variable of pattern dimensions. Furthermore, the linear regression equation between the fitting garment block pattern dimensions and the

Table 8

SUMMARY TABLE OF LINEAR REGRESSION ANALYSIS MODEL OF BODY CHEST CIRCUMFERENCE – PATTERN CHEST CIRCUMFERENCE

Model	**R**	**R-Squared**	**Adjusted R2**	**Error in standard estimation**	**Change statistics**					**Durbin-Watson**
					R-squared change amount	**F change amount**	**Freedom 1**	**Freedom 2**	**Significance F amount of change**	
1	0.975[a]	0.950	0.950	0.6941	0.950	2427.915	1	128	0.000	1.957

Note: a – predictive variables: (Constant), Bust; b – dependent variable: Bust.

Table 9

TABLE OF COEFFICIENTS FOR LINEAR REGRESSION ANALYSIS OF BODY CHEST CIRCUMFERENCE – PATTERN CHEST CIRCUMFERENCE

Model	**Unstandardized coefficient**		**Standardized coefficient**		**t**	**Significance**	**Covariance statistics**	
	B		**Standard Error**	**Beta**			**Tolerances**	**VIF**
1	(Constant)	7.022	0.986	/	7.124	0.000	/	/
	Bust	0.455	0.009	0.975	49.274	0.000	1.000	1.000

Note: a – dependent variable: Bust.

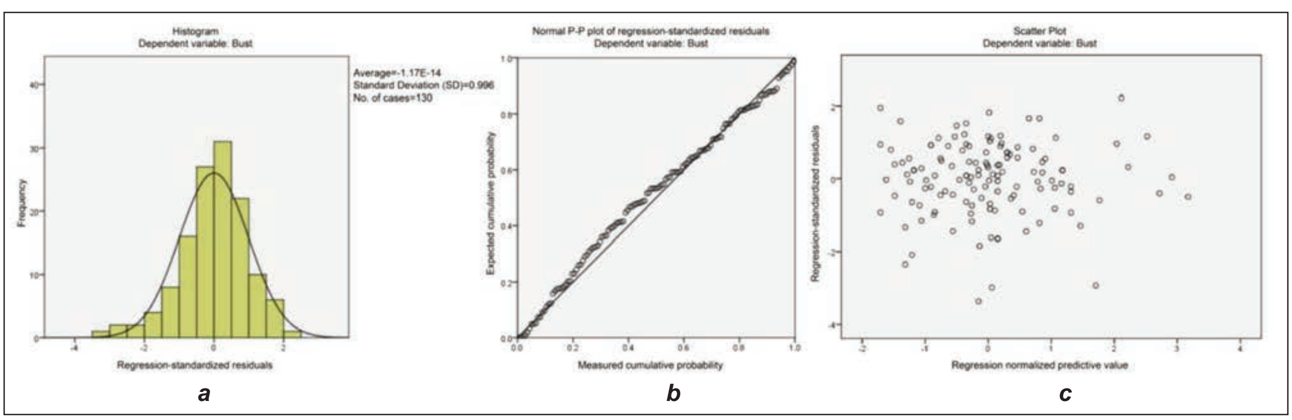


Fig. 7. Linear Regression model of body dimension data and pattern dimension data: *a* – histogram of standardized residuals from body bust – pattern bust regression; *b* – normal P-P plot of regression-standardized residuals; *c* – body bust – pattern bust regression standardized predictive scatter plot

Table 10

LINEAR REGRESSION EQUATION FOR KEY HUMAN BODY MORPHOLOGICAL DIMENSION-FITTING GARMENT BLOCK PATTERN DIMENSION	
Pattern dimension	**Linear regression equation**
Front garment length (FGL)	FGL = 0.345S + 2.504
Back garment length (BGL)	BGL = 0.324S + 8.485
1/2 front bust (1/2FB)	1/2FB = 0.455B + 7.022
1/2 back bust (1/2BB)	1/2BB = 0.455B + 7.022
1/2 front waist (1/2FW)	1/2FW = 0.438W + 9.043
1/2 back waist (1/2BW)	1/2BW = 0.438W + 9.043
1/2 pattern chest width (1/2PCW)	1/2PCW = 0.361CW + 4.958 = 0.068B + 12.220
1/2 pattern back width (1/2PBW)	1/2PBW = 0.518BW – 1.421 = 0.112B + 8.596
1/2 front hem (1/2FH)	1/2FH = 0.423W + 11.147
1/2 back hem (1/2BH)	1/2BH = 0.423W + 11.147
1/2 pattern shoulder width (1/2PSW)	1/2 PSW = 0.408SW + 3.493
Front collar width (FCW)	FCW = 0.244NC – 0.630 = 0.068B + 2.571
Front collar depth (FCD)	FCD = 0.222NC – 0.113 = 0.062B + 2.800
Back collar width (BCW)	BCW = 0.276NC – 1.318 = 0.077B + 2.300
Back collar depth (BCD)	BCD = 0.155NC – 2.341 = 0.043B – 0.307
Front armhole depth (FAD)	FAD = 0.12B + 0.094S – 5.109
Back armhole depth (BAD)	BAD = 0.125B + 0.104S – 6.919
Front shoulder point depth (FSPD)	FSPD = 0.159SW – 2.957
Back shoulder point depth (BSPD)	BSPD = 0.09SW + 1.881
Front waist point depth (FWPD)	FWPD = 0.355S – 16.617
Back waist receipt (BWR)	BWR = 0.098W – 10.403
Back hem receipt (BHR)	BHR = 1.084BWR – 0.019 = 0.106W – 11.296
Back chest receipt (BCR)	BCR = 0.603BWR + 0.002 = 0.059W + 6.293
The front middle extension (FME)	FME = –0.033(B – W) + 2.714
Front waist extension (FWE)	FWE = –0.052(B – W) + 1.444
Front chest extension (FCE)	FCE = 0.652 FWE – 0.085 = – 0.037(B – W) + 0.932
Front hem extension (FHE)	FHE = 1.268 FWE – 1.307 = – 0.066(B – W) + 0.524

key human body morphological dimensions is established based on the interconnection between the detailed body dimensions and the key body dimensions.

RESULT AND DISCUSSION

In this section, we undertake the validation and evaluation of the findings obtained in the study. Employing the model developed in this paper, which predicts the dimensions of the garment block pattern based on key human body morphological dimensions, we construct a suit garment block pattern specifically designed for individuals with a convex belly. Subsequently, both virtual and physical fitting sessions are conducted to try on the fitting-ensured men's suits tailored using the extended model derived from this study. To ensure comprehensive evaluation, experts are invited to assess the fitting effect, while subjective feedback regarding the wearing experience is gathered from the individuals participating in the physical fitting. This comprehensive assessment aims to validate the feasibility and practicality of the study's outcomes.

For the research scope, this study focuses on the Japanese suit (H-type) characterized by a suitable amount of ease and a well-fitted design. Moreover, the specific suit style selected for investigation features flat lapels, a one-button closure, and no slits, as exemplified in figure 8 [34].

The linear regression model established in this study, which correlates key human body morphological dimensions with fitting garment block pattern dimensions, serves as an initial garment block pattern for patterned garments. To validate the feasibility of the study results, the pattern function model is to be reconfigured to accommodate the specific structure of the convex belly men's suit. As an example, the suit's sleeve pattern can be parametrically designed based on the functional relationship derived from the traditional empirical formula, considering the minimal difference between the convex belly body type and the normal body type in the arm region. Additionally, components such as the collar and pocket can also be parametrically designed using the traditional

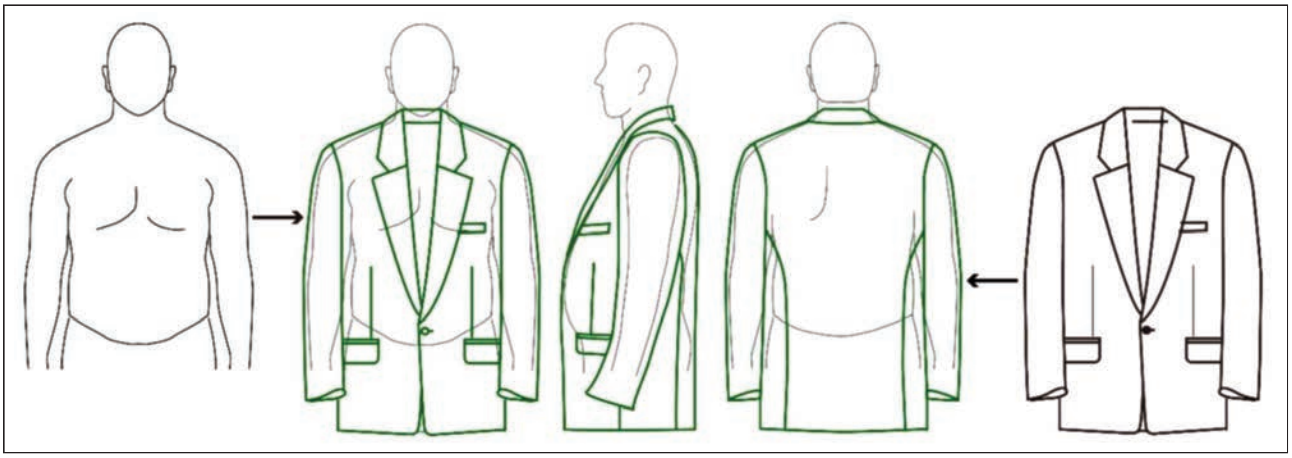


Fig. 8. Dress style diagram of H suit with a convex belly

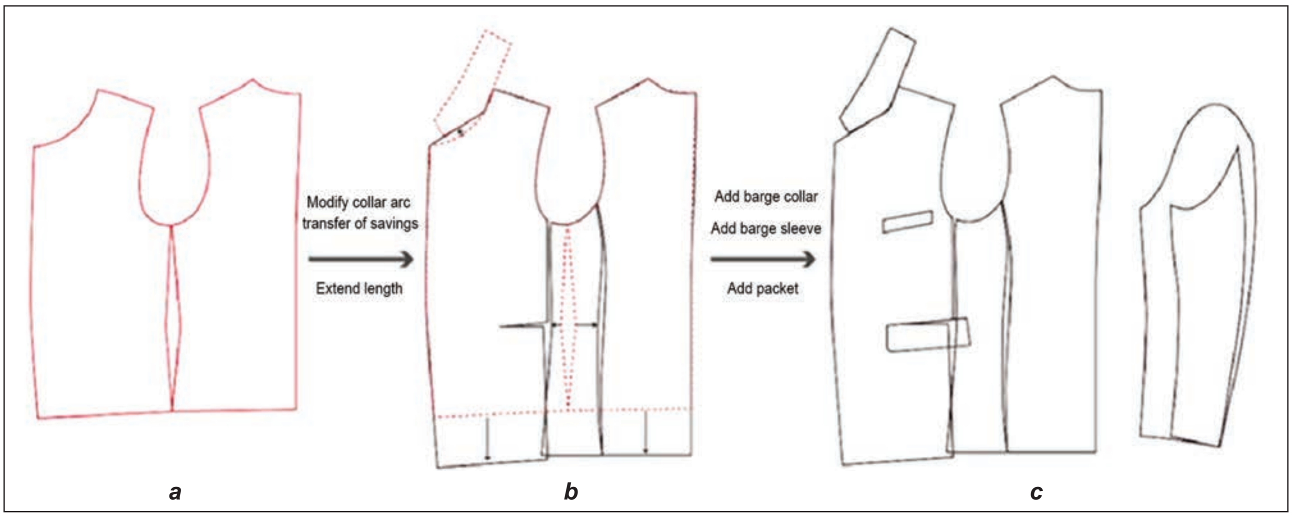


Fig. 9. The flow chart of transforming the fitting-ensured garment block pattern into the fitting-ensured suit pattern: *a* – fitting-ensured garment block pattern for convex belly; *b* – the suit pattern after modifying the front collar arc, transferring the dart, and lengthening the back of the garment; *c* – fitting-ensured suit pattern for convex belly

empirical formula. The outlined process is illustrated in figure 9.

In the virtual fitting evaluation session, a sample of ten subjects with convex belly body types is carefully selected, and their anthropometric measurements are conducted based on the key body dimensions identified in this study. Subsequently, ten virtual mannequins and ten sets of men's suit patterns are established within a virtual environment. These patterns are then tried on using virtual fitting software [16]. Figures 10 and 11 provide a comprehensive visual analysis through a tripartite presentation of Subject 10's virtual fitting process, juxtaposed with the subject's real-life depictions. Specifically, figure 10 elucidates the virtual fitting rendering, offering a perspective view alongside a stress diagram for Subject 10,

Fig. 10. Three views of the virtual fitting rendering, perspective view and stress diagram for subject 10

Fig. 11. Three views of subject 10 in real life

thereby facilitating a multifaceted understanding of the garment's virtual fit. Conversely, figure 11 presents three distinct real-life views of Subject 10, enabling a direct comparison between the simulated garment fit and its actual physical manifestation. This comparative visual documentation serves to underscore the fidelity and practical applicability of the virtual fitting process. Finally, a panel of 30 experts from the apparel field is invited to evaluate the fitting of the virtual garments.

During the physical fitting evaluation session, two subjects with convex belly body types are purposefully selected, and their five key human body morphological dimensions are accurately measured. Two sets of men's suit patterns are generated based on the findings of this research. The garments are constructed using non-elastic black suit fabric. Finally, a panel of 30 experts from the apparel field is invited to score the visual fit of the garments, while the subjects themselves evaluate the subjective comfort.

The evaluation process employs a five-level Likert scale, as previously mentioned. By combining the virtual fitting evaluation results with the fuzzy comprehensive evaluation method [35], ten sets of rubric affiliation are derived, constituting a judgment matrix.

$$R_1 = \begin{bmatrix} 0 & 0.0333 & 0.1 & 0.4333 & 0.4333 \\ 0 & 0 & 0.0333 & 0.5 & 0.4667 \\ 0 & 0.0333 & 0.1 & 0.6667 & 0.2 \\ 0 & 0 & 0.1667 & 0.5 & 0.3333 \\ 0 & 0 & 0.0333 & 0.6333 & 0.3333 \\ 0 & 0 & 0.1 & 0.5 & 0.4 \\ 0 & 0 & 0.1667 & 0.5 & 0.3333 \\ 0 & 0.0333 & 0.0333 & 0.5667 & 0.3667 \\ 0 & 0 & 0.1333 & 0.4333 & 0.4333 \\ 0 & 0 & 0.0667 & 0.4333 & 0.5 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 0 & 0.0667 & 0.0667 & 0.0667 & 0.2 \\ 0 & 0 & 0.1333 & 0.5 & 0.3667 \\ 0 & 0.0333 & 0.1 & 0.3667 & 0.5 \\ 0 & 0 & 0.1 & 0.4667 & 0.4333 \\ 0 & 0 & 0.0333 & 0.4 & 0.5667 \\ 0 & 0 & 0.1667 & 0.4 & 0.4333 \\ 0 & 0 & 0 & 0.5667 & 0.4333 \\ 0 & 0 & 0.1 & 0.5333 & 0.3667 \\ 0 & 0.0667 & 0.0667 & 0.4 & 0.4667 \\ 0 & 0.0333 & 0.1667 & 0.3333 & 0.4667 \end{bmatrix}$$

$$R_3 = \begin{bmatrix} 0 & 0.0333 & 0.0333 & 0.4667 & 0.4667 \\ 0 & 0 & 0.1 & 0.5 & 0.4 \\ 0 & 0 & 0.2 & 0.4333 & 0.3667 \\ 0 & 0 & 0.1 & 0.5333 & 0.3667 \\ 0 & 0 & 0.0333 & 0.5 & 0.4667 \\ 0 & 0 & 0.1333 & 0.5667 & 0.3 \\ 0 & 0 & 0.0667 & 0.4667 & 0.4667 \\ 0 & 0 & 0.0667 & 0.4 & 0.5333 \\ 0 & 0.0333 & 0.1333 & 0.4333 & 0.3667 \\ 0 & 0.1 & 0.2333 & 0.3 & 0.3667 \end{bmatrix}$$

$$R_4 = \begin{bmatrix} 0 & 0.0333 & 0.1 & 0.4333 & 0.4333 \\ 0 & 0 & 0.0667 & 0.4667 & 0.4667 \\ 0.0333 & 0 & 0.0667 & 0.5667 & 0.3333 \\ 0.0333 & 0 & 0.0667 & 0.5333 & 0.3667 \\ 0 & 0 & 0.0667 & 0.4667 & 0.4667 \\ 0 & 0 & 0.0667 & 0.5 & 0.4333 \\ 0 & 0 & 0.0333 & 0.5667 & 0.4 \\ 0 & 0 & 0.0667 & 0.5 & 0.4333 \\ 0 & 0 & 0.1667 & 0.4667 & 0.3667 \\ 0 & 0.1 & 0.1 & 0.5 & 0.3 \end{bmatrix}$$

$$R_5 = \begin{bmatrix} 0 & 0.0333 & 0.0333 & 0.3333 & 0.6 \\ 0 & 0 & 0.1333 & 0.6333 & 0.2333 \\ 0 & 0 & 0.1 & 0.4333 & 0.4666 \\ 0 & 0 & 0 & 0.5333 & 0.4667 \\ 0 & 0 & 0.0333 & 0.5 & 0.4667 \\ 0 & 0 & 0.1 & 0.4333 & 0.4667 \\ 0 & 0 & 0.0667 & 0.4333 & 0.5 \\ 0 & 0 & 0.1667 & 0.4 & 0.4333 \\ 0 & 0 & 0.1667 & 0.4 & 0.4333 \\ 0 & 0.0667 & 0.1333 & 0.4 & 0.4 \end{bmatrix}$$

$$R_6 = \begin{bmatrix} 0 & 0.0333 & 0 & 0.4333 & 0.5333 \\ 0 & 0 & 0.0667 & 0.5 & 0.4333 \\ 0 & 0 & 0.1333 & 0.5333 & 0.3333 \\ 0 & 0.0333 & 0.2 & 0.4 & 0.3667 \\ 0 & 0 & 0.0667 & 0.4 & 0.5333 \\ 0 & 0 & 0.0667 & 0.5 & 0.4333 \\ 0 & 0.0333 & 0.0333 & 0.5333 & 0.4 \\ 0 & 0 & 0.1 & 0.5333 & 0.3667 \\ 0 & 0 & 0.1667 & 0.4 & 0.4333 \\ 0 & 0.0333 & 0.1 & 0.4667 & 0.4 \end{bmatrix}$$

$$R_7 = \begin{bmatrix} 0 & 0.0333 & 0.0667 & 0.4333 & 0.4667 \\ 0 & 0 & 0.1 & 0.5 & 0.4 \\ 0 & 0 & 0.0667 & 0.5 & 0.4333 \\ 0 & 0 & 0.1333 & 0.3667 & 0.5 \\ 0 & 0 & 0 & 0.4333 & 0.5667 \\ 0 & 0 & 0.0667 & 0.4 & 0.5333 \\ 0 & 0 & 0.0333 & 0.5 & 0.4667 \\ 0 & 0 & 0.1333 & 0.3667 & 0.5 \\ 0 & 0 & 0.1 & 0.4667 & 0.4333 \\ 0 & 0.0333 & 0.1 & 0.4333 & 0.4333 \end{bmatrix}$$

$$R_8 = \begin{bmatrix} 0 & 0.0333 & 0.0667 & 0.3333 & 0.5667 \\ 0 & 0 & 0.1333 & 0.5 & 0.3667 \\ 0 & 0 & 0.2667 & 0.4333 & 0.3 \\ 0 & 0 & 0.1 & 0.4667 & 0.4333 \\ 0 & 0 & 0.0667 & 0.3333 & 0.6 \\ 0 & 0 & 0.1 & 0.4 & 0.5 \\ 0 & 0 & 0.0333 & 0.4667 & 0.5 \\ 0 & 0 & 0.1667 & 0.3667 & 0.4667 \\ 0 & 0 & 0.0667 & 0.5667 & 0.3667 \\ 0 & 0.0333 & 0.0667 & 0.5333 & 0.3667 \end{bmatrix}$$

$$R_9 = \begin{bmatrix} 0 & 0.0667 & 0.0667 & 0.4 & 0.4667 \\ 0 & 0 & 0.1667 & 0.5333 & 0.3 \\ 0 & 0 & 0.1333 & 0.5 & 0.3667 \\ 0 & 0 & 0.1 & 0.4333 & 0.4667 \\ 0 & 0 & 0.0667 & 0.5 & 0.4333 \\ 0 & 0 & 0.1667 & 0.4333 & 0.4333 \\ 0 & 0 & 0 & 0.5 & 0.5333 \\ 0 & 0 & 0.0667 & 0.4 & 0.5333 \\ 0 & 0 & 0.2333 & 0.4667 & 0.3 \\ 0 & 0.0333 & 0.1333 & 0.5333 & 0.3 \end{bmatrix}$$

$$R_{10} = \begin{bmatrix} 0 & 0.0333 & 0.0333 & 0.4667 & 0.4667 \\ 0 & 0 & 0.3 & 0.3667 & 0.3333 \\ 0 & 0 & 0.1 & 0.6 & 0.3 \\ 0 & 0 & 0.2 & 0.2667 & 0.5333 \\ 0 & 0 & 0.0667 & 0.3667 & 0.5667 \\ 0 & 0.0333 & 0 & 0.5 & 0.4667 \\ 0 & 0 & 0.0667 & 0.5333 & 0.4 \\ 0 & 0.0333 & 0.1 & 0.4667 & 0.4 \\ 0 & 0.0333 & 0.1667 & 0.6333 & 0.1667 \\ 0 & 0.0667 & 0.2 & 0.4333 & 0.3 \end{bmatrix}$$

In this study, the Delphi method is used to interview five university teachers of fashion design and engineering to determine the weights of 10 apparel evaluation parts. The resulting weight set is *W={Garment length, Bust, Waist, Hip, Shoulder width, Collar width, Back collar fit, Armhole depth, Sleeve fat, Sleeve length}={0.15, 0.15, 0.15, 0.1, 0.1, 0.05, 0.05, 0.1, 0.05, 0.1}*. Thus, the ten sets of integrated affiliation vectors are as follows.

$B_1 = W \times R_1 =$
$= \{0, 0.013320, 0.084995, 0.524995, 0.376660\}$

$B_2 = W \times R_2 =$
$= \{0, 0.021665, 0.096670, 0.471675, 0.410010\}$

$B_3 = W \times R_3 =$
$= \{0.001665, 0.016660, 0.109990, 0.456665, 0.415020\}$

$B_4 = W \times R_4 =$
$= \{0.008325, 0.014995, 0.078355, 0.496675, 0.401665\}$

$B_5 = W \times R_5 =$
$= \{0, 0.011665, 0.089990, 0.4566450, 0.441670\}$

$B_6 = W \times R_6 =$
$= \{0, 0.013320, 0.090005, 0.471655, 0.424985\}$

$B_7 = W \times R_7 =$
$= \{0, 0.008325, 0.081670, 0.443330, 0.466665\}$

$B_8 = W \times R_8 =$
$= \{0, 0.008325, 0.120015, 0.431660, 0.440015\}$

$B_9 = W \times R_9 =$
$= \{0, 0.013335, 0.111675, 0.468325, 0.406670\}$

$B_{10} = W \times R_{10} =$
$= \{0, 0.018325, 0.133335, 0.451680, 0.396670\}$

The formula gives the final evaluation score of $Y_1 = 4.2649$, $Y_2 = 4.2701$, $Y_3 = 4.2667$, $Y_4 = 4.2684$, $Y_5 = 4.3282$, $Y_6 = 4.3082$, $Y_7 = 4.3683$, $Y_8 = 4.3034$, $Y_9 = 4.2683$ and $Y_{10} = 4.2267$. It can be seen that the virtual fitting results of the ten groups of virtual mannequins are between relatively fit and very fit, which indicates that the mathematical model proposed in this study has some rationality.

From the physical fitting evaluation results and fuzzy comprehensive evaluation method, we can obtain the following two groups of rubric affiliation consisting of a judgment matrix.

$$R_{11} = \begin{bmatrix} 0 & 0 & 0 & 0.3667 & 0.6333 \\ 0 & 0 & 0.0667 & 0.5000 & 0.4333 \\ 0 & 0 & 0.0667 & 0.4333 & 0.5000 \\ 0 & 0 & 0.0667 & 0.4000 & 0.5333 \\ 0 & 0 & 0.1667 & 0.5000 & 0.3333 \\ 0 & 0 & 0.0667 & 0.4333 & 0.5000 \\ 0 & 0 & 0 & 0.4667 & 0.5333 \\ 0 & 0 & 0.1667 & 0.5667 & 0.2667 \\ 0 & 0 & 0 & 0.6000 & 0.4000 \\ 0 & 0 & 0.0333 & 0.4000 & 0.5667 \end{bmatrix}$$

$$R_{12} = \begin{bmatrix} 0 & 0 & 0 & 0.7000 & 0.3000 \\ 0 & 0 & 0.1000 & 0.4667 & 0.4333 \\ 0 & 0 & 0.1000 & 0.5667 & 0.3333 \\ 0 & 0 & 0.0667 & 0.3667 & 0.5667 \\ 0 & 0 & 0.1333 & 0.5000 & 0.3667 \\ 0 & 0 & 0.0667 & 0.5000 & 0.4333 \\ 0 & 0 & 0.0333 & 0.3000 & 0.6667 \\ 0 & 0 & 0.1000 & 0.5667 & 0.3333 \\ 0 & 0 & 0.0667 & 0.7333 & 0.2000 \\ 0 & 0 & 0 & 0.5667 & 0.4333 \end{bmatrix}$$

Based on the weight set: *W={Garment length, Bust, Waist, Hip, Shoulder width, Collar width, Back collar fit, Armhole depth, Sleeve fat, Sleeve length}={0.15, 0.15, 0.15, 0.1, 0.1, 0.05, 0.05, 0.1, 0.05, 0.1}* determined by the Delphi method in the virtual fitting evaluation experiment, the affiliation vector for the visual evaluation of the fit of the real person fitting is calculated as follows.

$B_{11} = W \times R_{11} = \{0, 0, 0.066667, 0.456667, 0.476667\}$

$B_{12} = W \times R_{12} = \{0, 0, 0.068333, 0.536667, 0.395000\}$

The final evaluation scores are: $Y_{11} = 4.4100$; $Y_{12} = 4.3267$.

The results of the subjective comfort evaluation conducted with the subjects are presented in figure 12, *a* and *b*. The average scores for the subjective comfort

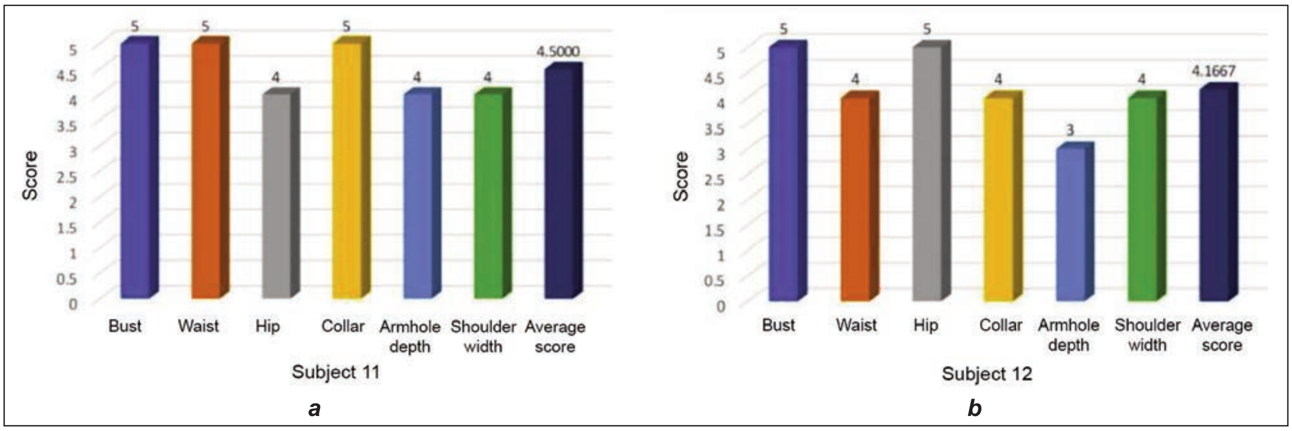


Fig. 12. The results of the subjective comfort evaluation conducted with the subjects: *a* – convex belly fitting-ensured suit subjective comfort evaluation experiment subject 11 evaluation results; *b* – convex belly fitting-ensured suit subjective comfort evaluation experiment subject 12 evaluation results

evaluation of the two types of suits are 4.5 and 4.1667, respectively. These scores, both exceeding 4, signify a high level of comfort. The comprehensive evaluation outcomes outlined above collectively demonstrate that the mathematical model developed in this study possesses a degree of rationality and practicality.

CONCLUSIONS

This study presents a novel prediction model for developing fitting-ensured garment block patterns tailored to individuals with convex bellies (PWCB). The research begins by creating digitalized 3D human body models using CLO 3D software and analyzing them to extract crucial human body morphological dimensions and fitting-ensured garment block pattern dimensions. Subsequently, a linear regression model is employed to establish the mapping relationship between the identified human body morphological dimensions and the corresponding fitting-ensured garment block pattern dimensions. To evaluate the effectiveness of the model, a fuzzy comprehensive evaluation method is conducted, involving both virtual fitting and physical fitting to assess its accuracy and efficiency in clothing design. Throughout the entire modeling process, emphasis is placed on incorporating the unique characteristics of individuals with convex bellies (PWCB) and establishing the relationship between the human body and garment block patterns as fundamental guiding principles.

The current study is confined to the identification of a well-fitted men's suit for individuals with a protruding abdomen without establishing a comprehensive framework for generating suit samples that vary in fit, collar style, and lapel design. Future research endeavors will aim to systematically categorize and organize the drafting rules for suit samples that differ in terms of fit, collar types, and lapels. These rules will be meticulously compiled and integrated into an automated sample generation system. This enhancement will empower customers with the autonomy to select and combine different suit elements, thereby enabling the system to offer a more diverse array of suit sample designs to meet individual preferences and requirements [36].

ACKNOWLEDGEMENTS

This research was funded by the National Natural Science Foundation of China (Grant Number: 61906129), the China Association for Science and Technology Youth Support Talent Project (Grant Number: 2021-298), and the Hong Kong Polytechnic University GBA Startup Postdoc Programme 2022 (Grant Number: SP-22-13).

REFERENCES

[1] Acar, E., Ofluoğlu, P., Kanat, S., Ünal, Z.B., Atilgan, T., *Analyzing buying behavior of plus-size clothing consumers in e-commerce*, In: Industria Textila, 2017, 68, 5, 396–404, https://doi.org/10.35530/IT.068.05.1393

[2] Schneider R., *The Typical Irregularity of Virtual Convex Bodies,* In: Journal of Convex Analysis, 2018, 25, 1, 103–118

[3] Hong, Y., Zeng, X., Bruniaux, P., *Interactive virtual try-on based three-dimensional garment block design for disabled people of scoliosis type,* In: Textile Research Journal, 2017, 87, 10, 1261–1274

[4] Hong, Y., Bruniaux, P., Zeng, X., Liu, K., Curteza, A., Chen, Y., *Visual-simulation-based personalized garment block design method for physically disabled people with scoliosis (PDPS),* In: Autex Research Journal, 2018, 18, 1, 35–45

[5] Avadanei, M., Curteza, A., Dulgheriu, I., Ionesi, S.D., Viziteu, D., Loghin, E.C., *A digital-integrated solution for a customised 3D design process of garments*, In: Industria Textila, 2022, 73, 3, 333–338, http://doi.org/10.35530/IT.073.03.202171

[6] Cupar, A., Rudolf, A., *Construction of adapted garments for people with scoliosis using virtual prototyping and CASP method*, In: Industria Textila, 2016, 67, 141–149

[7] Olaru, S., Filipescu, E., Niculescu, C., Filipescu, E., *Morphological assessment of human body for clothing patterns design*, In: Industria Textila, 2013, 64, 5, 254–259

[8] Au, C.K., Ma, Y.S., *Garment pattern definition, development and application with associative feature approach*, In: Computers in Industry, 2010, 61, 6, 524–531

[9] Zhu, C., Liu, K., Wang, R., Wang, J., Bruniaux, P., Zeng, X., *The mathematical model of men's garment prototype*, In: International Journal of Clothing Science and Technology, 2022, 34, 6, 892–904

[10] Liu, K., Zhu, C., Tao, X., Bruniaux, P., Zeng, X., *Parametric design of garment pattern based on body dimensions,* In: International Journal of Industrial Ergonomics, 2019, 72, 212–221

[11] Abtew, M., Bruniaux, P., François, B., Loghin, C., Cristian, I., Chen, Y., *Development of comfortable and well-fitted bra pattern for customized female soft body armor through 3D design process of adaptive bust on virtual mannequin*, In: Computers in Industry, 2018,100, 7–20

[12] Wang, Z., Wang, J., Xing, Y.M., Yang, Y., Liu, K., *Estimating human body dimensions using RBF artificial neural networks technology and its application in activewear pattern making*, In: Applied Sciences, 2019, 9, 6, 1140

[13] Kolose, S., Stewart, T., Hume, P., Tomkinson, G.R., *Prediction of military combat clothing size using decision trees and 3D body scan data*, In: Applied Ergonomics, 2021, 95, 103435

[14] Jin, S.N., Gu, B.F., Zhang, B.B., Xia, Y.P., He, H.Z., *Pants design and pattern generation based on body images*, In: Industria Textila, 2023, 74, 1, 74–80, http://doi.org/10.35530/IT.074.01.20223

[15] Hong, Y., Bruniaux, P., Zeng, X., Curteza, A., Liu, K., *Design and evaluation of personalized garment block for atypical morphology using the knowledge-supported virtual simulation method*, In: Textile Research Journal, 2018, 88, 15, 1721–1734

[16] Liu, H., Jiang, G., Dong, Z., Xia, F., Cong, H., *The size prediction and auto-generation of garment template*, In: International Journal of Clothing Science and Technology, 2021, 33, 1, 74–92

[17] Wang, Z., Wang, J., Zeng, X., Tao, X., Xing, Y., Bruniaux, P., *Construction of Garment Pattern Design Knowledge Base Using Sensory Analysis, Ontology and Support Vector Regression Modeling*, In: Int. J. Comput. Intell. Syst., 2021, 14, 1, 1687–1699

[18] Wang, X., Xue, Y., Zhang, J., Hong, Y., Guo, S., Zeng, X., *A Sustainable Supply Chain Design for Personalized Customization in Industry 5.0 Era*, In: IEEE Transactions on Industrial Informatics, 2024

[19] Li, Y., Jiang, L., Li, X., Feng, W., *Non-contact clothing anthropometry based on two-dimensional image contour detection and feature point recognition*, In: Industria Textila, 2023, 74, 1, 67–73, http://doi.org/10.35530/IT.074.01.202279

[20] Popescu, G., Olaru, S., Niculescu, C., *Innovative technologies for the design and simulation of children's clothing products using anthropometric data obtained by 3D standardized scanning*, In: Industria Textila, 2017, 68, 2, 95-102, http://doi.org/10.35530/IT.068.02.1356

[21] Wang, J., Lu, G., Chen, L., Geng, Y., Deng, W., *Customer participating 3D garment design for mass personalization*, In: Textile Research Journal, 2011, 81, 2, 187–204

[22] Chen, J.Z., Guo, Z.Y., Li, T., Du, L., Zou, F.Y., *An undamaged pattern generation method from 3D scanned garment sample based on finite element approach*, In: Industria Textila, 2023, 74, 1, 35–41, http://doi.org/10.35530/IT.074.01.202185

[23] Irovan, M., Indrie, L., Frunze, V., Florea-Burduja, E. and Raru, A., *Digital methods in the development of adaptive clothing for people with disabilities*, In: Industria Textila, 2023, 74, 1, 28–34, http://doi.org/10.35530/IT.074.01.202295

[24] Li, J., Ye, J., Wang, Y., Bai, L., Lu, G., *Fitting 3D garment models onto individual human models*, In: Computers & graphics, 34, 6, 742–755

[25] Dai, X., Hong, Y., *Fabric mechanical parameters for 3D cloth simulation in apparel CAD: A systematic review*, In: Computer-Aided Design, 2023, 103638

[26] Huang, S., Huang, L., *CLO3D-Based 3D Virtual Fitting Technology of Down Jacket and Simulation Research on Dynamic Effect of Cloth*, In: Wireless Communications and Mobile Computing, 2022

[27] Ying, X., Liu, Z., Chen, G., Zou, F., *The impact of body surface convex angle on dressed waist ease*, In: International Journal of Clothing Science and Technology, 2020, 32, 4, 571-587

[28] Ancutiene, K., *Comparative analysis of real and virtual garment fit*, In: Industria Textila, 2014, 65, 3, 158–165

[29] Zhang, D., Liu, Y., Wang, J., Li, J., *An integrated method of 3D garment design*, In: The Journal of the Textile Institute, 2018, 109, 12, 1595–1605

[30] Volino, P., Cordier, F., Magnenat-Thalmann, N., *From early virtual garment simulation to interactive fashion design*, In: Computer-aided design, 2005, 37, 6, 593–608

[31] Hong, Y., Bruniaux, P., Zhang, J., Liu, K., Dong, M., Chen, Y., *Application of 3D-TO-2D garment design for atypical morphology: a design case for physically disabled people with scoliosis*, In: Industria Textila, 2018, 69, 1, 59–64, http://doi.org/10.35530/IT.069.01.1377

[32] Dianat, I., Molenbroek, J., Castellucci, H.I., *A review of the methodology and applications of anthropometry in ergonomics and product design*, In: Ergonomics, 2018, 61, 12, 1696–720

[33] Wang, C.C., Wang, Y., Yuen, M.M., *Feature based 3D garment design through 2D sketches*, In: Computer-aided Design, 2003, 35, 7, 659–672

[34] Zhou, X., Xu, Y., Chen, T., *Research on optimization design of men's suit considering users' perception*, In: International Journal of Clothing Science and Technology, 2022, 34, 3, 379–390
[35] Lin, Y.L., Wang, M.J.J., *The development of a clothing fit evaluation system under virtual environment*, In: Multimedia Tools and Applications, 2016, 75, 7575–7587
[36] Wei, L., Wang, X., Wang, T., Duan, Z., Hong, Y., He, X., Huang, H., *Recommendation systems for the metaverse*, In: Blockchains, 2023, 1, 19–33

Authors:

MENGSHU DING[1], TIANYU LUO[2], YAN HONG[1,2,3]

[1]School of Fashion, Henan University of Engineering, Zhengzhou, Henan, 451191, China

[2]College of Textile and Clothing Engineering, Soochow University, Suzhou 215021, China

[3]Department of Computing, The Hong Kong Polytechnic University, Hong Kong, China

Corresponding author:

YAN HONG
e-mail: hongyan@suda.edu.cn

The utilisation of polydopamine interlayer to add silver nanoparticles (AgNPs) to PET fabrics

DOI: 10.35530/IT.076.02.2024104

ABDURRAHMAN TELLI

ABSTRACT – REZUMAT

The utilisation of polydopamine interlayer to add silver nanoparticles (AgNPs) to PET fabrics

Silver nanoparticles are structures used in many areas such as antibacterial materials, increasing conductivity, wastewater treatment, etc. In recent years, demand for their use in textile products has been increasing. Starting from this point, this study aimed to produce silver nanoparticles on the surface of PET fabric to meet the different properties expected from silver. For this purpose, polydopamine coating was applied to PET fabric by in situ polymerization. Then, fabric structures containing polydopamine and silver nanoparticles were obtained with a reduction reaction of three different molarity silver nitrate salts. The after-washing condition of the fabric with the highest produced amount of silver nanoparticles was examined. Spectrophotometric colour measurement, FT-IR, SEM and EDX techniques were performed. The best results were obtained on the fabric where silver nitrate was applied at 50 mM. The amount of silver nanoparticles in this fabric was measured as 1.35% after washing.

Keywords: *polyethyleneterephthalate, polydopamine, silver, silver nitrate, nano-coating*

Utilizarea stratului intermediar de polidopamină pentru adăugarea de nanoparticule de argint (AgNP) la țesăturile PET

Nanoparticulele de argint sunt structuri utilizate în multe domenii, cum ar fi materialele antibacteriene, creșterea conductivității și tratarea apelor reziduale etc. În ultimii ani, cererea pentru utilizarea lor în produsele textile a crescut. Pornind de la acest punct, acest studiu a urmărit să producă nanoparticule de argint pe suprafața țesăturii PET pentru a satisface diferitele proprietăți așteptate de la argint. În acest scop, s-a aplicat un strat de polidopamină pe țesătura PET prin polimerizare in situ. Apoi, structurile țesăturilor care conțin polidopamină și nanoparticule de argint au fost obținute printr-o reacție de reducere a trei săruri de nitrat de argint cu molarități diferite. A fost examinată starea de după spălare a țesăturii cu cea mai mare cantitate de nanoparticule de argint produsă. Au fost efectuate tehnici de măsurare spectrofotometrică a culorii, FT-IR, SEM și EDX. Cele mai bune rezultate au fost obținute pe țesătura în care nitratul de argint a fost aplicat la 50 mM. Cantitatea de nanoparticule de argint din această țesătură a fost măsurată la 1,35% după spălare.

Cuvinte-cheie: *polietilentereftalat, polidopamină, argint, nitrat de argint, acoperire nano*

INTRODUCTION

Surface modifications have great importance in expanding the application areas of textile materials and in the production of technical textiles. Modifying surfaces enables control and improvement of surface properties and imparts new functions such as electrical conductivity, UV protection, antibacterial activity and super hydrophobic character. Many different approaches have been investigated in the literature to activate the surface of textile materials. Plasma treatments and chemical methods appear to be the most promising techniques for providing functional groups. However, these techniques damage the fabric surface and may negatively affect the mechanical properties of the fabrics. Apart from these, using an intermediate layer containing functional groups between the coating and the fabric is a new approach.

Dopamine, a substance with strong adhesion and high reactivity, can be used as an intermediate layer to provide fabrics with properties such as super hydrophobic, antibacterial, UV protection and dye adsorption on their surfaces. Adhesive polydopamine can be obtained by self-oxidative polymerization of dopamine under alkaline environmental conditions. Many surfaces can be functionalized by using this simple but versatile intermediate layer. The used surface modification technique here is both easy and solvent-free [1, 2]. Xu et al. tried to provide antibacterial activity by modifying the surface of cotton fabrics with dopamine. In their studies, the reduction of silver nitrate on the intermediate layer formed by the polymerization of dopamine was attempted. It has been observed that silver nanoparticles formed on the cotton fabric surface in this way provide significant antibacterial activity. In the study, dopamine molarity was used as 0.2 mol/l and silver nitrate solution as 0.29 mol/l. It was reported that there was no change in activity after 30 washings [3]. Xu et al. conducted similar studies on polyester fabric, where the application process is more difficult than cotton, by reducing the dopamine molarity by 50% (0.1 g/mol) without changing the silver nitrate molarity. Similarly, researchers reported significant antibacterial activity before and after washing [4]. Zhang et al. conducted studies to accelerate dopamine polymerization [5]. With the method recommended by these researchers, Ou et al. used polydopamine to make superhydrophobic cotton fabrics. The durability of nano-coated fabrics under different conditions was also examined by researchers [6]. Ding et al. tried to provide photocatalytic activity by using iron (III) chloride in addition to silver nitrate reduction on polydopamine-treated cotton fabric. The researchers, who achieved successful results in their studies, stated that they proposed an efficient method for cleaning dye-containing textile wastewater. They also emphasized that this would have a facilitating effect on the recovery of photocatalytic materials [7]. Miao et al. applied polydopamine and silver to a textile fabric whose contents they did not specify. It has been stated that the resulting surface can be used to effectively separate oil/oil mixtures of different polarities and oil/water mixtures. It has been emphasized that this surface can be efficient for dye removal and wastewater cleaning with the photocatalytic effect and that this effect can be significantly accelerated in the presence of sodium borohydride [8]. Sodium borohydride ($NaBH_4$) is a reducing agent used to produce nano-sized silver by reducing silver nitrate ($AgNO_3$) salt. It has been used for this purpose in many studies [9, 10]. However, these and similar materials are toxic and corrosive. The polydopamine technique is not dangerous to humans and the environment, unlike cross-linkers frequently used for surface functionalization, and is a green technology inspired by mussel shells. The functional groups of polydopamine have a high affinity for various functional molecules, giving it good adhesion properties. Therefore, the polydopamine film adheres well to the substrate. It can be estimated that it will have wide usage areas in the coming years due to its more harmless nature and it will be produced at lower costs.

As cotton was at the forefront of applying polydopamine to textile materials in previous years, there has been a focus on applying polydopamine to different textile materials in the last few years. Applications on fabrics such as acrylic [11], polypropylene [12] and wool [13] were reported. However, there are a limited number of studies on polyester fabrics, which are the most consumed among all fibres [14]. Silver nanoparticles are structures used in many areas such as antibacterial materials, increasing conductivity, wastewater treatment, etc. In recent years, demand for their use in textile products has been increasing. Starting from this point, this study aimed to produce silver nanoparticles on PET fabric to meet the different properties expected from silver. For this purpose, polydopamine coating was applied to PET fabric by in situ polymerization. Then, fabric structures containing polydopamine and silver nanoparticles were obtained with a reduction reaction of three different molarity silver nitrate salts. The after-washing condition of the fabric with the highest produced amount of silver nanoparticles was examined. Fourier Transform Infrared Spectroscopy (FT-IR), scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) techniques were performed.

MATERIAL AND METHODS

In this study, PET fabric with a weight of 150 grams per square meter, was used. The fabric was supplied by Karesi Holding, a PET fabric manufacturer in Bursa/Turkey. The fabric was washed with acetone to remove impurities before use in the experiment. Polydopamine coatings were carried out on PET Fabric with oxidative self-polymerization. For polydopamine synthesis, dopamine hydrochloride (99 wt.%) obtained from Alfa Aesar and tris (hydroxymethyl)-methylamine (99 wt.%) obtained from Fisher Scientific were used. Dopamine hydrochloride was prepared as 10 mM by dissolving it in purified water. Aqueous dopamine solution was mixed homogeneously with tris (hydroxymethyl)-methylamine at 10 mM to keep the pH constant at 8.5 throughout the reaction. Tris buffer is an alkaline compound used to deprotonate dopamine solution. Then, the fabric was placed in the solution and polydopamine (dopamine-melanin) nanofilms on the fabric were formed by mixing at 50 rpm in the shaker of Ataç Laboratory machines, a textile machinery manufacturer in Turkey. The process was carried out for 24 hours in standard atmospheric conditions (20±2°C, 65±2% relative humidity) according to EN ISO 139.

Polydopamine nanofilm-covered surfaces were formed by oxidative self-polymerization of dopamine on the fabric surface under constant alkaline conditions. The fabrics taken from the solution after 24 hours were rinsed with cold water and left to dry for 24 hours under standard atmospheric conditions. In this way, the first stage of the study was completed.

In the second stage, silver nitrate (99 wt.%) salt obtained from Sigma Aldrich was prepared in three different molarities (10 mM, 20 mM, 50 mM) for the synthesis of silver nanoparticles. Dried polydopamine-coated fabric surfaces were treated in these solutions for 6 hours. In this way, PET fabrics were coated with silver nanoparticles with the help of a polydopamine interlayer. Thus, the fabric structures consisting of polydopamine and silver nanoparticles were obtained by reduction reaction. These layered fabric surfaces were dried in an oven at 105°C for 4 hours. To determine the durability of polydopamine (PDA) nano-coating and silver nanoparticles (AgNPs) on the fabric, washing according to EN ISO 105-C06 (A2S method) was applied to two of the dried samples (PET+PDA and PET+PDA+50 mM Ag).

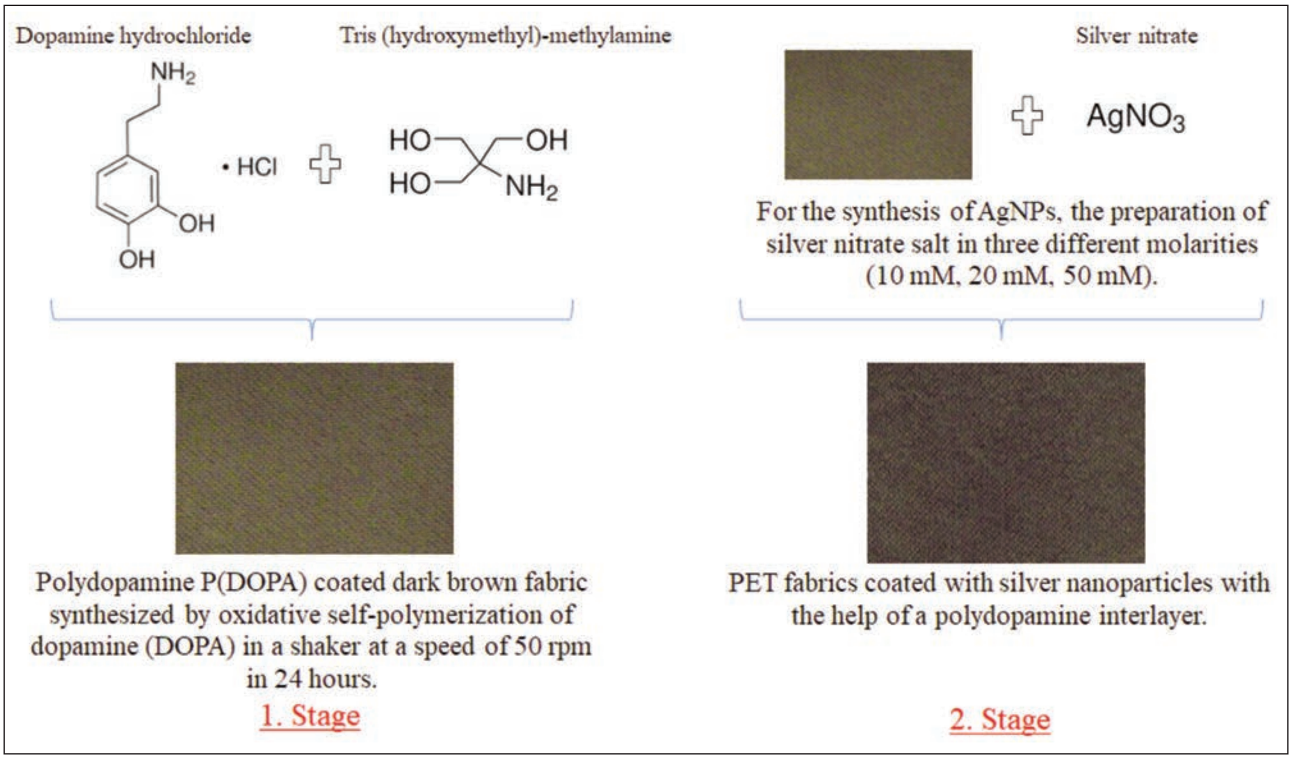


Fig. 1. Graphical abstract for all process steps

In this method, the fabric was washed with sodium perborate for 30 minutes at 40°C. In this way, the second stage of the study was completed. All process steps are summarized in figure 1.

After the applications were made, spectrophotometric colour measurements of the fabrics were measured using the Minolta CM 3600 D device and the lightness (L*), level of redness or greenness (a*) and level of yellowness or blueness values (b*) were examined. FT-IR (Jasco FT/IR-6700) spectrum, scanning electron microscope (FEI Quanta 650 Field Emission SEM) and energy dispersive spectrometer (EDX) were used to characterize the fabrics. The bonds in the sample structure, the status of the bonds and the functional groups were examined with FT-IR. The surface shapes of the samples were imaged at a magnification ratio of 10000 with a SEM device. The elemental analysis of the sample surface was performed with EDX.

RESULTS AND DISCUSSION

Colour (L*, a*, b*) values

Polydopamine (PDA) is a dark brown-black biopolymer, insoluble in organic solvents, synthesized by the oxidative self-polymerization of dopamine (DOPA). Additionally, the reduction of silver ions to silver nanoparticles is confirmed by the colour changing to dark yellow-beige [15]. For these reasons, spectrophotometric colour measurement results of fabrics were taken. Lightness (L*) values of fabrics are presented in figure 2.

According to figure 2, there was a significant decrease in the L* value of the PET fabric after polydopamine coating by 48.05% from 87.44 to 45.42, as expected. It was also similarly reported in previous studies that the colour of the samples changes towards dark brown-black with polydopamine coating [13–14, 16–18]. After washing, an increase in the L value was observed in the PDA-coated fabric. This shows that the washing process caused some removal of the coating from the fabric. This finding corroborates the results of Telli and Arabaci, who found that the washing process caused increases in the lightness values of PDA-coated fabrics [18]. It was determined that L* values decreased slightly with the production of silver nanoparticles on the fabric. The reduction was measured as 5.09% from 45.42 to 43.11 at 10 mM silver molarity, 6.52% from 45.42 to 42.46 at 20 mM silver molarity, and 11.74% from 45.42 to 40.09 at 50 mM silver molarity. A further decrease was observed with increasing applied molarity. The lowest L* value was measured on the fabric to which 50 mM silver nitrate was applied. Decreased L* value due to silver in this study confirms earlier findings of other researchers. Ilic et al. found that the silver nanoparticle ratio in the fabric caused insignificant colour changes at low levels, but there was a significant change in colour as the amount increased. Fabrics containing AgNPs were described as darker, redder and more yellow than the undyed control fabric [19]. After washing, the L* value of PET+PDA fabric increased by 13.18% from 45.42 to 51.41. Similarly, the L* value of PET+PDA+50mM Ag fabric increased by 13.17% from 40.09 to 45.37 after washing. After washing, a colour difference was seen that may indicate the presence of silver on the fabric when the L* values of PET+PDA fabric (51.41) and PET+PDA+50mM Ag fabric (45.37) were compared.

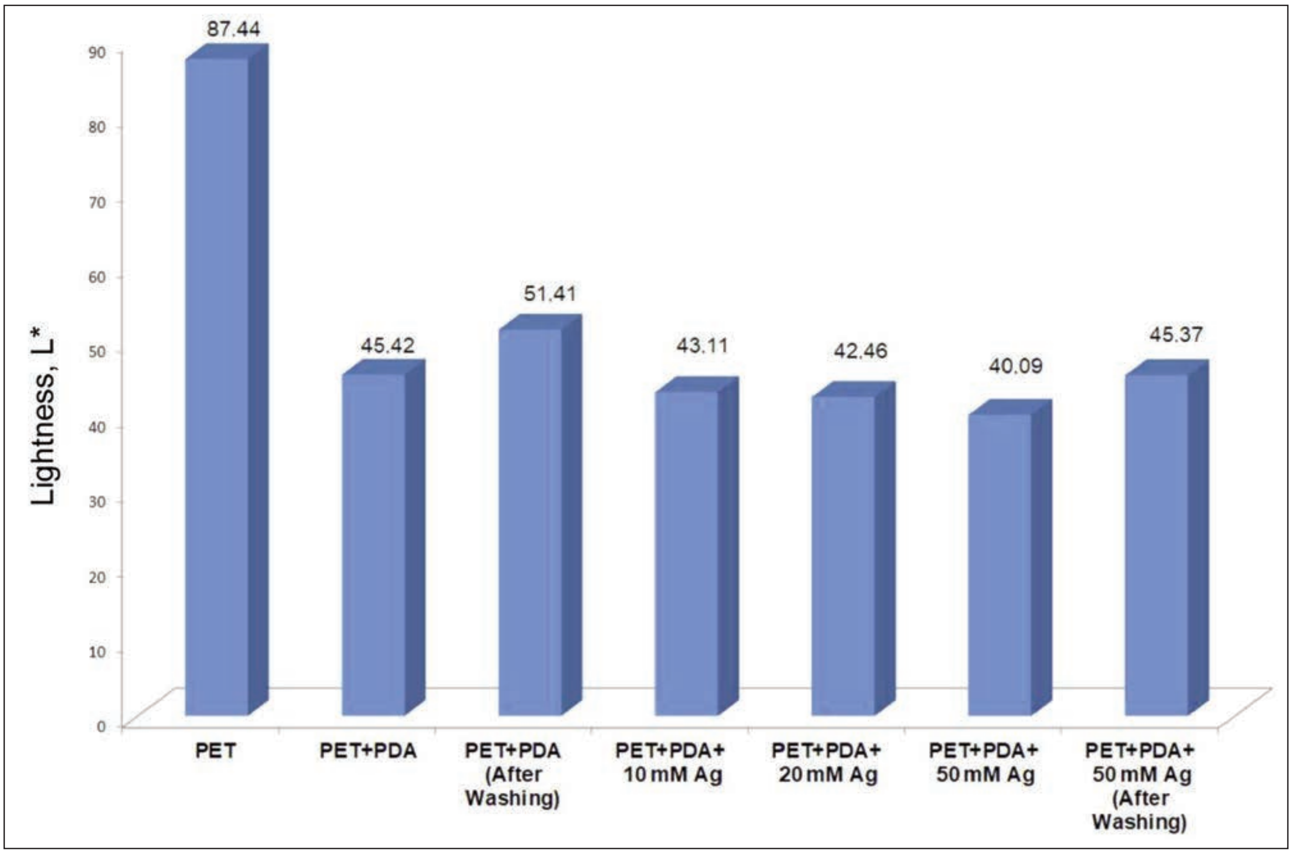


Fig. 2. Lightness (L*) values of fabrics

In previous studies, it was emphasized that the most significant change in colour with silver application was in the b* value [19]. Silver ions were used to provide antibacterial properties in a polyester and polyamide fabric by Yuranova et al. Researchers pointed out that Ag deposition on the fabric surface in the processes by RF-plasma and vacuum-UV techniques gave a more yellow colour depending on the deposition rate [15]. Figure 3 provides the b* values in this study.

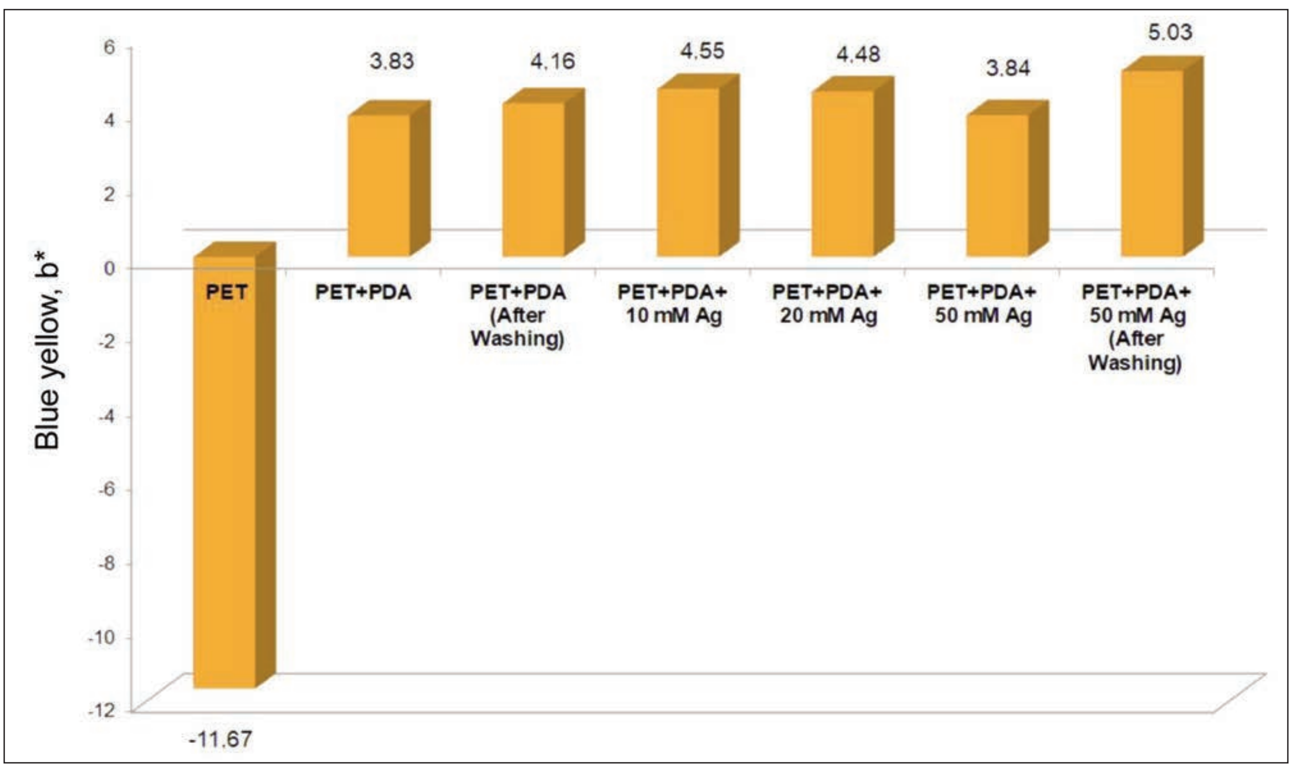


Fig. 3. Blue Yellow (b*) values of fabrics

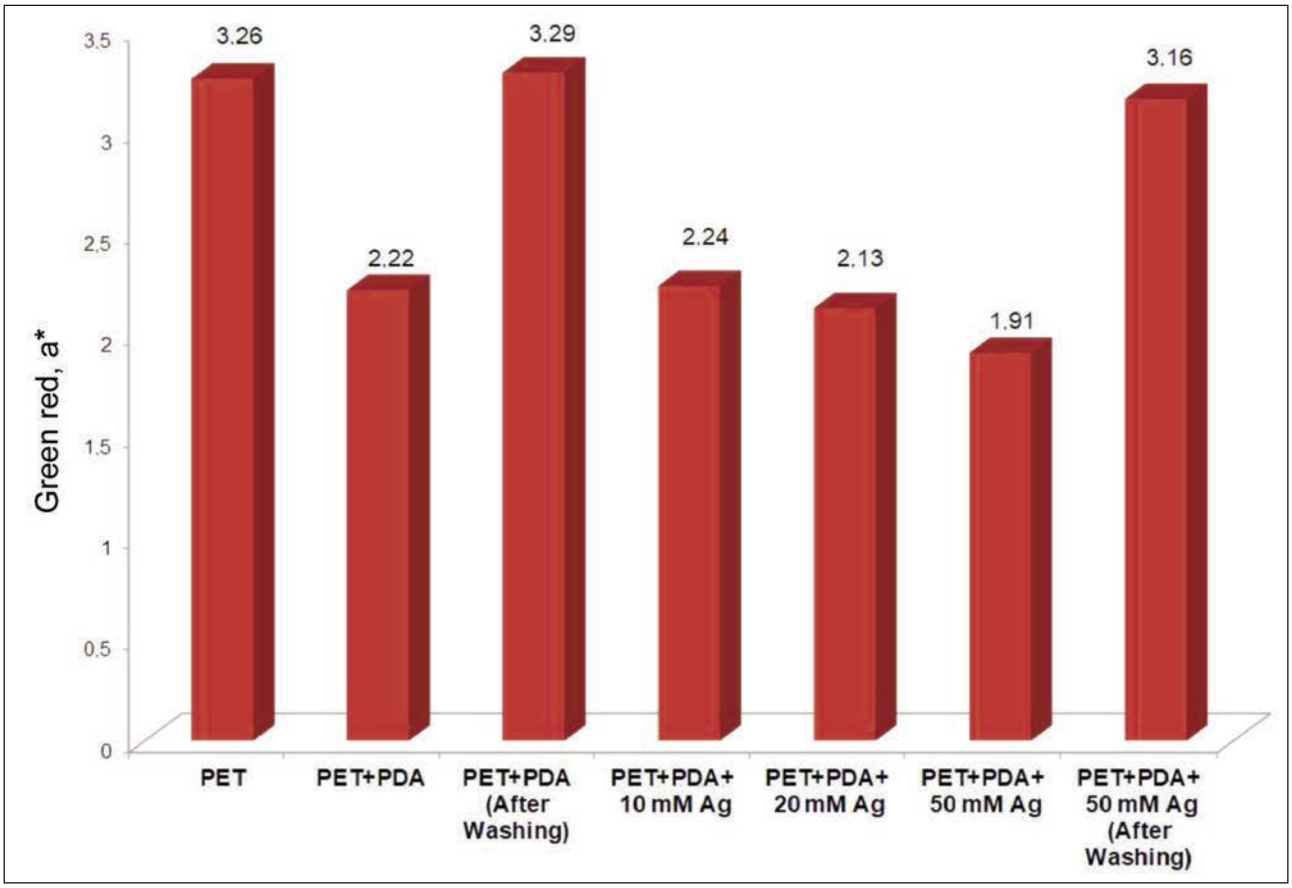


Fig. 4. Green Red (a*) values of fabrics

As the b value increases, yellowness increases and blueness decreases. Yellowness showed an increase clearly in coated fabrics compared to uncoated fabrics. Silver-applied fabrics were found to be more yellow than PDA-coated fabrics. However, the highest yellowness was obtained at the lowest molarity of 10 mM. As the molarity increased, yellowness decreased slightly. This is because the silver application was made on PDA-coated fabrics. Ilic et al. also stated that silver application caused a significant change in the dyed fabric colour like undyed fabric and that L, a* and b* values were directly affected by the dye colour or whether the silver application was made before or after dyeing [19]. After washing, a colour difference was seen that may indicate the presence of silver on the fabric when the b* values of PET+PDA fabric (4.16) and PET+PDA+50mM Ag fabric (5.03) were compared. The highest b* value in the study was measured on PET+PDA+50mM Ag fabric after washing. Figure 4 compares a* values in this study.

As a* value increases, redness increases and greenness decreases. PDA coating caused a slight decrease in a* value. Silver applications also caused a decrease in the a* value with increasing molarity. After washing, the a* values in both PET+PDA fabric and PET+PDA+50mM Ag fabric were close to the uncoated fabric.

FT-IR results

The framework of polyester fibres consists of ester bonds. When the FTIR spectrums of esters are examined, it is well known that they comply with “The Rule of Three peaks”. PET fibres are also a type of polyester fibre. PET fibres have been reported in previous studies to have a series of strong peaks, including C=O stretch vibration in the ~1700 cm^{-1}, C-C-O Stretch vibration in the ~1200 cm^{-1}, and O-C-C stretch vibration in the ~1100 cm^{-1} [20]. The combined FT-IR results of the used fabrics in this study are presented in figure 5. In table 1, the obtained peaks and their intensities are shown in detail.

It can be seen from table 1 that the three-peak rule was valid in all tested four fabrics. These three peaks are highlighted in table 1. Additionally, due to weak C–H stretching and C–C bending vibrations of benzene rings, peaks were observed at 2967–2966 cm^{-1}, 870.7–871.67 cm^{-1} and 721.25 cm^{-1} in all fabrics.

When PET fabric and polydopamine-coated fabric were compared, it was seen that they gave similar results. Differently, the intensity values of the peaks seen in PET fabric showed a decrease in the polydopamine-coated fabric. In the presence of silver, it was seen that the intensity values of the broadband seen in the range of 3600–2100 cm^{-1} showed an increase. These values showed a decrease slightly after washing. In the polydopamine coating of PET fabric and the reduction of silver ions, bonds that indicate the presence of polydopamine and silver cannot

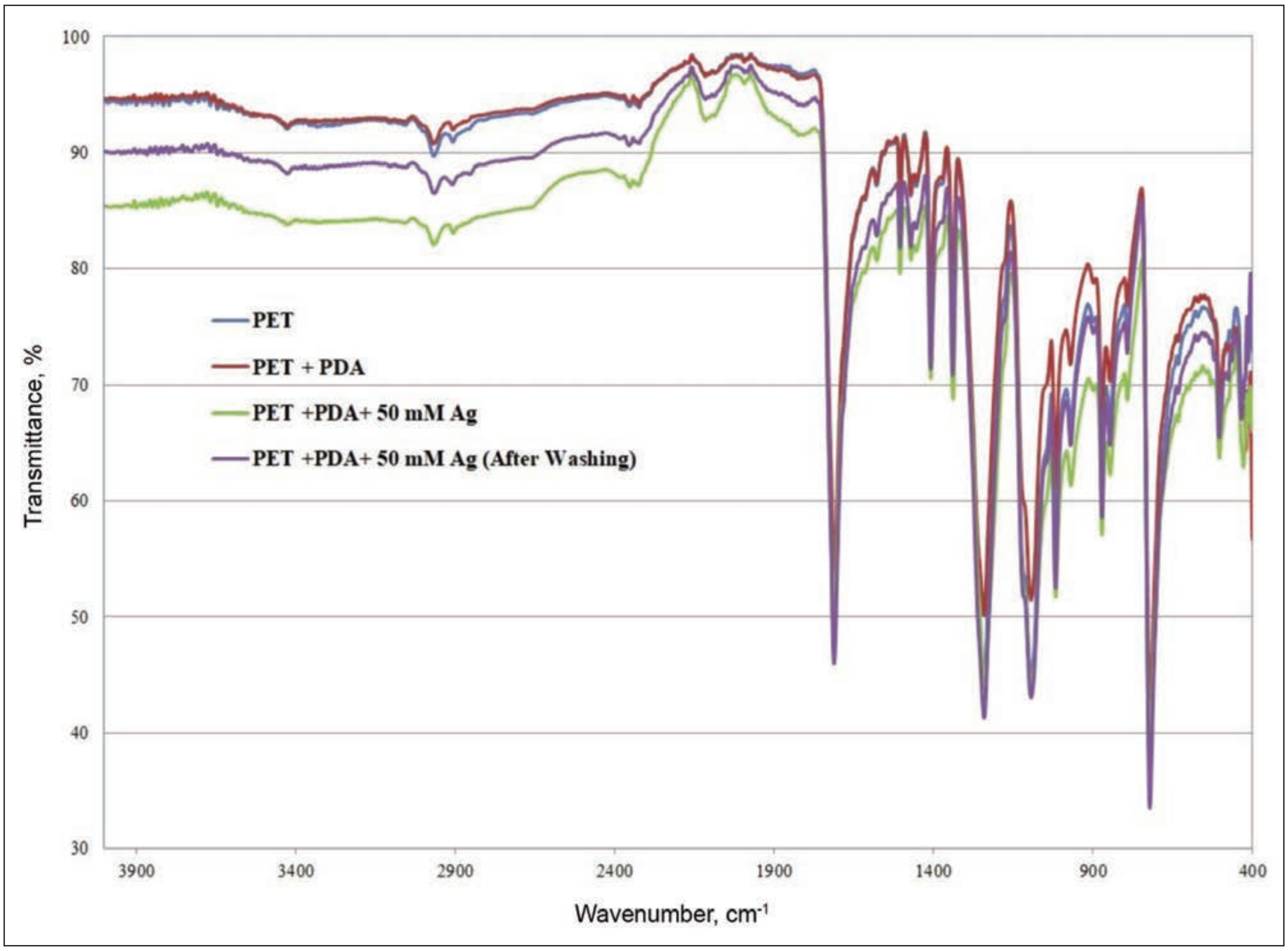


Fig. 4. The combined FT-IR results of the used fabrics

Table 1

THE OBTAINED PEAKS AND INTENSITIES FROM FT-IR RESULTS							
PET		PET+PDA		PET+PDA+50mM Ag		PET+PDA+ 50mM Ag (After Washing)	
Peak	Intensity	Peak	Intensity	Peak	Intensity	Peak	Intensity
400.16	31.87	400.16	61.37	400.16	42.21	401.12	23.60
		409.80	44.41	410.76	41.12	411.73	30.06
427.16	38.48	419.44	49.46	427.16	47.18	433.91	36.48
503.33	39.49	503.33	41.41	503.33	45.91	503.33	38.74
721.25	100.0	721.25	100.0	721.25	100.00	721.25	100.0
791.64	30.94	791.64	29.65	791.64	38.20	791.64	29.10
846.60	41.65	846.60	39.55	845.63	48.22	845.63	39.64
871.67	52.46	870.70	49.83	870.70	57.10	870.70	48.95
969.05	42.03	970.02	37.28	969.05	49.73	969.05	39.73
1016.3	62.70	1016.3	55.11	1016.3	67.11	1016.3	58.93
1093.4	**82.17**	**1093.4**	**74.62**	**1093.4**	**83.13**	**1093.4**	**77.13**
1241.0	**83.79**	**1241.0**	**77.56**	**1239.0**	**84.13**	**1241.0**	**80.94**
1338.4	32.25	1339.3	29.59	1338.4	38.09	1339.3	31.49
1407.8	30.89	1407.8	30.22	1407.8	35.43	1407.8	30.77
1470.4	15.18	1470.5	16.38	1470.5	21.69	1470.5	18.23
1504.2	16.75	1504.2	16.55	1504.2	23.23	1504.2	18.33
1712.5	**74.94**	**1711.5**	**69.64**	**1712.5**	**72.63**	**1711.5**	**71.06**
2967.0	11.19	2966.9	10.85	2966.9	20.05	2966.0	13.25

be distinguished in the FT-IR graph. For this reason, studies were continued with SEM and EDX analysis to detect the presence of silver nanoparticles on the fabric surface.

SEM and EDX analysis

SEM images of the fabrics taken at 10000x magnification were presented in figure 6. The presence of polydopamine nanocoating on the PET fabric is visible in SEM images. Nanospheres formed after the coating processes were observed in all fabric samples. In silver nanoparticle applications, extra particles accumulated in the regions where polydopamine nanospheres were located. Thanks to the reduction reaction, there were differentiated and denser regions in silver nanoparticle applications compared to PET + PDA fabric. However, no obvious differences can be detected between SEM images of different molarity applications and images after washing. EDX analyses were also performed to examine these differences.

EDX analysis is used together with SEM. Analysis of elements near the surface and their percentage amounts can be performed. The chemical composition results obtained as a result of EDX analysis were given collectively in table 2.

PET Polyester fibres are long-chain polymers that are the condensation product of ethylene glycol with

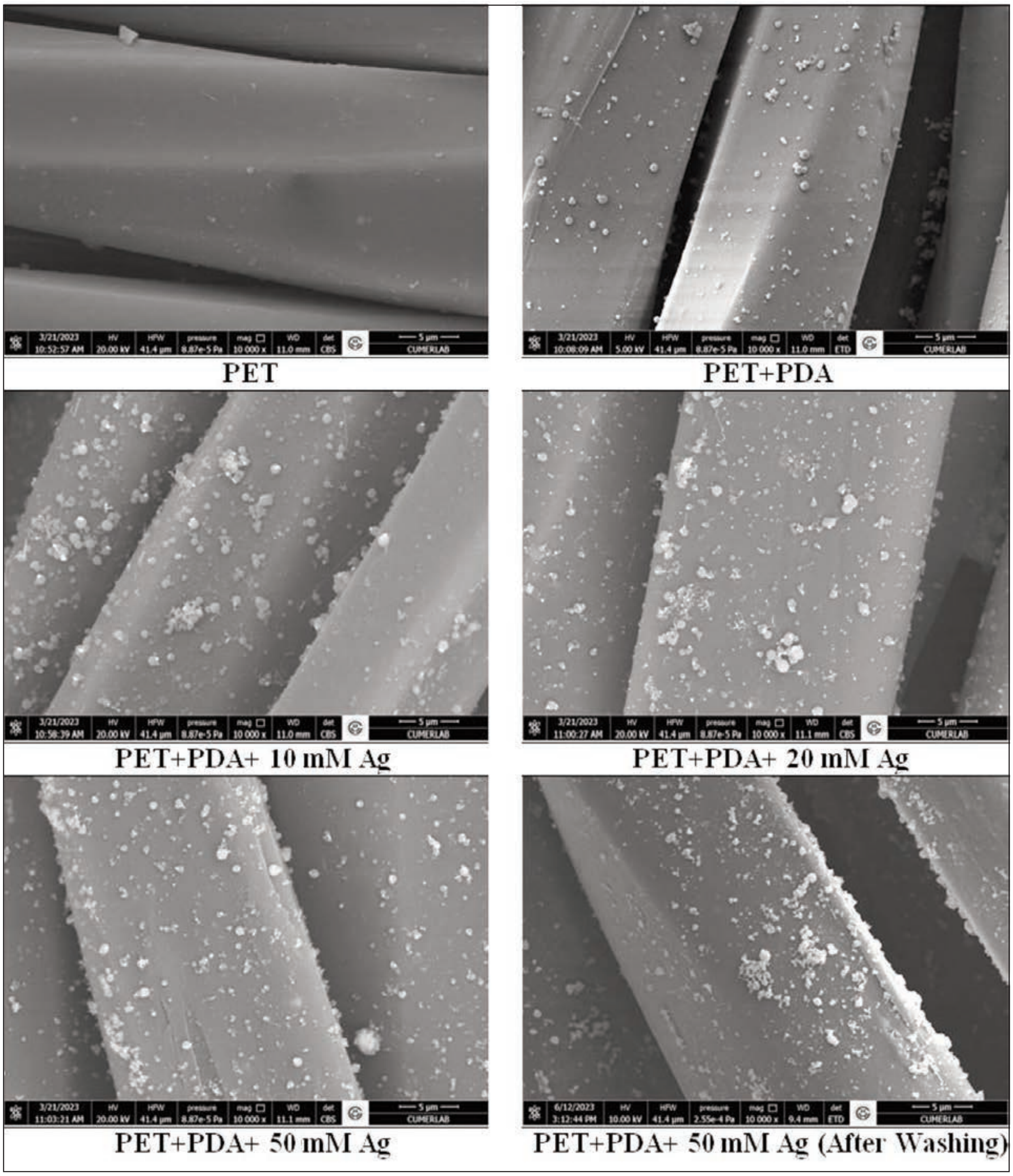


Fig. 6. SEM images of fabrics (10000x)

Table 2

ELEMENT WEIGHT (%) OF FABRICS				
Element weight %	**C (carbon)**	**O (oxygen)**	**N (nitrogen)**	**Ag (silver)**
PET	59.59	40.41	-	-
PET+PDA	54.79	39.72	5.49	-
PET+PDA (After Washing)	54.40	40.36	5.24	
PET+PDA+ 10mM Ag	55.16	39.02	5.50	0.33
PET+PDA+ 20mM Ag	53.98	39.38	5.58	1.06
PET+PDA+ 50mM Ag	53.84	39.02	5.43	1.71
PET+PDA+ 50mM Ag (After Washing)	54.71	38.76	5.18	1.35

terephthalic acid. In this chain, the ester group (-CO-O-) is repeated many times. The structure of PET consists of carbon and oxygen in addition to hydrogen. Differently, polydopamine has N molecules in its structure. Table 2 shows that polydopamine-coated fabric contains 5.49% nitrogen, unlike PET fabric. After the washing process, it was seen that this value decreased to 5.24%. The observed decrease in the N ratio seems to be similar to earlier findings. Ou et al. found that the nitrogen content of the polydopamine coating showed a decrease in all different durability tests, including washing, compared to the results before the test [21]. As expressed in the L* values from the colour results, it was seen that the PDA coating was removed to some quantity with the washing process.

When silver applications were evaluated, it was seen that there were the lowest silver nanoparticles in the PET+PDA+ 10 mM Ag fabric with 0.33%. Ahmed et al. achieved 99.33% antibacterial efficiency in PP melt-blown fabrics to which silver nanoparticles were applied with different techniques, with a silver content of 0.28% measured in EDX analysis [22]. From the data in table 2, it was seen that this silver ratio (0.33%) in the fabric, which can be considered successful, increases as the molarity of silver nitrate increases. The silver ratio increased to 1.06% at 20 mM Ag and 1.71% at 50 mM Ag. The highest silver content (1.71%) was reached at the highest molarity. 89% for S. aureus and 80% for E. coli antibacterial efficiency in cotton fabrics with a silver content of 1.58% measured in EDX analysis by Tania et al. were reported [23]. In previous studies on the application of silver nanoparticles to different fabrics with in situ formation, it was stated that the lowest efficiency was in polyester fabrics. It was stated that cotton fabrics were 8 times more efficient than polyester fabrics [24]. As table 2 shows, higher silver nanoparticle levels with the technique applied in the study were obtained in polyester fabric (1.71%) than earlier findings related to cotton fabrics (1.58%).

After the washing process, it was seen that this value decreased to 1.35%. According to previous studies, depending on the fabric structure, it can provide various functional properties to the fabric with the formation of at least 0.28% silver nanoparticles on the fabric [22]. In this study, a silver content of 1.35% was obtained even after washing in polyester fabric which was stated to be difficult to apply silver in previous studies. Furthermore, no pretreatment was applied to the polyester fabric in this study [24].

In addition, it was seen that the nitrogen content in PET+PDA+ 50 mM Ag fabric decreased after washing, as in the washing of PET+PDA fabric. It decreased from 5.43% to 5.18%. The decrease in nitrogen content of both fabrics after washing was proportionally similar. It was seen that both the polydopamine that enables the AgNPs to adhere to the PET fabric and some silver were removed from the fabric after washing.

CONCLUSIONS

In this study, PET fabrics were coated with silver nanoparticles with the help of a polydopamine interlayer. In the first stage, polydopamine-coated surfaces were formed by oxidative self-polymerization of dopamine on the fabric surface under constant alkaline conditions. In the second stage, silver nitrate salt was applied to the polydopamine-coated fabric in three different molarities (10 mM, 20 mM, and 50 mM) for the synthesis of silver nanoparticles. With the production of polydopamine coating and silver nanoparticles, fabric lightness values decreased. The lowest L* value was measured on the fabric to which 50 mM silver nitrate was applied. In the SEM images of the fabrics taken at 10000x magnification, the presence of polydopamine nano-coating on the PET fabric was seen. By EDX analysis, it was determined that the amount of silver nanoparticles in the fabric increased as the molarity of silver nitrate increased. The highest silver nanoparticle ratio was reached at 1.71% at 50 mM molarity. After the washing process, it was seen that this value decreased to 1.35%. Compared to the minimum ratios required to impart various functional properties to fabrics with silver nanoparticles in previous studies, the silver nanoparticle ratio obtained after washing in this study will enable polyester fabrics to gain functional properties such as antibacterial, electrical conductivity electromagnetic shielding etc.

ACKNOWLEDGEMENTS

This work was supported by the Cukurova University Scientific Research Projects Unit (Project Code: FBA-2021-13420).

REFERENCES

[1] Li, Y., Wang, B., Sui, X., Xie, R., Xu, H., Zhang, L., Zhong, Y., Mao, Z., *Durable flame retardant and antibacterial finishing on cotton fabrics with cyclotriphosphazene/polydopamine/silver nanoparticles hybrid coatings*, In: Applied Surface Science, 2018, 435, 1337–1343

[2] Liu, C., Liu, J., Ning, X., Chen, S., Liu, Z., Jiang, S., Miao, D., *The effect of polydopamine on an Ag-coated polypropylene nonwoven fabric*, In: Polymers, 2019, 11, 4, 627, 1–15

[3] Xu, H., Shi, X., Ma, H., Lv, Y., Zhang, L., Mao, Z., *The preparation and antibacterial effects of dopa-cotton/AgNPs,* In: Applied Surface Science, 2011, 257, 15, 6799–6803

[4] Xu, H., Shi, X., Lv, Y., Mao, Z., *The preparation and antibacterial activity of polyester fabric loaded with silver nanoparticles,* In: Textile Research Journal, 2013, 83, 3, 321–326

[5] Zhang, C., Ou, Y., Lei, W.X., Wan, L.S., Ji, J., Xu, Z.K., *$CuSO_4/H_2O_2$-induced rapid deposition of polydopamine coatings with high uniformity and enhanced stability*, In: Angewandte Chemie International Edition, 2016, 55, 9, 3054–3057

[6] Ou, J., Ma, J., Wang, F., Li, W., Fang, X., Lei, S., Amirfazli, A., *Unexpected superhydrophobic polydopamine on cotton fabric*, In: Progress in Organic Coatings, 2020, 147, 105777, 1–8

[7] Ding, K., Wang, W., Yu, D., Gao, P., Liu, B., *Facile formation of flexible Ag/AgCl/polydopamine/cotton fabric composite photocatalysts as an efficient visible-light photocatalysts*, In: Applied Surface Science, 2018, 454, 101–111

[8] Miao, G., Li, F., Gao, Z., Xu, T., Miao, X., Ren, G., Zhu, X., *Ag/polydopamine-coated textile for enhanced liquid/liquid mixtures separation and dye removal*, In: Iscience, 2022, 25, 5, 1–14

[9] Mavani, K., Shah, M.*, Synthesis of silver nanoparticles by using sodium borohydride as a reducing agent*, In: International Journal of Engineering Research & Technology, 2013, 2, 3, 1–5

[10] Chen, X., Zhou, T., Pan, X., Li, H., *Polydopamine microcapsules loaded Ag nanoparticles for catalytic reduction of organic pollutants*, In: Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2023, 663, 131085, 1–10

[11] Allehyani, E.S., Almulaiky, Y.Q., Al-Harbi, S.A., El-Shishtawy, R.M., *Polydopamine-AgNPs coated acrylic fabric for antimicrobial and antioxidant textiles*, In: Journal of Coatings Technology and Research, 2023, 20, 3, 1133–1143

[12] Cheng, H., Han, N., Bai, Z., Li, Z., Xu, W., Xiao, S., *Ag-decorated PP nonwoven for excellent catalytic reduction of 4-nitrophenol and antibacterial study*, In: Surfaces and Interfaces, 2023, 39, 102929, 1–12

[13] Huang, H., Zhang, W., Han, X., Han, Z., Song, D., Li, W., Xu, W., *Effect of polydopamine deposition on wool fibers on the construction of melanin,* In: Journal of Applied Polymer Science, 2023, 140, 5, e53396

[14] Telli, A., Tas, M., *The use of mussel-inspired polydopamine interlayer for high-efficiency surface functionalization of PET fabrics*, In: Journal of Polymer Research, 2022, 29, 4, 1–9

[15] Yuranova, T., Rincon, AG., Bozzi, A., Parra, S., Pulgarin, C., Albers, P., Kiwi, J., *Antibacterial textiles prepared by RF-plasma and vacuum-UV mediated deposition of silver*, In: Journal of Photochemistry and Photobiology A: Chemistry, 2003, 161, 1, 27–34

[16] Du, X., Li, L., Li, J., Yang, C., Frenkel, N., Welle, A., Levkin, P.A., *UV-triggered dopamine polymerization: control of polymerization, surface coating, and photopatterning,* In: Advanced Materials, 2014, 26, 47, 8029–8033

[17] Zhang, C., Ou, Y., Lei, W. X., Wan, L. S., Ji, J., Xu, Z.K., *CuSO4/H2O2□induced rapid deposition of polydopamine coatings with high uniformity and enhanced stability*, In: Angewandte Chemie International Edition, 2014, 2055, 9, 3054–3057

[18] Telli, A., Arabaci, S., *Investigation of the oxidative self-polymerization of dopamine under alkaline conditions on wool fabrics,* In: Textile Research Journal, 2024, https://doi.org/10.1177/00405175241274763

[19] Ilić, V., Šaponjić, Z., Vodnik, V., Potkonjak, B., Jovančić, P., Nedeljković, J., Radetić, M., *The influence of silver content on antimicrobial activity and color of cotton fabrics functionalized with Ag nanoparticles*, In: Carbohydrate Polymers, 2009, 78, 3, 564–569

[20] Smith, B., *Infrared Spectroscopy of Polymers, VIII: Polyesters and the Rule of Three*, In: Spectroscopy, 2022, 37, 10, 25–28

[21] Ou, J., Ma, J., Wang, F., Li, W., Fang, X., Lei, S., Amirfazli, A., *Unexpected superhydrophobic polydopamine on cotton fabric*, In: Progress in Organic Coatings, 2020, 147, 105777

[22] Ahmed, T., Sezgin Bozok, S., Ogulata, RT., *Comparison of in situ and padding method to incorporate Green synthesized AgNPs by using Calendula arvensis into nonwoven fabrics*, In: Journal of Adhesion Science and Technology, 2024, 1–18

[23] Tania, I.S., Ali, M., Bhuiyan, R.H., *Experimental study on dyeing performance and antibacterial activity of silver nanoparticle-immobilized cotton woven fabric*, In: Autex Research Journal, 2021, 21, 1, 45–51

[24] Montes-Hernandez, G., Di Girolamo, M., Sarret, G., Bureau, S., Fernandez-Martinez, A., Lelong, C., Eymard Vernain, E., *In situ formation of silver nanoparticles (Ag-NPs) onto textile fibers*, In: ACS omega, 2021, 6, 2, 1316–1327

Author:

ABDURRAHMAN TELLI

Cukurova University, Faculty of Engineering, Department of Textile Engineering,
Balcalı Campus, 01330, Adana, Turkey

Corresponding author:

ABDURRAHMAN TELLI
e-mail: atelli@cu.edu.tr

Impact of production methods on waste minimization in v-bed flat knitting: a case study

DOI: 10.35530/IT.076.02.2024123

NADIIA BUKHONKA
OLENA KYZYMCHUK
MARIJA PESIC
INETA NEMESA
JOVAN RADISIC

ABSTRACT – REZUMAT

Impact of production methods on waste minimization in v-bed flat knitting: a case study

Sustainable development in the textile industry is challenging due to growing demand and urgent environmental impact. Waste minimization at every production stage is a promising way toward sustainability. Knitting is the most flexible textile technology for zero-waste production.

This study aims to investigate the impact of production methods on production efficiency and waste minimization using the V-bed flat knitting machine and the men`s cardigan as an example. The comparative analysis of yarn consumption and production time for different production methods (part cut and fully fashioned) was used.

Research results of men`s cardigan manufacturing by four distinct methods derived from part-cut and fully fashioned methods highlight their significant effect on yarn consumption, duration of production cycle, and cardigan performance. The fully fashioned method minimizes yarn consumption by 16.5%, with 3.9% waste compared to the part-cut method. The advanced fully fashioned method using a front knitted part with integrated cardigan pockets decreases yarn consumption by 2.6% more and incurs only 3.0% waste. This method produces the highest cardigan performance compared to the other methods due to its linking stitching and integrated knitted pockets. Within the part-cut method, using the part-shaped panel instead of the rectangular panel for sleeves leads to a 9.7 % decrease in yarn consumption and a 2.6% reduction in waste. It also leads to better product performance because of minimizing the overlocking seams. These findings underscore the importance of selecting appropriate production methods to enhance efficiency and reduce waste in knitwear manufacturing. Embracing waste reduction measures, mainly through natural yarn, holds promise for environmentally friendly garment production. This research emphasizes the need for ongoing exploration of eco-conscious manufacturing processes to promote sustainable knitwear production.

Keywords: *knitting waste, production cycle, fully fashioned method, part-cut method, product performance, sustainability, integrated pocket, zero-waste technology*

Impactul metodelor de producție asupra minimizării deșeurilor în cazul tricotării pe mașini rectilinii V-BED: un studiu de caz

Dezvoltarea durabilă în industria textilă este o provocare din cauza cererii în creștere și a impactului asupra mediului. Minimizarea deșeurilor în fiecare etapă de producție este o cale promițătoare către durabilitate. Tricotarea este cea mai flexibilă tehnologie textilă pentru producția de zero deșeuri.

Acest studiu își propune să investigheze impactul metodelor de producție asupra eficienței producției și minimizării deșeurilor, folosind ca exemplu mașina rectilinie de tricotat în V și cardiganul bărbătesc. A fost utilizată analiza comparativă a consumului de fire și a timpului de producție pentru diferite metode de producție (croire parțială și modelare completă).

Rezultatele cercetării efectuate asupra procesului de fabricație a cardiganului de bărbați prin patru metode distincte derivate din metodele croire parțială și modelare completă evidențiază efectul lor semnificativ asupra consumului de fire, duratei ciclului de producție și performanței cardiganelor. Metoda de modelare completă minimizează consumul de fire cu 16,5%, cu 3,9% deșeuri în comparație cu metoda de croire parțială. Metoda avansată, de modelare completă, care utilizează o parte frontală tricotată a cardiganului cu buzunare integrate, reduce consumul de fire cu 2,6% și generează doar 3,0% deșeuri. Această metodă produce cea mai mare performanță a cardiganului în comparație cu celelalte metode datorită asamblării și buzunarelor tricotate integrate. În cadrul metodei de croire parțială, utilizarea panoului în formă de reper în locul panoului dreptunghiular pentru mâneci conduce la o scădere cu 9,7% a consumului de fire și la o reducere cu 2,6% a deșeurilor. De asemenea, duce la o performanță mai bună a produsului datorită minimizării asamblărilor overlock. Aceste constatări subliniază importanța selectării metodelor de producție adecvate pentru a spori eficiența și a reduce deșeurile în fabricarea tricotajelor. Adoptarea măsurilor de reducere a deșeurilor, în principal prin fire naturale, este promițătoare pentru producția de îmbrăcăminte ecologică. Această cercetare subliniază necesitatea explorării continue a proceselor de fabricație ecologice pentru a promova producția durabilă de tricotaje.

Cuvinte cheie: *deșeuri de tricot, ciclu de producție, metodă de modelare completă, metodă de croire parțială, performanța produsului, durabilitate, buzunar integrat, tehnologie zero deșeuri*

INTRODUCTION

The textile industry has a significant impact on both the environment and society. This impact spans from the production process to the disposal of garments [1, 2]. Knitting is one of the three primary technologies in textile clothing manufacturing, alongside weaving and nonwoven. The second-highest environmental impact is associated with knitting, while weaving is found to have the highest environmental impact [3]. Implementing sustainable clothing manufacturing practices [4, 5] is essential as our world's resources become scarcer and the population grows. The key elements of clothing production are using eco-friendly materials [6, 7] and optimizing manufacturing processes to minimize waste at every stage [8, 9]. Some common methods to minimize waste include "zero-waste" production [10–20], reducing the amount of fabric used [21], utilizing fabric scraps for other purposes [22, 23], optimizing pattern layout to reduce fabric waste [24], properly disposing of any waste materials that cannot be reused or recycled [25–27], and upcycling [28–30]. Implementing these strategies before production can help garment manufacturers reduce their environmental impact [31] while reducing production costs.

The development of V-bed flat knitting machines [32] has transformed the production landscape by paying attention to the end product's quality and the equipment's technological possibilities. Manufacturers using V-bed flat knitting used various production methods, each impacting waste generation by up to 50%. These machines create different fabric types, facilitating the shaping of pre-sized parts with integrated knitted parts [33–36]. Each production method requires special knitting and making-up processes. Effective collaboration between design and pattern-making teams is necessary to minimize waste during the design process to achieve success [14, 17]. This will help reduce yarn and/or fabric consumption and enhance the utilization of knitted fabrics per garment. For this purpose, the knitting fully stitched-shaped parts of the knitted products are the most suitable method of production of knitted products in a V-bed flat knitting machine [33, 36], which requires skill and precision in garment-making and is valuable in producing high-quality garments. Using this method with integrated parts during knitting, not during the assembling process, results in the development of the seamless parts of products or complete products. This way is the premier choice among low-waste or waste-free concepts. The advent of whole garment or knit-and-wear V-bed flat knitting machines has moved the knitting industry to commercial success in the 21st century [34, 37]. This method is achieved through different knitting techniques such as whole garment (Shima Seiki, Japan) [38] or knit-and-wear (Stoll, Germany) [39], which means integrating all garment parts with bands or trimmings, accessories, and buttonholes to produce garments in a V-bed flat knitting machine. It enhances the appearance of the garment. Considerations such as garment size, fit, and intended use are essential for efficient production and waste reduction [40]. Designers can enhance knitting technology by using data and insights to create customized, seamless garments, reducing waste and production time for greater efficiency and cost-effectiveness in "ready-to-wear" fashion [41–43]. Also, this method can be suitable for producing customized products using the concept of "knit on demand" [44, 45] or mass customization for mass individualization [46]. Garment knitting technology has the potential to reduce manufacturing time and enable fast delivery to customers, even within hours [47]. However, this technique is only suitable for a limited range of garments that do not require seams [34]. The textile industry can streamline production by quickly creating customized clothing, meeting demand for personalized garments, and reducing unsold inventory. However, implementing complete garment knitting technology poses challenges, including high initial investment, prolonged preparation time, and fixed overhead costs [33, 36]. These garments offer superior fit and quality but require more time and resources than traditional knitwear. The advanced technological capabilities of knitting machines needed for complete garments pose a challenge as they require expertise to operate effectively and can be a barrier to entry for some manufacturers [48].

The examination of published literature on diverse production methods in knitwear manufacturing reveals a notable gap in comprehensive coverage. While foundational information is available in textbooks [34, 36], insights into management aspects can be found in sources such as [41, 42, 45, 46, 49] and a handful of publications [32, 35, 37, 40, 43] delve into advanced developments in V-bed flat knitting technology. Yet, a detailed analysis comparing production methods to elucidate strategies for minimizing raw material consumption, waste generation, and production time still needs to be improved.

Minimizing waste throughout knitted garments' design and production phases holds paramount importance. This imperative is particularly pronounced in knitting technologies, renowned for their considerable environmental footprint, alongside weaving.

This case study aims to conduct a comprehensive and detailed analysis of diverse production methods for V-bed flat knitting machines to minimize waste and production time. It is focused on the cut and fully fashioned methods and their derivatives. Emphasis was placed on assessing the generated production waste and the overall manufacturing time. The research findings offer valuable insights into knitwear production, aiding designers and manufacturers in enhancing product quality and optimizing the production process while minimizing waste. By leveraging these insights, manufacturers can streamline production processes, reduce waste, and sustainably produce high-quality knitwear garments.

MATERIALS AND METHODS

Materials

The men's cardigan (figure 1) of size 42 (in cm) was chosen for this study.

This cardigan is designed for men and is perfect for workouts, outdoor activities, or casual outings. It features long sleeves, a stand-up collar, a front zipper from the neck to the hem (which can be opened in two ways), and side slash pockets. The cardigans were made on a 12-gauge V-bed flat knitting machine CMS 340 TC-L from Stoll, Germany, from pure cotton yarn 50/2 Nm. Before knitting, the yarn was waxed with 0.5% wax. Plain stitches were used for the main section of the cardigan, while 1×1 rib stitches were used for the collar, cuffs, and hem.

The production methods

The two most used production methods for V-bed flat knitting machines were chosen for this study: part cut and fully fashioned. The knitted parts of the cardigan can be split into two groups for knitting the main parts (front, back, and sleeves) and the secondary parts (collar, front bands, pocket band, and pocket lining). They differ by the types of the main knitted parts presented in table 1.

The front, back, and sleeve parts were knitted as rectangular panels for the part cut method (PC-1). The other possible variant for the part cut method (PC-2) was also used: the front and back parts were knitted as rectangular panels, but the sleeves were part-shaped (table 1). The fully fashioned method ensures knitting the cardigan's front, back, and sleeves as stitch-shaped parts. The study is divided into two variants: simple fully fashioned (SFF) when knitted parts fit the paper patterns and advanced fully fashioned (AFF) when, additionally, the pocket was integrated into the front part during the knitting.

The post-knitting process of men's cardigans consists of washing the cardigan`s parts according to ISO 6330:2021 [50] using a washing machine (WM) and ironing using a hand iron or press (IM), which includes ironing all parts after washing, ironing the pocket during assembly to the front part, and final ironing of the finished cardigan. It also consists of part cutting using a round knife and/or scissors (CM) and assembling the cardigan using different machines such as the overlock machine (OM) for only part cut method, linking machine (LM), and sewing machine (SM). And consists of doing any necessary handwork (HW). The fundamental handwork operations (HW) mainly entail the removal of technical yarns from shaped knitted parts.

The summarized technological chart is presented in figure 2.

RESULTS AND DISCUSSION

The yarn consumption

The main difference in yarn consumption depends on the configuration of the main knitted parts (table 2). The secondary parts are the same (table 1) for all methods except AFF when the pocket is integrated into the front part directly during knitting.

Generally, the fully fashioned method, in which the main knitted parts are pre-sized and shaped, offers a substantial weight reduction compared to the part-cut method. Using the stitch-shaped parts (SFF) instead of the panels (PC-1) saves 25 g (15.2 %) for the front, 22 g (14.2 %) for the back, and 60 g (30.0 %) for both sleeves. This leads to a reduction of 16.5 % (107 g per cardigan) yarn consumption for the simple fully fashioned method (SFF) compared to the part cut method (PC-1).

The study results show that even small changes in the shape of panels can reduce yarn consumption. Using the part-shaped panel for sleeves in the PC-2 method leads to a 10.0 % decrease in their weight compared to the PC-1 method. It should be noted that these and similar panels can be produced on V-bed flat knitting machines in old models. Thus, the manufacturer can change the yarn consumption by

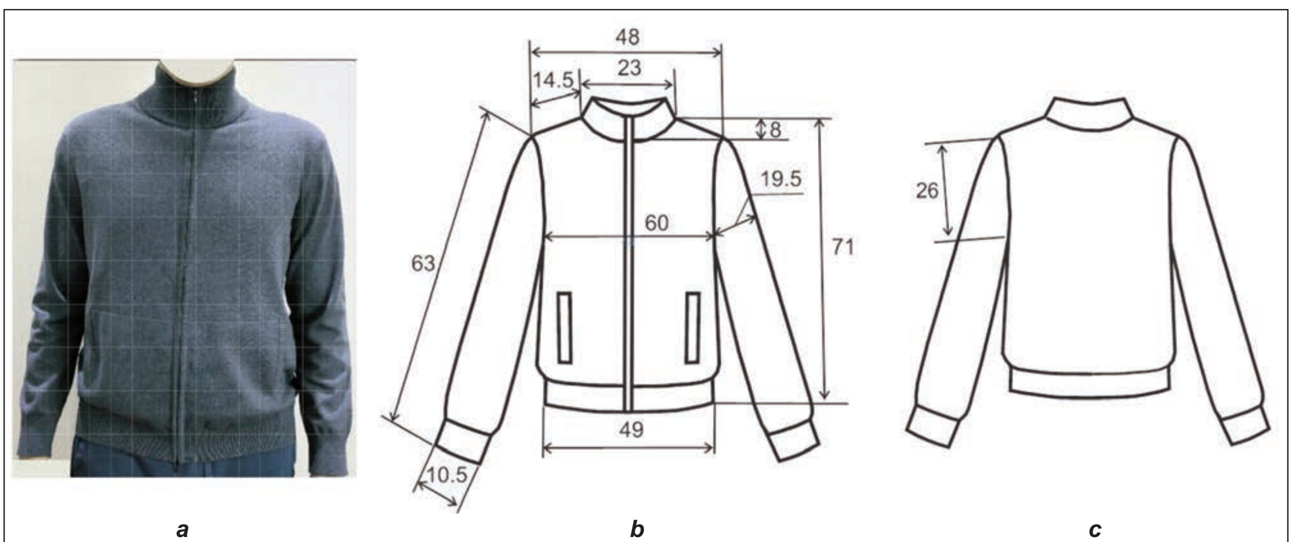


Fig. 1. The men's cardigan: *a* – real product; *b* – technical sketch of the cardigan for the front side; *c* – technical sketch of the cardigan for the backside

Table 1

<table>
<tr><th colspan="5">THE PHOTOS OF THE KNITTED PARTS OF A MEN'S CARDIGAN DEPEND ON THE PRODUCTION METHODS</th></tr>
<tr><th rowspan="2">Knitted parts</th><th colspan="4">Production method</th></tr>
<tr><th>PC-1</th><th>PC-2</th><th>SFF</th><th>AFF</th></tr>
<tr><td rowspan="2">Front ×1</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td colspan="2">Panel</td><td>Shaped S</td><td>Shaped A</td></tr>
<tr><td rowspan="2">Back ×1</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Panel</td><td colspan="2">Shaped</td></tr>
<tr><td rowspan="2">Sleeve ×2</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Panel</td><td>Part shaped</td><td colspan="2">Shaped</td></tr>
<tr><td rowspan="4">Secondary parts</td><td colspan="3"></td><td>-</td></tr>
<tr><td colspan="3">Pocket's lining ×1 – part-shaped</td><td></td></tr>
<tr><td colspan="2"></td><td></td><td></td></tr>
<tr><td colspan="2">Left front band ×1, and right front band ×1 - shaped</td><td>Collar ×1 – part-shaped</td><td>Pocket's band ×2 – part-shaped</td></tr>
</table>

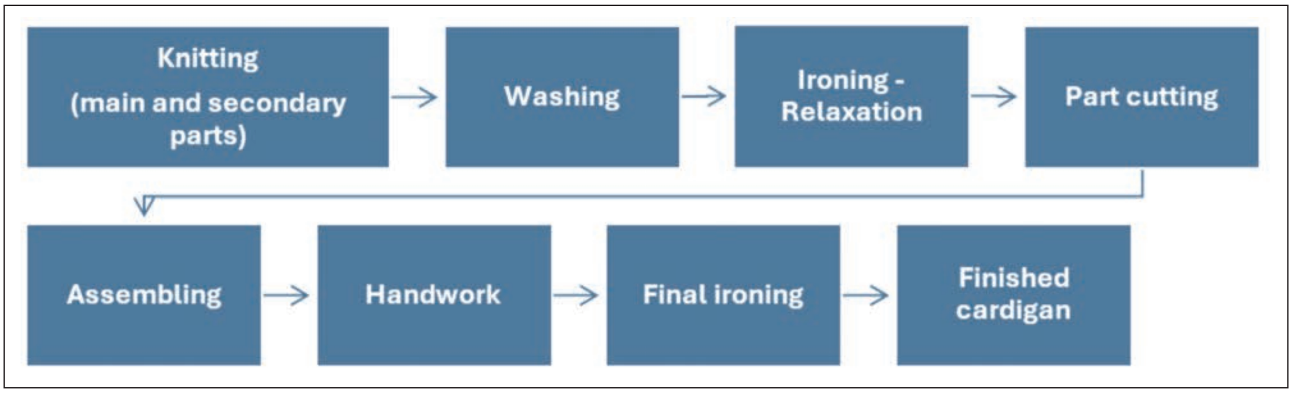


Fig. 2. Technological chat for men's cardigan

Table 2

THE WEIGHT [g] OF THE KNITTED PARTS (Mi) AND CORRESPONDENT WASTE (Wi) OF THE CARDIGAN

Cardigan`s part	Type	PC-1		PC-2		SFF		AFF	
		M_i	W_i	M_i	W_i	M_i	W_i	M_i	W_i
Front	Panel	165	32	165	32	-	-	-	-
	Shaped S	-	-	-	-	140	1	-	-
	Shaped A	-	-	-	-	-	-	162	1
Back	Panel	155	27	155	27	-	-	-	-
	Shaped	-	-	-	-	133	6	133	6
Sleeves	Panel	200	48	-	-	-	-	-	-
	Part shaped	-	-	180	28	-	-	-	-
	Shaped	-	-	-	-	140	2	140	2
Total main parts:		*520*	*107*	*500*	*87*	*413*	*9*	*435*	*9*
Collar	Panel	55	2	55	2	55	2	55	2
Right front band	Shaped	15	2	15	2	15	2	15	2
Left front band	Shaped	15	2	15	2	15	2	15	2
Pocket bands	Shaped	10	1	10	1	10	1	10	1
Pocket lining	Panel	36	5	36	5	36	5	-	-
Total secondary parts:		*131*	*12*	*131*	*12*	*131*	*12*	*95*	*7*
TOTAL:		651	119	631	99	544	21	530	16
The finished cardigan		532		532		523		514	
Waste in %		18.3		15.7		3.9		3.0	

slightly changing the panel`s shape using the part-cut method. A comparison of the weight of the front part with integrated pockets using the AFF method with the summary weight of the front part and the pocket lining using the SFF method has shown a 14 g decrease in yarn consumption per cardigan. It is only 2.6 % of the total weight, leading to valuable amounts within mass production. Thus, there is the possibility of changing the yarn consumption using the AFF method as well. Sustainability in clothes production emphasizes waste reduction at each production stage. In this case, it is essential to understand the effect of production methods on generated waste. As the shapes of the knitted secondary parts fit the patterns, the generated waste is not huge (table 2): 7 g for AFF and 12 g for other methods. The production waste for men`s cardigans is 18.3 % of total yarn consumption for part-cut method PC-1 with simple rectangular panels. Using the PC-2 method for sleeves only decreases waste by 2.6%. However, if pre-sized shaped main knitted parts are used, the amount of waste decreases significantly. The total waste is 3.9% and 3.0% for SFF and AFF methods, respectively.

The knitting time

Figure 3 presents the contribution of the main and secondary parts to the total knitting time for the cardigan.

Most of the knitting time is for the main parts (figure 3), and it significantly depends on the production method: around 74% for part cut and 82–86% for fully fashioned. It can be observed that the knitting time needed for pre-sized shaped front and back parts is double the time required for panels. This is because the time-consuming process of loops` transferring is used to shape the armhole and neck sections, especially for the front panel. However, the difference in the knitting time for sleeves is big. The time difference between knitting panels for sleeves and shaped sleeves is 4.3% (1.5 min) for part-shaped sleeves and 9.7% (3.4 min) for full-shaped sleeves. It can be explained that simple needle adding is used for panel widening. The loops` transferring for narrowing are simpler than the front and back panels. The fully shaped front part with integrated pockets (AFF) takes 7.5% (3.9 min) more time to knit compared to a regular fully shaped front (SFF). But it enabled to skip the knitting pocket lining separately, which took 8.5 min. Generally, it leads to 5.6 min saving time, i.e., 3.3% of total knitting time. The knitting time for other secondary parts, such as a collar, front, and pocket bands, is the same for all production methods. In conclusion, the research data shows that the fully fashioned method is time-consuming for the knitting stage. It leads to a 45% increase in the total knitting time of the cardigan compared to the part-cut method.

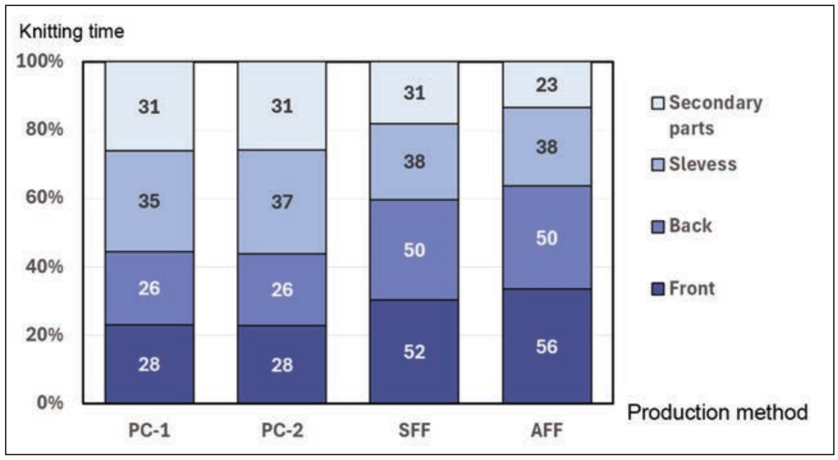


Fig. 3. The contribution of the main and secondary parts in total knitting time for the cardigan

The post-knitting time

Figure 4 presents the main stages' contribution to the cardigan's total production time. The washing, cutting, and assembly take 80% of the post-knitting time for all production methods. The assembly remains the most time-consuming stage, with 48% of the total post-knitting time for the part-cut method and up to 53% for the fully fashioned method.

The washing of knitted parts and general handwork processes remain consistent across all production methods (figure 4); they are set up for the same knitted cardigan made from the same yarn. The cutting time (figure 4) varies significantly depending on the production methods. The part-cut method requires the longest time for cutting, accounting for 13.4% (PC-1) and 10.0% (PC-2) of the total post-knitting time. In contrast, the fully fashioned method (SFF) reduces cutting time by 48.4% compared to PC-1 with the rectangular panels and 27.3 % compared to PC-2 with the shaped panels. Furthermore, the AFF method minimizes cutting time even further, 2.7% of the total post-knitting time.

The disparity between SFF and AFF methods lies in cutting the pocket lining, which is unnecessary for the second one. The assembly process primarily involves operations using linking machines (figure 4). This is a labour-intensive process that requires high operator skills and ensures high-quality products. As with the fully fashioned method, all parts of the cardigan were assembled by a linked machine. It took longer than the part-cut method, where armhole seams were overlocked. The explanation for this trend lies in the impact of the edges of the full-shaped parts, which are "clean" and require additional time to join using a loop-to-loop method on a linking machine. The assembly time for full-shaped parts is extended when joining the linking machines, in contrast to the overlocked edge of the panel parts using the part-cut method. The difference is 28.4% (23 min) for the SFF method. Integrating the pocked into the front part during knitting within the AFF method significantly reduces the time for the linking by 19.2% (20 min) less than for the SFF method. It is almost like the PC method: 3.6% (3 min) difference. The assembly stage is the longest for the SFF method and the shortest for the ADF method. The difference is 25 min, i.e., the ADF method saves 20.0% assembly time. Ironing is an important part of a cardigan`s manufacturing as it eliminates wrinkles, creases, and folds and helps the piece look better. As described in "The production methods", ironing is used a few times within the cardigan`s production: for knitted parts after washing, for the pocket during assembly

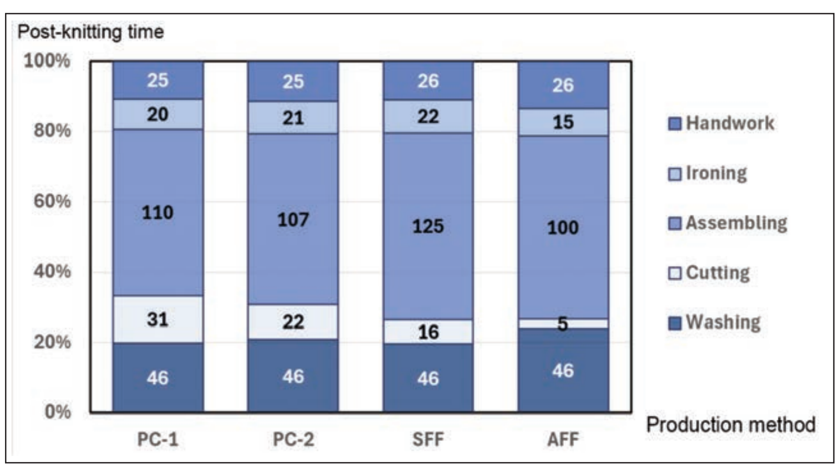


Fig. 4. The contribution of the main stages to the total post-knitting production time for the cardigan

to the front panel, and for the finished product. It generally depends on the shape of the knitted parts. As plain stitches were used for the main parts of the cardigan, these stitches tend to curl coursewise onto the back side and walewise onto the face side. The shaped parts require longer ironing before assembly (figure 4) than panel parts. Thus, the partly shaped (PC-2) and shaped (SFF and AFF) parts need a correspondently 16.7% (1 min) and 28.5% (2 min) more ironing time after washing compared to rectangular panels (PC-1). On the other hand, if the pocket were integrated into the front panel during knitting (AFF), it would lead to the absence of the ironing process during assembly. The ironing stage takes up to 9.5% of the total post-knitting time. The AFF method requires less ironing time and can be characterized as more environmentally friendly because ironing is an energy-consuming stage with high humidity emissions.

In conclusion, the research data shows that the PC-1 and SFF methods are time-consuming for the post-knitting stage. Using the PC-2 method can reduce the post-knitting stage by 5.0% time. At the same time, the AFF method saves up to 16.7% of the post-knitting time. The production process duration for the three (PC-1, PC-2, and AFF) of the studied methods is similar (351, 342, and 361, respectively) and is around 351 min. The difference is only ±2.7% (±10 min). The SFF requires 16.0% (56 min) more time than other methods. The knitting takes 33.9-35.4% of total production time for PC-1 and PC-2 part-cut methods, increasing to 42.3% for SFF and 46.5% for AFF methods. The research data shows that the AFF method, with increasing time for the knitting stage, can ensure the same total production as the part-cut method. At the same time, both the energy-intensive ironing stage and the labour-intensive linking process are reduced.

Overall product`s performance

The production method used while manufacturing a cardigan significantly impacts its overall performance, quality, and aesthetic appeal. The construction of pockets and the type of stitches used for the cardigan`s assembly are important factors influencing the final product's performance. Figure 5 presents visual representations of pockets on the front parts of the cardigan, illustrating both the front and back sides.

There is a visible difference in a pocket created simultaneously with the front side (figure 5, *b*) by the AFF method and those using separate pocket lining linked to the front part (figure 5, *a*). Thus, the AFF method allows the production of knitted garments of higher quality to avoid unnecessary and bulky seams. As was mentioned above, the type of stitches used for the cardigan`s assembly depends on the type of knitted part. Using rectangular or partly shaped panels for the cardigan`s main parts requires cutting on the sides and tops to form armholes, shoulders, and necklines. It is followed by an additional stage – the overlocking of the seams to create finished sides and avoid unexpected unravelling (figure 5, *c*). The overlock seams are usually thicker and bulky. This stage is attributed to both part-cut methods. In the case of PC-2, overlocking is used for shoulders and armhole seams only, while in PC-1, the side joints of the side of sleeve stitches are overlocked. The linking stitches (figure 5, *d*) are usually used for stitch-shaped sides; they create a flat seam with a good appearance. In our case, linking was the only method for cardigan assembly by both fully fashioned methods (SFF and AFF). It was partly used for the part cut method, pocket lining joining (PC-1 and PC-2), the front and back parts, and the side of sleeve stitches (PC-2). Another advantage of linking seams is that it keeps the knitted part in the original stage; thus, it allows the unravelling of the yarn, even from ready-to-use knitted products. This is a big step toward upcycling and circularity in the knitting industry. In conclusion, it can be stated that the overall performance of men`s cardigans increased using a fully fashioned method compared to the part-cut method. Within both methods, there are separate ways to improve the quality and performance of the final product. Using part-shaped panels (PC-2) instead of rectangular panels (PC-1) is a good choice for manufacturers equipped with old models of the V-bed flat knitting machines. It will be an advanced decision for those equipped with V-bed flat knitting machines with technological capabilities for integrating additional parts, such as a pocket, into the main part during the knitting.

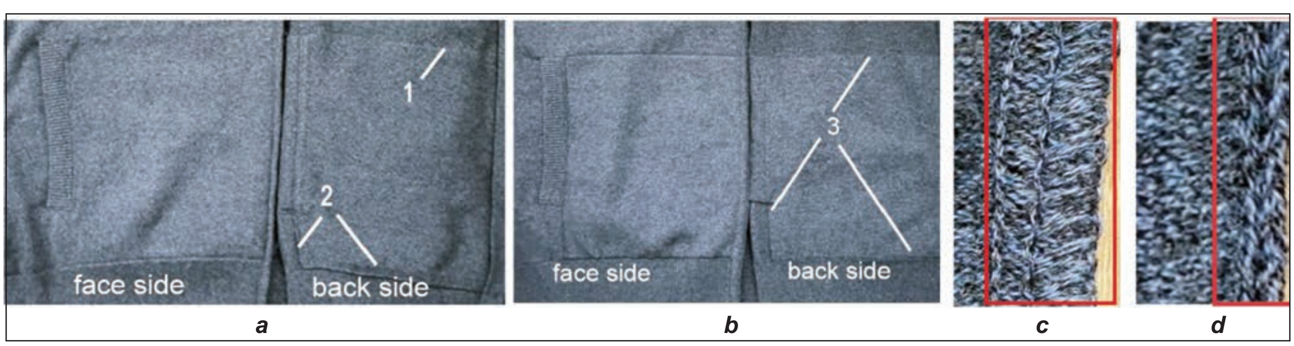


Fig. 5. The photos of the pockets on the front and back of the finished cardigan: *a* – pocket knitted as a separate part (PC-1. PC-2, and SFF); *b* – integrated pocket (AFF); *c* – overlock stitch; *d* – linking stitch (1, 2 – sewing seam on the pocket, 3 – knitted stitch on the pocket)

CONCLUSION

The study reveals valuable insights into how men's cardigan manufacturing production methods can improve efficiency using V-bed flat knitting machines. Analysed part-cut and fully fashioned methods significantly impact yarn consumption, overall production time, and product performance. The fully fashioned method reduces yarn consumption and production waste compared to the part-cut method. Although the fully fashioned (SFF) production cycle is 16.0% longer than the part-cut (PC-1) due to increased knitting time for stitch-shaped panels, it results in a higher-quality product and promotes sustainability. The stitch-shaped panels have the greatest advantage: they allow the yarn`s unravelling at both production and consumer stages for its future upcycling. Integrating secondary parts into main parts during knitting is a promising step toward zero-waste production. For example, combining the pocket into the front part of the cardigan within the fully fashioned method reduces yarn consumption by 3.0%, waste by 0.9%, and production time by 17.9% while reducing the need for ironing and linking processes. Waste reduction and improved product performance are achievable even within the part-cut method. Using part-shaped panels for sleeves decreases yarn consumption by 9.7% and waste by 2.6% while enhancing product performance without extending the production cycle.

The main finding of this work is in understanding the balance between two objectives, namely waste minimization and production cycle reduction, for the production of high-quality products and sustainable development of the knitwear industry. This research emphasizes the importance of selecting the right production methods for knitting garments. Implementing waste reduction measures, especially with natural yarns, can significantly improve eco-friendly knitted clothing production. Manufacturers can achieve sustainable, high-quality knitwear production by choosing and applying appropriate methods.

ACKNOWLEDGEMENT

This work was supported by the Provincial Government of the Autonomous Province of Vojvodina, Provincial Secretariat for Higher Education and Scientific Research of the Republic of Serbia (No. 00106414, Decision on Approval of Funds No. 001064141 2024 09418 003 000 000 001 04 003).

REFERENCES

[1] Siliņa, L., Dāboliņa, I., Lapkovska, E., *Sustainable textile industry – wishful thinking or the new norm: A review*, In: Journal of Engineered Fibers and Fabrics, 2024, 19, https://doi.org/10.1177/15589250231220359

[2] Mazzitelli, M., Papile, F., Del Curto, B., *Materials selection and fashion design: strengthening reflections on fibre's nature in fibres and textiles selection*, In: Discov Sustain, 2024, 5, 180, https://doi.org/10.1007/s43621-024-00294-3

[3] Palamutcu, S., *Sustainable Textile Technologies*, In: Muthu, S. (eds) Textiles and Clothing Sustainability. Textile Science and Clothing Technology, Springer, Singapore, 2017, https://doi.org/10.1007/978-981-10-2474-0_1

[4] Daukantienė, V., *Analysis of the sustainability aspects of fashion: A literature review*, In: Textile Research Journal, 2023, 93, 3–4, 991–1002, https://doi.org/10.1177/00405175221124971

[5] Abrishami, S., Shirali, A., Sharples, N., Kartal, G.E., Macintyre, L., Doustdar, O., *Textile Recycling and Recovery: An Eco-friendly Perspective on Textile and Garment Industries Challenges*, In: Textile Research Journal, 2024, 0, 0, https://doi.org/10.1177/00405175241247806

[6] Marcu, F., Ilies, D.C., Wendt, J.A., Indrie, L., Ilies, A., Burta, L., Caciora, T., Herman, G.V., Todoran, A., Baias, S., Albu, A., Gozner, M., *Investigations regarding the biodegradation of the cultural heritage. Case study of traditional embroidered peasant shirt (Maramures, Romania)*, In: Rom Biotechnol Lett., 2020, 25, 2, 1362–1368, https://doi.org/10.25083/rbl/25.2/1362.1368

[7] Pashkevych, K.L., Yezhova, O.V., Gerasymenko, O.D., Protsyk, B.O., Kolosnichenko, M.V., *Ecological design of underwear: Technological and educational approaches*, In: Man-Made Textiles in India, 2024, 52, 2, 65–74

[8] Textile Exchange, *Materials Market Report*, December 2023, Available at: https://textileexchange.org/app/uploads/2023/11/Materials-Market-Report-2023.pdf [Accessed on July 2024]

[9] Gojic, A., Bukhonka, N., *Recycled Textile Fibers And Materials – Current State And Development Perspectives*, In: Conference Proceedings ICPAE 2023, 24th August – 26th August, Zrenjanin, Serbia, 95–100

[10] Carrico, M., Kim, V., *Expanding zero-waste design practices: A discussion paper*, In: International Journal of Fashion Design 2014, 7, https://doi.org/10.1080/17543266.2013.837967

[11] Han, S., Suh, S-H., *A Study on the Design Development Methods and the Characteristics of Zero Waste Fashion Design*,-In: Journal of the Korean Society of Costume, 2016, 66, 61–76, https://doi.org/10.7233/jksc.2016.66.4.061

[12] Rissanen, T., *Zero-waste fashion design: a study at the intersection of cloth, fashion design and pattern cutting*, Ph.D. Thesis, Sydney Australia: University of Technology, 2013

[13] James, A., Roberts, B., Kuznia, A., *Transforming the sequential process of fashion production: where zero-waste pattern cutting takes the lead in creative design*, In: International Journal of Fashion Design, Technology and Education, 2016, 1–11, https://doi.org/10.1080/17543266.2016.1167253

[14] Han, S., Suh, S-H., *A Study on the Design Development Methods and the Characteristics of Zero Waste Fashion Design*, In: Journal of the Korean Society of Costume, 2016, 66, 61–76, https://doi.org/10.7233/jksc.2016.66.4.061

[15] Saeidi, E., Wimberley, V., *Precious cut: exploring creative pattern cutting and draping for zero-waste design*, In: International Journal of Fashion Design, Technology and Education, 2017, 11, https://doi.org/10.1080/17543266.2017.1389997

[16] Nemeša, I., Pešić, M., Csanák, E., *Flexible Design of Garment Styles to Support the Minimal Waste Concept in the Fashion Industry*, In: Fibres & Textiles in Eastern Europe, 2023, 31, 64–73, https://doi.org/10.2478/ftee-2023-0029

[17] Townsend, K., Mills, F., *Mastering zero: How the pursuit of less waste leads to more creative pattern cutting*, In: International Journal of Fashion Design, 2013, 6, https://doi.org/10.1080/17543266.2013.793746

[18] McQuillan, H., Archer-Martin, J., Menzies, G., Bailey, J., Kane, K., Derwin, E., *Make/Use: A System for Open Source, User-Modifiable, Zero Waste Fashion Practice*, In: Fashion Practice, 2018, 10, 1–27, https://doi.org/10.1080/17569370.2017.1400320

[19] Hatef, M., Hosseini, K., *Quest for the Fashion Market: Zero-Waste Skirt Design as a Solution toward Sustainable Pattern Making,* In: The Chitrolekha Journal on Art and Design, 2020, 4, 1–11, https://doi.org/10.21659/cjad.41.v4n205

[20] McQuillan, H., Rissanen, T., Roberts, J., *The Cutting Circle: How Making Challenges Design*, In: Research Journal of Textile and Apparel, 2013, 17, 39–49, https://doi.org/10.1108/RJTA-17-01-2013-B004

[21] Gwilt, A., Rissanen, T., *Shaping Sustainable Fashion: Changing the Way We Make and Use Clothes*, In: (1st ed.). Routledge, 2011, 1–192, https://doi.org/10.4324/9780203126172

[22] Sawitri, S., *How to Minimize the Fabric Waste in Fashion Industries*, In: Conference: International Conference on Technology and Vocational Teachers (ICTVT 2017), 2017, https://doi.org/10.2991/ictvt-17.2017.18

[23] Fridrichová, L., Němeček, P., Knížek, R., Buczkowska, K.E., *Opportunities to use textile waste for the production of acoustic panels*, In: Textile Research Journal, 2024, 0, 0, https://doi.org/10.1177/00405175241256593

[24] Enes, E., Kipoz, S., *The Role Of Fabric Usage For Minimization Of Cut-And-Sew Waste Within The Apparel Production Line: Case Of A Summer Dress*, In: Journal of Cleaner Production, 2019, 248, https://doi.org/119221.10.1016/j.jclepro.2019.119221

[25] Lau, Y.I., *Reusing pre-consumer textile waste*, In: SpringerPlus 4, 2015, Suppl 2, O9, https://doi.org/10.1186/2193-1801-4-S2-O9

[26] Lewis, T., Park, H., Netravali, A., Trejo, H., *Closing the loop: a scalable zero-waste model for apparel reuse and recycling,* In: International Journal of Fashion Design, Technology and Education, 2016, 10, 1–10, https://doi.org/10.1080/17543266.2016.1263364

[27] Eunjin, K., Namkyung, J., *Fashion Design for Environment using Pre-Consumer Textile Waste*, In: The Research Journal of the Costume Culture, 2009, 17, 2, 225–237

[28] He, C., McQueen, R., Kozlowski, A., Strickfaden, M., *From Waste to Wardrobe: Exploring Textile Upcycling from a Local Perspective,* 2024, https://doi.org/10.31274/itaa.17529

[29] Han, S.L.C., Chan, P.Y.L., Venkatraman, P., Apeagyei, P., Cassidy, T., Tyler, D.J., *Standard vs. Upcycled Fashion Design and Production*, In: Fashion Practice, 2017, 9,1, 69–94, https://doi.org/10.1080/17569370.2016.1227146

[30] Bukhonka, N.P., Kyzymchuk, O., *Circularity in Knitting: The Potential of Re-Using Natural Yarns After Unraveling*, In: Journal of Natural Fibers, 2024, 21, 1, https://doi.org/10.1080/15440478.2024.2375517

[31] Baloyi, R.B., Gbadeyan, O.J., Sithole, B., Chunilall, V., *Recent advances in recycling technologies for waste textile fabrics: a review*, In: Textile Research Journal, 2024, 94, 3–4, 508–529, https://doi.org/10.1177/00405175231210239

[32] Holderied P., Streitenberger L., Mutschler T., Klausmann J., Kyzymchuk O., Weber M., *Innovationen und Trends in Flat Knitting at ITMA 2023*, In: Melliand Textilberichte, 2023, 4, 38–41

[33] Brackenbury, T*., Knitted clothing technology*, In: Oxford: Blackwell Scientific Publications, 1992, 197

[34] Cassidy, T., *Knitwear Design and Technology,* In: Textile and Clothing Design Technology, 2018, https://doi.org/10.1201/9781315156163-16

[35] Kanakaraj, P., Ramachandran R., *Evolution of Weft Knitted Fabric Design: Seamless Knitwear Production Technology,* In: Review of International Geographical Education (RIGEO), 2021, 11, 7, 3869–3880, https://doi.org/10.48047/rigeo.11.07.356

[36] Spenser, D.J., *Knitting technology*, 3rd ed, Cambridge, Woodhead Publishing Limited, 2001, 393

[37] Čuden, A.P., *Recent developments in knitting technology*, In: The Textile Institute Book Series, Advanced Knitting Technology, Editor(s): Subhankar Maity, Sohel Rana, Pintu Pandit, Kunal Singha, Woodhead Publishing, 2022, 13–66, ISBN 9780323855341, https://doi.org/10.1016/B978-0-323-85534-1.00020-9

[38] Shima Seiki, *Wholegarment*, Available at: https://www.shimaseiki.com/wholegarment/ [Accessed on July 2024]

[39] Stoll, *Knit and Wear*, Available at: https://www.stoll.com/en/products-and-solutions/machines/knit-and-wear/ [Accessed on July 2024]

[40] Kaspar, A., Wu, K., Luo, Y., Makatura, L., Matusik, W., *Knit Sketching: from Cut & Sew Patterns to Machine-Knit Garments*, In: ACM Transactions on Graphics, 2021, 40, 1–15, https://doi.org/10.1145/3450626.3459752

[41] Peterson, J., Ekwall, D., *Production and business methods in the integral knitting supply chain*, In: AUTEX Research Journal, 2007, 7, 4, 264–274

[42] Peterson, J., *The Co-design Process in Mass Customization of Complete Garment Knitted Fashion Products*, In: J Textile Sci Eng, 2016, 6, 270, https://doi.org/10.4172/2165-8064.1000270

[43] Choi, W., Powell, N., *Three-dimensional seamless garment knitting on V-bed flat knitting machines,* In: JTATM 2005, 4, 3

[44] Peterson, J., *Customisation and Fashion Logistics Effects of Flat Knitted Fashion Products using Complete Garment Technology SAMAND' OR – A Case Study*, In: J Textile Sci Eng, 2016, 6, 232, https://doi.org/10.4172/2165-8064.1000232

[45] Larsson, J., Peterson, J., Mattila, H., *The Knit on Demand supply chain*, In: Autex Research Journal, 2012, 12, 3, 67–75, https://doi.org/10.2478/v10304-012-0013-9

[46] Peterson, J., *Customisation of Fashion Products Using CompleteGarment Technology*, PhD Thesis, Tampere, Swedish, 2012

[47] Peterson, J., Larsson, J., Carlsson, J., Andersson, P., *Knit on demand – development and simulation of a production and shop model for customised knitted garments*, In: International Journal of Fashion Design, Technology and Education, 2008, 1, 89–99, https://doi.org/10.1080/17543260802353399

[48] Čuden, A.P.*, Knitting towards sustainability, circular economy and Industry 4.0*, In: Applied Research, 2023, 2, 6, e202200087, https://doi.org/10.1002/appl.202200087

[49] Enes, E., Kipoz, S., *Turkey fashion industry's cut-and-sew waste, problem and its waste management strategies*, In: Journal of Textiles and Engineer, 2019, 113:26, 93–103

[50] ISO 6330:2021. *Textiles. Domestic washing and drying procedures for textile testing*, 2021

Authors:

NADIIA BUKHONKA[1], OLENA KYZYMCHUK[2], MARIJA PESIC[1], INETA NEMESA[1], JOVAN RADISIC[1]

[1]University of Novi Sad, Technical Faculty "Mihajlo Pupin" Zrenjanin, Department of basic and applied science, Djure Djakovica nn, Zrenjanin, 23000, Serbia
e-mail: marija.stankovic.986@gmail.com, inetavil@gmail.com, jovan.radisic998@gmail.com

[2]Kyiv Professional College of Applied Science, Dzhona Makkeina St, 29, 01601, Kyiv, Ukraine
e-mail: okyzymchuk@gmail.com

Corresponding author:

NADIIA BUKHONKA
e-mail: nbukhonka@gmail.com

A segmentation method for virtual clothing effect images

DOI: 10.35530/IT.076.02.2024111

RUIHONG CHEN
KAIJIE YU
YU CHEN
ZENGBO XU

ABSTRACT – REZUMAT

A segmentation method for virtual clothing effect images

Based on Efficient Channel Attention (ECA) mechanism, multi-level feature fusion and multi-scale channel attention mechanism, this paper proposes an improved VGG16-UNet clothing effect image segmentation method, commanded as EF-UNet, which aims to address the problems of insufficient semantic labels, poor local segmentation accuracy, and rough segmentation edges in clothing effect images. For this purpose, an ECA mechanism is first added to the fifth layer of the VGG16-UNet to assign greater weight and better extract target feature information to enhance the segmentation ability for clothing data. Subsequently, a multi-level feature fusion approach is adopted in a decoder to extract these features of various scales more efficiently and improve segmentation results. Finally, a multi-scale channel attention module is added to the skip connection to extract spatial information from multi-scale feature maps and to enable cross-dimensional interaction of salient visual features. Experimental findings show that the improved segmentation model has higher training indicators and better segmentation outcomes than similar networks such as FCN, U-Net, SegNet, PSPNet, DeepLabv3+, and VGG16-UNet semantic segmentation models. Compared with the original VGG16-UNet, the improved network has recorded an increase of 4.91% in the Mean Intersection over Union (MIoU), an increase of 4.98% in Mean Pixel Accuracy (MPA), and an increase of 0.43% in Accuracy, respectively.

Keywords: *clothing image, Efficient Channel Attention (ECA) mechanism, Multi-Level Feature Fusion, Multi-Scale Channel Attention, semantic segmentation, VGG16-UNet network*

O metodă de segmentare a imaginilor cu efect de îmbrăcăminte virtuală

Pe baza mecanismului Atenție Eficientă asupra Canalului (ECA), a fuziunii caracteristicilor pe mai multe niveluri și a mecanismului de atenție a canalelor pe mai multe scări, această lucrare propune o metodă îmbunătățită de segmentare a imaginilor cu efecte vestimentare VGG16-UNet, denumită EF-UNet, care își propune să abordeze problemele legate de etichetele semantice insuficiente, acuratețea scăzută a segmentării locale și marginile de segmentare aspre în imaginile cu efecte vestimentare. În acest scop, un mecanism ECA este mai întâi adăugat la cel de-al cincilea strat al VGG16-UNet pentru a atribui o pondere mai mare și a extrage mai bine informațiile despre caracteristicile țintă pentru a îmbunătăți capacitatea de segmentare a datelor despre îmbrăcăminte. Ulterior, o abordare de fuziune a caracteristicilor pe mai multe niveluri este adoptată într-un decodor pentru a extrage aceste caracteristici de diferite scări într-un mod mai eficient și pentru a îmbunătăți rezultatele segmentării. În cele din urmă, se adaugă un modul de atenție a canalului cu scări multiple la conexiunea de salt pentru a extrage informații spațiale din hărțile de caracteristici cu scări multiple și pentru a permite interacțiunea transdimensională a caracteristicilor vizuale proeminente. Rezultatele experimentale arată că modelul de segmentare îmbunătățit are indicatori de formare mai mari și rezultate de segmentare mai bune în comparație cu rețele similare, cum ar fi FCN, U-Net, SegNet, PSPNet, DeepLabv3+ și modele de segmentare semantică VGG16-UNet. În comparație cu VGG16-UNet original, rețeaua îmbunătățită a înregistrat o creștere de 4,91% a intersecției medii peste unire (MIoU), o creștere de 4,98% a preciziei medii a pixelilor (MPA) și, respectiv, o creștere de 0,43% a preciziei.

Cuvinte-cheie: *imaginea îmbrăcămintei, Mecanismul Atenție Eficientă asupra Canalului (ECA), Fuziunea caracteristicilor pe mai multe niveluri, Atenția asupra canalului pe scări multiple, segmentare semantică, rețea VGG16-UNet*

INTRODUCTION

As a crucial component of computer vision technology, image segmentation automatically divides images into segments based on specific criteria. In the digitalization of the apparel industry, this method not only separates garments from backgrounds but also distinguishes various parts and details within the garments, including patterns. Consequently, it has demonstrated significant potential applications in various aspects of clothing intelligence, such as virtual simulation design [1], virtual fitting [2], and magic mirror displays [3].

Traditional methods for garment image segmentation, such as threshold segmentation [4], edge detection [5], and the region growth method [6], which can meet the needs of conventional clothing region segmentation, but due to the varied changes in clothing styles and the existence of complex backgrounds, texture similarity, deformation wrinkles, and many other difficulties, the precise definition of the region still needs to be further improved. However, with the development of deep neural networks, semantic segmentation methods have emerged, which can significantly improve the accuracy of image segmentation in complex scenes while ensuring efficiency, for example Fully Convolutional Networks (FCN), U-shaped convolutional networks (U-Net), Generative Adversarial Networks (GAN), Convolutional Neural Networks (CNN), Pyramid Scene Parsing Network (PSPNet) [9]. Semantic Segmentation Network (SegNet) and DeepLab v3+ have demonstrated exceptional performance due to ongoing advancements in the field [7, 8]. A Fully Convolutional Network (FCN) for semantic segmentation, achieving pixel-level classification of images. Martinsson et al. significantly improved the segmentation accuracy of clothing images by using a Feature Pyramid Network (FPN) to expand the receptive field and better adapt to target shapes [9]. Furthermore, attention mechanisms in image segmentation techniques have garnered significant attention in recent years. Hu et al. introduced the concept of channel attention mechanism, where the Squeeze and Excitation (SE) module is employed to gather global semantic information and capture inter-channel relationships, thus enhancing the network's learning capability [10]. Additionally, Fu et al. proposed the Dual Attention Network (DANet), which utilizes both location attention and channel attention to capture more comprehensive contextual information [11]. All have automatic feature extraction capabilities, but also suffer from high computational resource requirements, training complexity, and potential computational speed issues.

This paper introduces an improved network based on VGG16-UNet, hereafter referred to as EF-UNet, which incorporates three key enhancements: the addition of Efficient Channel Attention (ECA) mechanism at the end of the encoder, the integration of a multi-level feature fusion module in the decoder, and the inclusion of a multi-scale channel attention module in the skip connection between the encoder and the decoder at the same horizontal layer. Upon creating a garment dataset and training and validating the network, the results demonstrate the improved segmentation accuracy of the EF-UNet for complex edge images.

NETWORK STRUCTURE

Overall structure

VGG16-UNet achieves precise segmentation of input images by combining the robust feature extraction capabilities of the VGG16 convolutional neural network with the segmentation strengths of the U-Net architecture [12]. The enhanced EF-UNet network structure, based on VGG16-UNet, is depicted in figure 1. The left half represents the encoder, while the right half represents the decoder, with skip connections linking corresponding horizontal layers. In the encoding section, the first 13 layers of VGG16 are used to extract features, with a convolution kernel size of 3×3, a stride of 1, and ReLU as the activation function. After four downsampling operations, the input image of size $512 \times 512 \times 3$ is compressed into a $32 \times 32 \times 512$ feature map, effectively concentrating the image's features. The VGG16 encoder uses pre-trained weights from a large dataset and applies transfer learning to accelerate network convergence, shorten training time, and reduce the risk of overfitting. An ECA mechanism is introduced in the fifth layer of the encoder, dynamically learning channel weights and enabling the model to self-adjust its attention, thereby enhancing generalization.

In the decoding section (right half of figure 1), the feature map is gradually upsampled, convolved, and fused at multiple levels, ultimately producing a segmented binary image of the garment at the original size of $512 \times 512 \times 3$. A multi-scale channel attention module is incorporated into the skip connections between the encoder and decoder at each horizontal

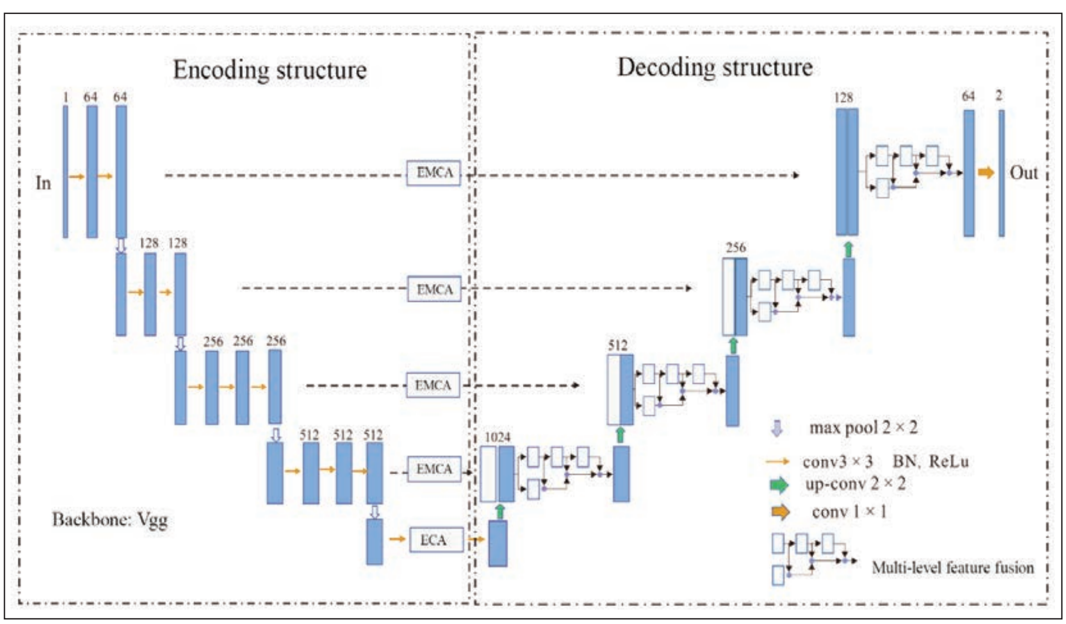


Fig. 1. EF-UNet network architecture diagram

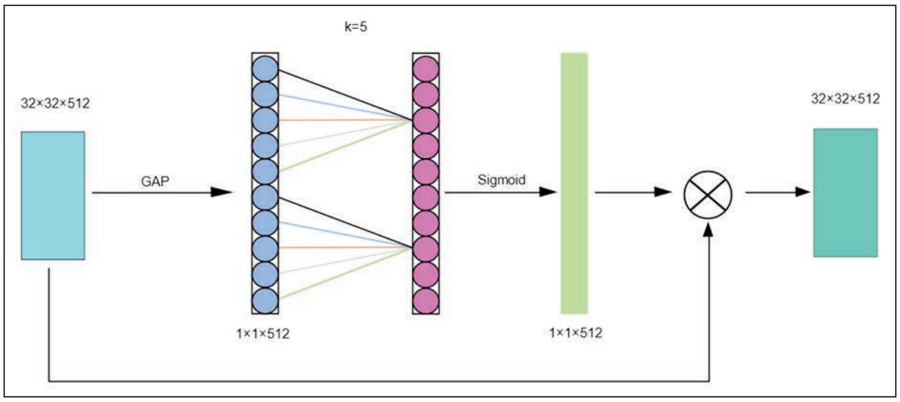


Fig. 2. Diagram of the structure of the ECA Attention Network

of 1, 3, and 5 void rates. The sequential arrangement of different void rates can expand the receptive field of the network without encountering local pixel loss issues, thereby increasing the model's learnable range. The second branch utilizes 1×1 convolutions for data transmission to optimize information flow and reduce the model parameters utilized by the residual structure.

layer, capturing multi-scale contextual information by leveraging feature information from different layers. In summary, EF-UNet enhances VGG16-UNet by integrating advanced attention mechanisms and multi-level feature fusion, resulting in more accurate and efficient image segmentation.

Efficient Channel Attention (ECA) mechanism module

The ECA attention mechanism is a lightweight attention mechanism used to improve the performance of neural networks by tuning the feature response of each channel to reduce the computational load and complexity without changing the dimensionality of the output feature map. Figure 2 illustrates the ECA structure used in this model, which is located after the fifth convolutional layer of the encoder. The attention mechanism first performs mean pooling (GAP) on the input feature map of size $32 \times 32 \times 512$ to obtain a $1 \times 1 \times 512$ tensor, followed by Sigmoid activation function processing of the output tensor, and then multiplies the processed one-dimensional convolutional product with the input feature map, which dynamically weights the input feature map to make the model better focus on the important feature information. Finally, the result of the multiplication is used as an input to the decoder for decoding operations, and the channel attention mechanism is optimized by adding the ECA module, which implements an effective channel attention computation through the steps of global average pooling, 1D convolution, and activation function as a way to improve the segmentation results in image segmentation tasks.

Multi-level Feature Fusion module

During the upsampling process using the VGG16-UNet network, the issue of contextual information loss can be encountered, leading to inaccurate recovery of input image details within deep feature maps. To address this, a multi-level feature fusion method has been introduced to merge different feature layers in the network and capture information features of various scales. The specific network structure is depicted in figure 3.

The multi-level feature fusion module comprises two branches (figure 3). The first branch involves cascades

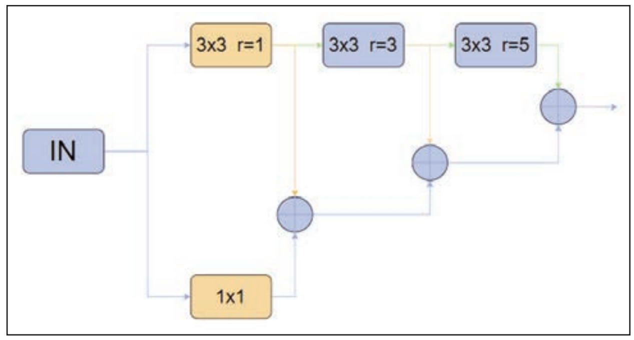


Fig. 3. Multi-level feature fusion network structure diagram

Furthermore, the enhanced model incorporates the concept of residuals for feature superposition. Initially, the convolution result with a void rate of 1 is fused with the second branch, and then the fusion result is combined with the convolution output using a void rate of 3 after cascading. The final layer applies the same residual method, ultimately yielding the result after multiple fusions. The improved module can obtain more feature information, facilitating the segmentation of subsequent models.

Efficient Multi-Scale Channel Attention module

Incorporating an attention mechanism in skip connections helps capture multi-scale contextual information, enhancing the model's ability to accurately segment garment regions by improving detail and global semantic perception. Therefore, this paper proposes the Efficient Multi-scale Channel Attention (EMCA) module (figure 4).

The EMCA attention module in figure 4 is analysed in detail as follows.

1. Firstly, the input tensor undergoes a 1×1 convolution operation followed by batch normalization to obtain (x1).

2. Subsequently, the tensor (x) is processed through convolution blocks with varying dilation rates of 1, 3, and 5, enabling incremental learning of information to produce (x2).

3. The features from both paths are then fused. The fused result is sequentially passed through the GELU

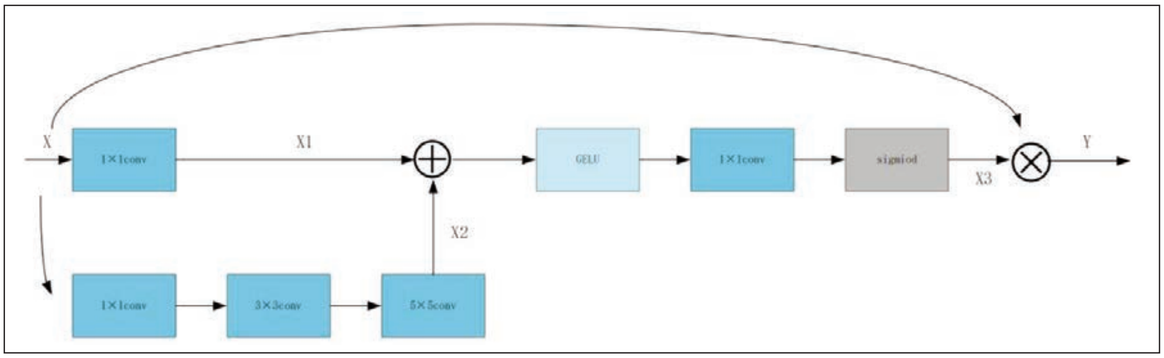


Fig. 4. Efficient Multi-scale Channel Attention Network Architecture Diagram

activation function, a 1×1 convolution, and the Sigmoid activation function to obtain (x3).

4. Finally, the tensor (x3) is multiplied element-wise with the tensor (x) to yield the output value (y).

The attention mechanism utilizes convolution kernels with different dilation rates to capture features at various scales, thereby enhancing image feature extraction and representation capabilities.

Additionally, the introduction of the GELU activation function, known for its smoothness and superior nonlinear expression, increases the algorithm's nonlinearity, mitigates the gradient vanishing problem, and improves the model's analytic performance. The use of residual connections for multi-level feature fusion, where the output and input of the modules are multiplied at the element level, further enhances the model's adaptability and robustness.

EXPERIMENT

Dataset creation

To facilitate the training of the network, this paper collected a dataset comprising 5000 images sourced from different e-commerce platforms. The dataset encompasses eight primary categories: coats, bags, shoes, dresses, pants, tops, skirts, and backgrounds. An 8:2 ratio was adopted for the division of the training set and validation set. Each clothing image in the dataset underwent manual annotation using the LABELME software, resulting in the creation of a labelled dataset conducive to training. Distinct clothing categories are represented by different colours within the dataset. Specifically, the coat is denoted by the grey label, bags are denoted by the red label, shoes are represented by the blue label, dresses are depicted by the dark red label, pants are denoted by the purple label, tops are indicated by the green label, skirts are represented by the deep yellow label, and the background is denoted by the black label.

Network training

This experiment utilizes an NVIDIA GeForce RTX 3090 Ti GPU for training and testing, leveraging CUDA 11.3 to accelerate the training process on the Ubuntu 20.04 operating system. The programming language used is Python 3.8, and the deep learning framework employed is PyTorch1.11.0 to construct the experimental environment. The training strategies adopted in this paper are divided into two main phases: the freezing phase and the thawing phase. During the freezing phase, the backbone network remains frozen for the first 50 epochs, meaning the feature extraction network does not change. The backbone network's learning rate is set to 1e-4, with a batch size of 4, using the Adam optimizer with a momentum of 0.9. In the thawing phase, the backbone network is no longer frozen, allowing the parameters of the entire model to be updated. During this phase, the backbone network's learning rate is adjusted to 10^{-5}, while maintaining the batch size at 4.

Network indicators and comparison

To quantitatively measure the image segmentation performance of the five models, cross-entropy Loss is selected as the loss function in the experiment. Additionally, three commonly used metrics in semantic segmentation – Mean Intersection over Union (MIoU), Mean Pixel Accuracy (MPA), and Accuracy – are adopted to evaluate the segmentation effect of the garment images.

To demonstrate the effectiveness of improved network segmentation, comparisons were made with current mainstream segmentation networks, including U-Net, PSPNet, DeepLabv3+, VGG16-UNet, and EF-UNet. The experimental dataset consisted of a self-constructed garment image dataset. According to the three measurement indicators proposed in this paper and as shown in table 1, the EF-Net algorithm's performance was improved by 4.91%, 4.98%, and 0.43%, respectively, compared to the unimproved VGG16-UNet network. Meanwhile, U-Net exhibited poor segmentation performance on the self-built dataset, whereas DeepLabv3+, PSPNet, and VGG16-UNet showed better segmentation performance. The segmentation performance of the proposed algorithm surpassed that of the four preceding algorithms, with improvements in performance over the PSPNet algorithm by 23.97%, 16.19%, and 5.31%, and over the DeepLabv3+ algorithm by 13.01%, 7.38%, and 3.30%, respectively. Therefore, the algorithm proposed in this paper demonstrates significant advantages over other algorithms in garment semantic segmentation.

Table 1

PERFORMANCE COMPARISON OF DIFFERENT SEGMENTED NETWORKS			
Item	**MIoU**	**MPA**	**Accuracy**
U-Net	32.17%	35.63%	93.14%
DeepLab v3+	57.13%	62.74%	96.27%
PSPNet	46.17%	53.93%	94.26%
VGG16-UNet	65.23%	65.14%	99.14%
Ours	70.14%	70.12%	99.57%

Network effect and comparison

To verify the applicability and effectiveness of the proposed algorithm, this paper uses garment effect diagrams as the prediction images and incorporates FCN and SegNet models in addition to the original comparison models. The experimental results are presented in table 2.

Table 2 illustrates the comparison diagram of different models, including the current mainstream segmentation networks U-Net, SegNet, FCN, PSPNet, DeepLabv3+, VGG16-UNet and the proposed EF-UNet network for comparison. It is observed that the last four types of network segmentation generally outperform the first three. In the first row, the segmentation result obtained from training and predicting with the PSPNet network closely resembles the real image; however, it exhibits larger segmentation errors in the regions of jackets, pants, and shoes. Similarly, using DeepLab v3+ and VGG16-UNet networks for training prediction results in errors in the shoe region. Conversely, the algorithm presented in this paper demonstrates superior segmentation accuracy without any errors. In the second row, both PSPNet and DeepLab v3+ networks exhibit some error in the shoes and skirts area, while VGG16-UNet and the algorithm achieve better segmentation accuracy. Nonetheless, VGG16-UNet still shows some errors in predicting the jacket region. Moving to the third row, the PSPNet network reveals significant segmentation errors at the skirt junction and jacket area, whereas DeepLab v3+, VGG16-UNet, and the algorithm perform better in terms of segmentation. Lastly, in the fourth row, the proximity of pixel values in the trouser and shoe regions leads to lower segmentation accuracy when using PSPNet, DeepLab v3+, and VGG16-UNet for shoes prediction, compared to the algorithm in this paper, which exhibits fewer errors. Consequently, the proposed algorithm is deemed more suitable for accurately segmenting clothing effects in diagrams.

Functional testing of the network and module

Ablation experiments were conducted on the effect diagram dataset to validate the integrity and rationality of the module design proposed in this study

Table 2

EFFECT SEGMENTATION DIAGRAM OF DIFFERENT ALGORITHMS								
	Image	**FCN**	**U-Net**	**SegNet**	**PSPNet**	**DeepLab v3+**	**VGG16-UNet**	**Ours**
1								
2								
3								
4								

Table 3

PERFORMANCE COMPARISON OF DIFFERENT MODULES							
Items	Initial network	ECA	Multi-level feature fusion	EMCA	MIoU	MPA	Accuracy
A	VGG16-UNet	-	-	-	65.23%	65.14%	99.14%
B	VGG16-UNet	+	-	-	65.42%	65.75%	99.12%
C	VGG16-UNet	+	+	-	69.85%	69.73%	99.43%
D	VGG16-UNet	+	+	+	70.14%	70.12%	99.57%

Note: "– / +" indicates not added/added.

(table 3). Firstly, the ECA module was incorporated into experiment A for comparison with the baseline. The inclusion of the ECA module led to an increase in MIoU and MPA by 0.19% and 0.61%, respectively, while the Accuracy showed a marginal decrease of 0.02%. Although the addition of the ECA module improved MIoU and MPA, enhancing the model's efficiency and performance, it resulted in a slight reduction in Accuracy. Subsequently, the multi-level feature fusion module was added in experiment B, MIoU, MPA, and Accuracy increased by 4.43%, 3.98%, and 0.31%, respectively. The introduction of the multi-stage feature fusion module allowed the network to capture more feature information by expanding the receptive field, thereby enhancing the localization information of clothing regions at different scales. Finally, in experiment D, after incorporating the MSFS module, the experimental indices MIoU, MPA, and Accuracy were further improved by 0.29%, 0.39%, and 0.14%, respectively, compared to experiment C. Notably, experiment D exhibited the highest values for MIoU, MPA, and Accuracy, demonstrating superior network segmentation performance. In summary, it can be concluded that Experiment D has the best network segmentation performance. Compared to Experiment A, the MIoU, MPA and Accuracy were improved by 4.62%, 4.59%, and 0.29%, respectively.

CONCLUSION

In this paper, an improved network of the VGG16-UNet network, named EF-UNet, is proposed to solve the problems of poor local segmentation accuracy and rough segmentation edges in garment images. This improvement is realized by adding an ECA attention mechanism at the end of the encoder, a multilevel feature fusion module in the decoder, and a multiscale channel attention module at the skip connections between the encoder and the decoder at the same horizontal layer. Experimental results validate the effectiveness of these improvements, demonstrating that EF-UNet delivers more accurate and robust segmentation outcomes compared to existing models. The manually labeled dataset will be affected by more subjective factors, which will lead to less accurate labeling results. networks such as U-Net, DeepLab v3+, PSPNet, etc. will encounter problems such as overfitting, large computation volume, and training complexity during training etc. The EF-UNet proposed in this paper significantly improves segmentation capability compared with other mainstream network structures.

By combining the ECA mechanism, multi-level feature fusion and multi-scale channel attention mechanism, EF-UNet can be applied in a garment fitting system to improve the image segmentation accuracy, which will promote the innovation and development of image segmentation technology. However, this paper also has certain shortcomings and limitations. Firstly, an efficient image segmentation model usually requires a large amount of labelled data for training, the data in this paper is mainly trained for clothing images, there are limitations in image types and the dataset is limited, and future research will further increase the segmentation of other types of images such as hats and gloves. Secondly, the network algorithms are updated and iterated at such a fast speed that it is necessary to continuously optimize the algorithms and improve the technology to ensure the effectiveness and reliability of its network structure.

ACKNOWLEDGEMENTS

This study was supported by the Artificial Intelligence Promotion Programme of the Shanghai Municipal Education Commission (Project No: 0239-A1-5300-24-13002).

REFERENCES

[1] Meng, Y., Mok, P.Y., Jin, X., *Interactive virtual try-on clothing design systems*, In: Computer Aided Design, 2010, 42, 4, 310–321

[2] Huang, S., Huang, L., *CLO3D-based 3D virtual fitting technology of down jacket and simulation research on dynamic effect of cloth*, In: Wireless Communications and Mobile Computing, 2022, 2, 1–11

[3] Badrinarayanan, V., Kendall, A., Cipolla, R., *Segnet: A deep convolutional encoder-decoder architecture for image segmentation*, In: IEEE Transactions on Pattern Analysis and Machine Intelligence, 2017, 39, 12, 2481–2495

[4] Liu, D., *Fabric Cutting Based on Iterative Thresholding Algorithm for Image Segmentation and Local Analysis,* Dissertation Thesis, 2010

[5] Li, Y., Jiang, L., Li, X., Feng, W., *Non-contact clothing anthropometry based on two-dimensional image contour detection and feature point recognition*, In: Industria Textila, 2023, 74, 1, 67–73, http://doi.org/10.35530/IT.074.01.202279

[6] Renzhong, L., Yangyang, L., Man, Y., Huanhuan, Z., *Three-dimensional point cloud segmentation algorithm based on improved region growing*, In: Laser & Optoelectronics Progress, 2018, 55, 5, 051502

[7] Chen, H., Shen, L., Zhang, X., Ren, X., Wang, M., Min, X., Li, X., *Digital design of regional characteristic apparel pattern driven by GAN*, In: Industria Textila, 2022, 73, 3, 233–240, http://doi.org/10.35530/IT.073.03.202117

[8] Li, T., Lyu, Y.-X., Ma, L., Xie, Y., Zou, F.-Y., *Research on garment flat multi-component recognition based on Mask R-CNN*, In: Industria Textila, 2023, 74, 1, 49–56, http://doi.org/10.35530/IT.074.01.202199

[9] Martinsson, J., Mogren, O., *Semantic segmentation of fashion images using feature pyramid networks*, IEEE, 2019, 0-0

[10] Hu, J., Shen, L., Sun, G., Albanie, S., *Squeeze-and-excitation networks*, In: IEEE Transactions on Pattern Analysis and Machine Intelligence, 2017, 7132-7141

[11] Fu, J., Liu, J., Tian, H., Li, Y., Bao, Y., Fang, Z., *Dual Attention Network for Scene Segmentation*, In: 2019 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), IEEE, 2020, 3146–3154

[12] Liu, X., Li, B., Chen, X., Zhang, H., Zhan, S., *Content-based attention network for person image generation*, In: Journal of Circuits, Systems and Computers, 2020, 29, 15, 2050250

Authors:

RUIHONG CHEN, JIEKAI YU, YU CHEN, ZENGBO XU

School of Textiles and Fashion, Shanghai University of Engineering Science, 201620, Shanghai, China
e-mail: 2321989826@qq.com,1343945491@qq.com

Corresponding author:

YU CHEN
e-mail:ychen0918@sues.edu.cn

From Hardship to Hope: the role of Cultural Intelligence to promote workplace harmony in the Indian garment industry

DOI: 10.35530/IT.076.02.202482

AALIYA ASHRAF
NANCY SAHNI
RAMONA BIRAU
DANIEL FRANK
GOKARNA VIDYA BAI

SUHAN MENDON
LUCIA PALIU-POPA
GABRIEL NICOLAE PRICINĂ
COSMIN MIHAI PRICINĂ

ABSTRACT – REZUMAT

From Hardship to Hope: the role of Cultural Intelligence to promote workplace harmony in the Indian garment industry

Migrants often encounter circumstances that call for the use of cultural intelligence (CQ), or the ability to communicate effectively with people from different cultural backgrounds. Empirical evidence suggests that developing cultural intelligence improves migrant workers' general well-being and aids in their adjustment to new environments. The purpose of this research endeavour is to explore the impact of cultural intelligence variables like cultural intelligence strategy, knowledge, motivation and behaviour with a mediating role of multicultural workforce on workplace harmony. The study employed a cross-sectional research design and implemented a convenience-sampling technique to collect primary data through nine months from March 2023 to November 2023 through a well-structured questionnaire, which was circulated among 358 migrant women workers from readymade garment industries in the Indian states of Karnataka and Punjab. Data was collected through a structured questionnaire and analysed using Partial Least Squares-Structural Equation Model. Hypothesis shows that cultural intelligence and multicultural workforce have a significant influence on workplace harmony. The results of IPMA and PLS-MGA analysis show the similarity in the results of total effect and path relationships. This study provides theoretical foundations and empirical findings on conceptualizing the antecedents of workplace harmony. The outcomes of this research serve as significant input to policymakers and readymade garment industries to facilitate the enhancement multicultural workforce to achieve workplace harmony.

Keywords: *migrants, well-being, strategy, multicultural workforce, empirical evidence, cultural intelligence*

De la dificultăți la speranță: rolul inteligenței culturale în a promova armonia la locul de muncă în industria de îmbrăcăminte din India

Migranții se confruntă adesea cu circumstanțe care necesită utilizarea inteligenței culturale (CQ) sau capacitatea de a comunica eficient cu persoane din medii culturale diferite. Dovezile empirice sugerează că dezvoltarea inteligenței culturale îmbunătățește bunăstarea generală a angajaților cu statut de migranți și ajută la adaptarea acestora la noile medii. Scopul acestui studiu de cercetare este de a explora impactul variabilelor inteligenței culturale, cum ar fi strategia de inteligență culturală, cunoștințele, motivația și comportamentul, cu un rol de mediere al forței de muncă multiculturale asupra armoniei la locul de muncă. Studiul a folosit un design transversal de cercetare și a implementat o tehnică de eșantionare convenabilă pentru a colecta date primare pe o perioadă de nouă luni, din martie 2023 până în noiembrie 2023, cu ajutorul unui chestionar bine structurat, care a fost distribuit în rândul a 358 de muncitoare migrante din industria de îmbrăcăminte din statele indiene Karnataka și Punjab. Datele au fost colectate pe baza unui chestionar structurat și analizate folosind modelul Partial Least Square-Structural Equation Model. Ipoteza arată că inteligența culturală și forța de muncă multiculturală au o influență semnificativă asupra armoniei la locul de muncă. Rezultatele analizei IPMA și PLS-MGA arată similitudinea dintre rezultatele efectului total și relațiile de tip pattern. Acest studiu de cercetare oferă baze teoretice și constatări empirice privind conceptualizarea antecedentelor armoniei la locul de muncă. Rezultatele acestei cercetări servesc drept contribuție semnificativă pentru factorii de decizie politică și pentru industriile de îmbrăcăminte pentru a facilita îmbunătățirea forței de muncă multiculturale pentru a atinge armonia la locul de muncă.

Cuvinte-cheie*: migranți, bunăstare, strategie, forță de muncă multiculturală, dovezi empirice, inteligență culturală*

INTRODUCTION

Women are migrating in greater numbers and with more varied experiences. It is essential for promoting shared wealth, reducing poverty, and furthering human development. The number of educated working-age female migrants has increased in many countries due to global advancements in women and girls' education as well as the growing demand for skilled labour in fields where women predominate. The likelihood for women migrant workers to contribute significantly to development is highlighted by this trend, which is referred to as the feminization of migration [1]. The financial impact of the remittances made by migrants is frequently the focus. In many developing countries, these remittances sometimes outweigh foreign direct investment and foreign development aid. This has raised interest in utilising labour migration for economic growth. Women migrants also typically send home a greater percentage of their earnings regularly. About half of the $601 billion in global remittances transmitted through formal channels, as estimated by the World Bank, come from female migrants who remit a sizable share of their salaries. About half of remittances from migrant workers in countries like Nepal, where they work primarily in domestic roles, come from these workers and make up roughly 23% of the GDP.

Every Indian citizen is entitled to freedom of movement and the ability to look for work anywhere in the nation under the terms of the Indian Constitution. Potential migrants, however, can balance the advantages and disadvantages of moving, taking into account several social, political, and economic aspects. India's changing demographics have been greatly impacted by migration, which has a variety of repercussions. However, there is no complete policy framework in place to deal with these implications. Though there are regional variations, it is important to note that women often show higher rates of labour market involvement following migration than they did prior [2]. Women migrate for a variety of reasons, such as urbanisation, industrialization, better infrastructure, more employment possibilities, marriage, pursuing higher education, and social issues. Nonetheless, the post-migration industry distribution of female migrants closely resembles the industrial distribution of India's female workforce as a whole. Unplanned migration can frequently have a negative impact on the economy. A study on the benefits of circular movement offered evidence of higher earnings, less reliance, and higher returns for people with strong social networks or skill sets [3]. Innovations in communication and transportation are also driving an increase in interstate movement, which is consistent with the worldwide trends of industrialization and urbanization.

The workforce must change if the textile and garment sectors are to remain competitive as they become more globally integrated. Professionals in various fields today need to be able to recognize and negotiate cultural differences as well as different points of view on a global scale. This is especially important because they are essential in managing the complex supply chain operations that often span international borders [4]. The workforce must be able to encourage successful communication, cooperation, and management across diverse cultural contexts due to the industry's dynamic nature. Furthermore, professionals working in the textile and clothing industries need to be able to adjust to and understand the subtleties of different foreign markets because they play a crucial role in ensuring the smooth coordination of activities within the global supply chain. This change emphasizes how crucial it is to develop a workforce that can fulfil the demands of an increasingly diversified and linked industry landscape by possessing both technical expertise and intercultural competence. Students at universities who want to work in these fields need to get the knowledge and abilities necessary to succeed in this fast-paced, international setting. Teachers must provide learning opportunities that enable students to meet the demands of the modern workforce and achieve their professional goals.

Comprehensive and innovative curricula are required by academic institutions to prepare students for the worldwide textile and apparel sectors. This entails combining technical expertise with a thorough comprehension of global issues, cultural quirks, and shifting trends in the sector. To promote successful communication and collaboration throughout the supply chain, professionals must be aware of and sensitive to the cultural quirks inherent in different geographical areas, according to Hodges et al. [4]. Globally, the textile sector serves a wide range of consumer demands. It is crucial to comprehend cultural variances while creating items that appeal to particular consumers. Cultural intelligence allows organizations to better cater to local interests and preferences, which increases market acceptance [5]. Research conducted in 2007 by Ang et al. revealed a favourable relationship between job satisfaction and cultural intelligence. Higher cultural intelligence levels enable textile sector workers to handle cross-cultural relationships more skilfully, which enhances the work environment. Earley and Peterson [6] highlight in their research how crucial good cross-cultural communication is to raising job satisfaction. Professionals in the textile sector with high levels of cultural intelligence are better able to communicate with people from different cultural backgrounds, which lowers miscommunication and boosts satisfaction at work. According to Rockstuhl et al. [7], cultural intelligence positively influences teamwork and collaboration in multicultural settings. In the textile industry, where global teams are common, employees with high cultural intelligence contribute to cohesive and harmonious teams, leading to higher levels of job satisfaction.

REVIEW OF LITERATURE

Technique used to measure students' "Cultural Intelligence" (CQ) both before and after they participated in the learning activities to assess the project's effect on their global competency. The term "Cultural Intelligence" (CQ) is a modern notion that was first used in the literature on international business in the early 2000s [8]. Cultural Intelligence (CQ) integrates the concept of intelligence by being based on the attitudes, values, and behaviours that are moulded by cultural environments. It is a type of social intelligence that allows people to successfully negotiate a variety of cultural contexts, each with its own unique set of cultural norms [9]. The idea of cultural quotient (CQ) has become better known in the literature because it emphasizes the capacity to adjust and engage productively in a range of cultural contexts. Additionally, scholars highlight the dynamic character of CQ, speculating that it entails ongoing learning and cultural sensitivity [10]. The complex components of CQ include motivation, strategy, metacognition, and cultural knowledge. These elements all play a part in an individual's capacity to perform well in cross-cultural encounters [8]. This approach emphasizes the significance of both cultural knowledge and the capacity to use that understanding in real-world, cross-cultural scenarios, which is consistent with the developing nature of global competence.

A theoretical framework for Cultural Intelligence (CQ) was developed by Thomas et al. [11], who distinguished three essential elements of CQ: behaviour, mindfulness, and knowledge. To be labelled as culturally intelligent, people need to have the following skills: The model integrates behavioural, perceptual, and cognitive factors that are critical for navigating a variety of cultural situations, emphasizing the complexity of Cultural Intelligence (CQ). This entails (i) understanding cross-cultural occurrences, (ii) paying attention to detail and using discernment while seeing and analysing particular circumstances, and (iii) having the capacity to modify behaviour in various contexts [11]. Academic consensus is that Cultural Intelligence (CQ) is a skill that develops gradually via experiences in cross-cultural interactions. A conceptual framework outlining the stages of the development of Cultural Intelligence (CQ) was put forth by Thomas et al. [12]. These stages are as follows: (i) initial openness to outside stimuli; (ii) recognition of different cultural norms and a desire to learn more; (iii) integration of new cultural norms and regulations into one's cognitive framework; and (iv) conversion of different cultural norms into alternative behaviours and (v) reaching the highest level of CQ, characterized by proactive cultural behaviour resulting from the recognition of evolving cues not apparent to others [12]. Thomas highlights the cumulative character of these developmental phases, claiming that people's total CQ capacities rise as they move through the phases. This viewpoint emphasizes how cultural intelligence is a skill that can be developed and enhanced over time, and how it is dynamic and ever-evolving.

Cultural Intelligence and multicultural strategies

Previous studies have highlighted a variety of proactive steps that people who are unfamiliar with a social setting take to facilitate their assimilation process [13]. These behaviours cover a wide range of tactics used to promote adjustment and assimilation in unfamiliar social environments. Studies show that people who are unfamiliar with a social environment use strategies like observation, data collection, feedback request, networking, job negotiation [14], and relationship building [15]. Cooper-Thomas and Burke [13] grouped these many approaches into three main themes based on interviews with eighty-six experienced novices: (i) changing roles or surroundings, (ii) learning new information or improving oneself, and (iii) encouraging reciprocal progress. According to Cooper-Thomas and Burke [13] self-initiated "change role or environment" strategies include actions like task minimization (doing work that closely matches one's abilities and expertise to improve performance), demonstrating competence (proving one's skills through hard work), offering support (giving colleagues advice or information), and modelling others (adopting behaviours and work approaches observed in others). These tactics are the result of newcomers' conscious attempts to mould their environments and positions for maximum effectiveness and integration.

H_1: Cultural Intelligence significantly influences the development of multicultural strategies in the workplace with a multicultural workforce.

Cultural Intelligence and multicultural knowledge

Perceived coherence is important since team members are free to decide how much and what kind of information they share. Sharing information is another important aspect [16]. Seven-step framework for experiential Cultural Intelligence (CQ) education, which is described in length in chapter three. This training regimen's last phases include "feedback and communication" and "group discussion and social sharing". These actions emphasize the value of candid communication and cooperative discussion within groups, which promotes the sharing of knowledge, expertise, and cultural viewpoints. Collaborative Cultural Intelligence (CQ) learning can be very beneficial for heterogeneous teams for two key reasons. First, people can share experiences and insights rather than depending only on their own CQ growth. Second, developing collective cultural intelligence helps the multicultural team's interpersonal relationships and teamwork become more cohesive. This cooperative approach enhances team performance and synergy by fostering a common awareness and appreciation of cultural diversity in addition to enriching individual learning experiences. Understanding these subtleties of communication can reduce miscommunication and encourage knowledge sharing. Cultural experiences also shed light on people's preferred methods of knowledge sharing; some people may suppress information and only divulge it to those in positions of authority, while others may favor egalitarian exchanges.

H_2: Cultural Intelligence significantly influences in gain of multicultural knowledge in the workplace with a multicultural workforce.

Cultural Intelligence and motivation in multicultural organizations

Cultural intelligence facilitates a profound comprehension and admiration of varied viewpoints, principles, and modes of communication. High CQ personnel in an organization are more likely to see and appreciate the subtle cultural differences among their peers. Regardless of their cultural background, employees need to feel included and like they belong, and this understanding helps to foster those feelings [10]. Effective interpersonal relationships and communication across cultural barriers are facilitated by high CQ levels. Employees who acknowledge and value differences are less likely to encounter miscommunications or disputes brought on by cultural differences. As a result, a peaceful workplace is established, which boosts motivation since people feel appreciated and understood [7]. Team members with different cultural origins may work together and trust each other more when they possess cultural intelligence. High Cultural Intelligence multicultural organizations frequently demonstrate a stronger inclination toward innovation and creativity. When people are free to share their special perspectives and ideas without worrying about being judged or marginalized, they are more likely to be motivated [17]. Programs for developing leaders that aim to raise managers' and executives' Cultural Intelligence can be put into place by organizations. Leaders may cultivate an inclusive and motivating culture across the entire organization by providing them with the skills they need to effectively negotiate cultural diversity [11].

H_3: Cultural Intelligence significantly motivates a multicultural workplace with a multicultural workforce.

Cultural Intelligence and adopting multicultural behaviours

The ability to exhibit appropriate verbal and nonverbal behaviours during cross-cultural contacts, such as employing language and gestures that are appropriate for the culture in question, is known as behavioural cultural intelligence, or CQ. These four components – metacognitive, cognitive, motivational, and behavioural – have different qualitative qualities, but taken as a whole, they represent the whole range of abilities needed for people to successfully negotiate and function in culturally heterogeneous environments [8]. People who have high Cultural Intelligence (CQ) are better able to gather and process information, draw conclusions, and respond cognitively, emotionally, or behaviourally to cultural cues in multicultural work settings [8, 18]. As such, they have an innate knowledge of proper conduct standards to reduce or eliminate cross-cultural miscommunication and promote constructive relationships in culturally diverse workplaces [11]. Furthermore, people with higher CQ tend to modify their decision-making procedures, communication methods, and approaches to problem-solving to conform to different cultural contexts. According to Ang et al. [10], people with high levels of Cultural Intelligence (CQ) have a greater comprehension of cultural frameworks, which helps them to correctly interpret cultural schemas, choose when and how to apply them, and actively learn new cultural norms continually.

H_4: Cultural Intelligence significantly influences in adoption of multicultural behaviours in the workplace with a multicultural workforce.

Cultural Intelligence strategies and workplace harmony

The various cultural views, habits, and traditions that various employee groups hold represent a substantial obstacle in multicultural management. Insufficient communication that takes cultural sensitivity into account can lead to employee dissatisfaction and conflict, creating internal barriers that limit overall productivity [19]. Minority groups may feel that some sectors are trying to impose their ideologies on them because their cultural values are not as strongly reflected in them. Misunderstandings and animosity often follow in these situations. To surmount these obstacles, institutions must foster strong intersectoral communication and cooperation while proactively tackling cultural disparities to guarantee a thorough comprehension and appreciation of one another's cultural perspectives [19]. Gaining knowledge of cultural differences helps foster understanding between people, which will improve the working environment as a whole. Consequently, this helps to build an organization that is more flexible and able to handle a range of problems. Collaboration and effective cross-cultural communication are essential to creating a peaceful and adaptable work environment. This proactive approach emphasizes how crucial it is to use diversity and cultural understanding within the workforce to navigate difficult business situations and meet the needs of a wide range of stakeholders.

H5: Cultural Intelligence Strategy significantly influences the workplace with a multicultural workforce to maintain workplace harmony.

Cultural Intelligence, knowledge and workplace harmony

There has been a great deal of discussion about knowledge sharing in higher education over the past 20 years, as research by Fullwood et al. [20]. But as Bhatti et al. [21] point out, not much thought has gone into researching how multicultural workers at higher education institutions (HEIs) share information. Firms that effectively manage their human capital have a significant competitive advantage over those that do not. Knowledge sharing is closely related to human capital. Furthermore, a culture of knowledge sharing fosters lifelong learning and growth, producing a workforce that is more adaptable to change and skilled at utilizing new trends and technology. Lum et al. [22] emphasize that for social workers to effectively serve multicultural clients, they must cultivate a repertoire of knowledge and skills rooted in cultural competence. This journey towards cultural proficiency commences with the exploration and comprehension of one's personal and professional cultural awareness.

H_6: Cultural Intelligence Knowledge significantly influences the workplace, as the multicultural workforce needs to maintain workplace harmony.

Cultural Intelligence, motivation, and workplace harmony

Motivational cultural intelligence (CQ) is defined by Ang et al. [10] as having two main components: cross-cultural self-efficacy, which refers to the belief that one can successfully navigate culturally heterogeneous environments, and cross-cultural intrinsic motivation, which refers to an innate curiosity and interest in different cultures. This construct highlights people's capacity to interact meaningfully and adaptably across cultural divides, motivated by a sincere interest in cultural variances as well as a sense of efficacy. People who possess high motivational cultural intelligence (CQ) are more likely to concentrate their attention and energy on cross-cultural interactions because they are naturally curious and have a strong sense that they can successfully negotiate a variety of cultural contexts [10]. As evidenced by the correlation between this propensity for cross-cultural engagement and better performance on intercultural tasks [8], people with higher motivational CQ are likely to be more successful in cross-cultural settings. People with high motivational CQ have an innate interest in different cultures [10]. Their proactive attitude to cross-cultural relationships is motivated by their self-assurance, which gives them the courage to confront obstacles and take advantage of possibilities in a variety of cultural situations. Their tenacious endeavours and proactive involvement highlight their dedication to cultivating significant cross-cultural connections and attaining reciprocal comprehension within multicultural environments.

H_7: Cultural Intelligence significantly motivates the workplace with a multicultural workforce to maintain workplace harmony.

Cultural Intelligence behaviour and workplace harmony

A multicultural workforce that exhibits intercultural behaviour cultivates a vibrant atmosphere full of many viewpoints, experiences, and ideas. According to research, being exposed to a variety of perspectives fosters originality and creativity. Workers with diverse [23] cultural origins contribute special perspectives and methods of problem-solving that result in the creation of original answers to challenging issues [24]. Multicultural behaviour promotes the development of cultural competence, which is the capacity to comprehend, value, and communicate with others from a variety of cultural backgrounds. Organizations that foster intercultural behaviour and have a diverse workforce are better able to handle cultural variety on a national and international level in the modern, globalized economic world. According to Caligiuri and Lazarova [25], companies that exhibit enhanced flexibility to a variety of markets, client demands, and global trends are ultimately better positioned to compete in the global economy.

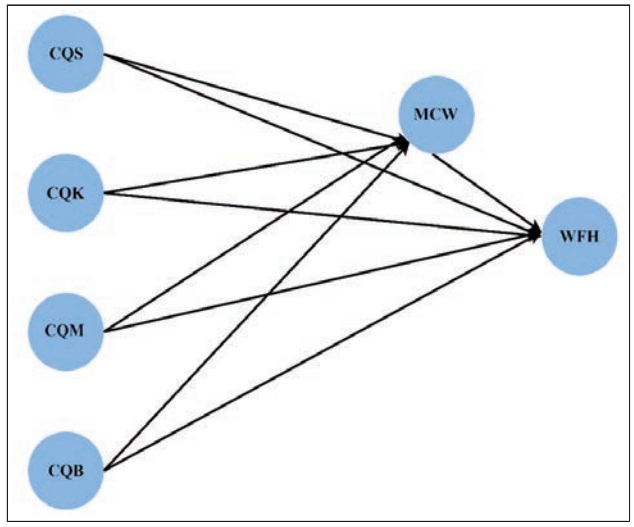


Fig. 1. Conceptual framework

H_8: Cultural Intelligence significantly influences the worker behaviour in a multicultural workplace, leading to workplace harmony.

Multicultural workforce and workplace harmony

Diverse viewpoints, life experiences, and approaches to problem-solving are frequently brought to the table by multicultural teams. According to Cox et al. [26] research, diversity encourages creativity and innovation because people with varied cultural origins can provide fresh perspectives and ideas that result in original solutions. More diverse workers may result in more comprehensive decision-making procedures. The quality of choices and results can be improved by this deliberate process. Employees who work in multicultural environments are more likely to become culturally competent and sensitive. According to Adler [27], being exposed to a variety of viewpoints aids in people's understanding and appreciation of cultural diversity, which promotes an inclusive and courteous work environment. Higher levels of worker engagement can be fostered by an inclusive and varied workplace where staff members feel valued and acknowledged for their unique contributions [28]. When workers feel that their identities and viewpoints are valued, they are more likely to be committed to both their job and the success of the company. Acknowledging diversity and unique perspectives can boost employee engagement and dedication to the organization's goals [28].

H_9: Multicultural workplace significantly influences workplace harmony in multicultural workplace.

EMPIRICAL SETTING AND PROCEDURE OF TESTING

This research work is highly focused on the role of Cultural Intelligence (CQ) to promote Workplace Harmony (WFH) in the readymade garment industry, with a focus on migrant women workers and empirically validates the formulated hypothesis. The reason for the study is manifold. First, Cultural Intelligence (CQ) has a major impact on industries multicultural strategy, knowledge, motivation and behaviour as people have diverse cultural backgrounds, which has its relevance and impact on the workplace. Second, multiculturalism involves values and beliefs that migrant workers bring from different geographical locations, like ethnic diversity, language, religion, and value systems, which will have a concrete impact on workplace performance. Third, cultural intelligence in decision-making encourages a multicultural workforce, promoting cultural awareness and tolerance among workers, leading to workplace harmony. Despite the desperate need for a multicultural workforce, there is very limited research on these parameters, making our study relevant to the present working conditions.

Sample and data description

Sampling frame for any research needs to be complete, accurate and up to date. In the absence of such a sampling frame, convenience sampling was adopted. Care has been taken to ensure representativeness and reduction of bias by keeping an audit trail during the data collection stage and by making conscious efforts to select samples with homogeneous attributes. The primary data collection was made through nine months from March 2023 to November 2023 through a well-structured questionnaire, which was circulated among 358 migrant women workers from the readymade garment industries in the Indian states of Karnataka and Punjab. The study used the following inclusion criteria for the sampling unit.

(i) Women working in readymade garment factories who are not the permanent residents of Karnataka and Punjab &

(ii) Temporary, permanent and contract women workers above the age of 18 years.

The instrument consists of a non-comparative-detailed rating scale utilizing a 5-point Likert scale, with 5 – Strongly agree and 1 – Strongly disagree, depending on the type of questions. The data collection procedure is based on the cross-sectional method using second-generation software, Smart PLS-4.0, for data analysis.

Measures

The exogenous construct Cultural Intelligence (CQ) is measured reflectively through the four influencing factors, ie., Cultural Intelligence Strategy (CQS) with three indicators, Cultural Intelligence Knowledge (CQK) with six indicators, Cultural Intelligence Motivation (CQM) with four indicators and Cultural Intelligence Behaviour (CQB) with four indicators. The mediating variable, Multicultural Workforce (MCW), is measured with three indicators and the dependent variable Workplace Harmony (WFH) with three indicators.

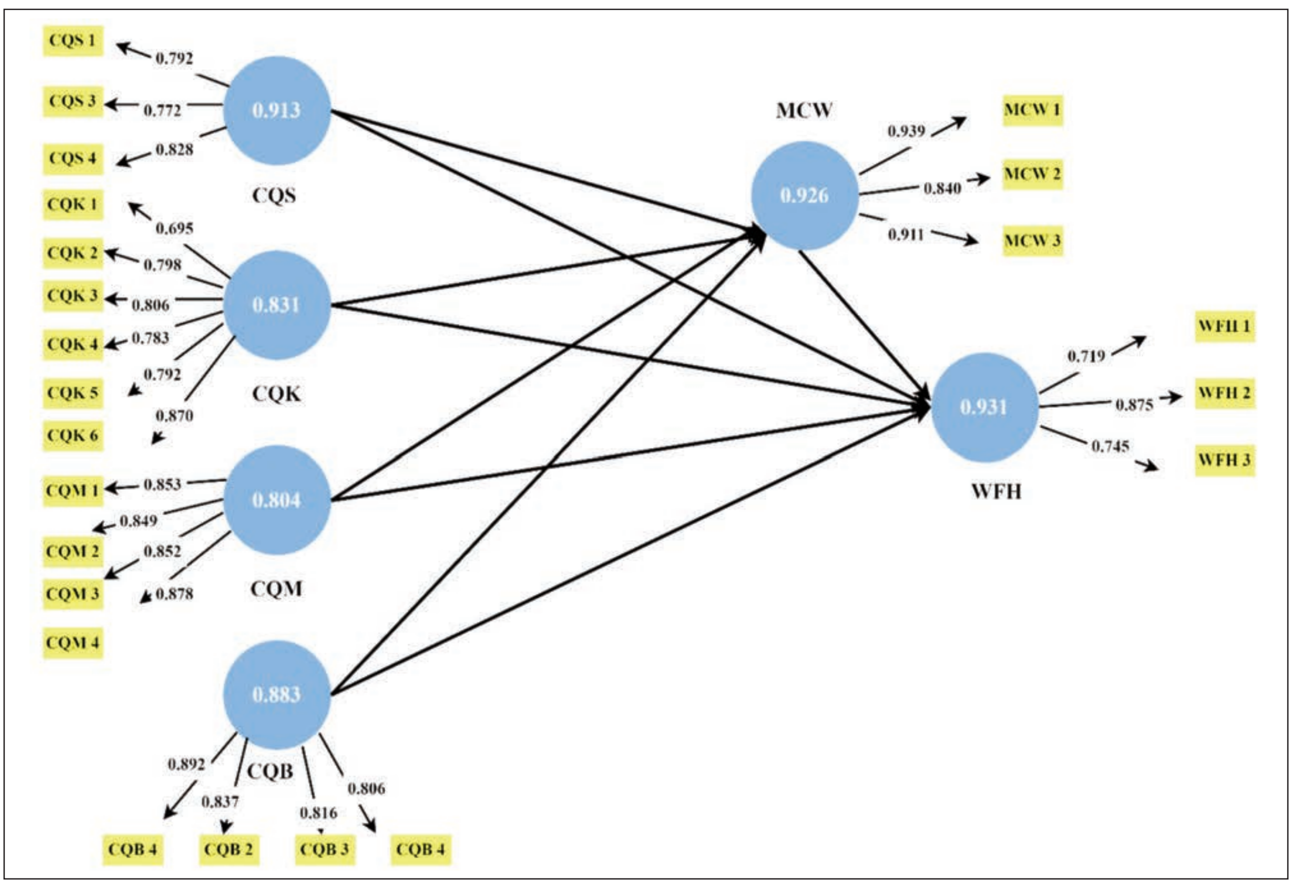


Fig. 2. Measurement model: Reliability

Table 1

MEASUREMENT MODEL EVALUATION							
Constructs	**Indicators**	**Outer loading**	**Composite reliability**	**AVE**	**Cronbach's alpha**	**Outer weight**	**VIF**
MQS	CQS1	0.792***	0.913	0.679	0.889	0.222***	1.982
	CQS3	0.772***				0.203***	2.006
	CQS4	0.828***				0.268***	2.453
MQK	CQK1	0.695***	0.831	0.796	0.863	0.352***	2.316
	CQK2	0.798***				0.268***	2.919
	CQK3	0.806***				0.374***	1.079
	CQK4	0.783***				0.458***	3.745
	CQK5	0.792***				0.281***	2.372
	CQK6	0.870***				0.261***	3.019
MQM	CQM1	0.853***	0.804	0.736	0.812	0.257***	2.473
	CQM2	0.849***				0.202***	2.941
	CQM3	0.852***				0.209***	2.738
	CQM4	0.878***				0.225***	3.273
MQB	CQB1	0.892***	0.883	0.715	0.821	0.456***	1.929
	CQB2	0.837***				0.378***	1.715
	CQB5	0.816***				0.238***	2.016
	CQB7	0.806***				0.344***	1.619
MCW	MCW1	0.939***	0.926	0.806	0.897	0.375***	3.697
	MCW2	0.840***				0.317***	2.087
	MCW3	0.911***				0.418***	2.808
MFH	MFH1	0.719***	0.931	0.694	0.919	0.185***	2.404
	MFH2	0.875***				0.218***	3.006
	MFH3	0.745***				0.157***	1.944

Note: *** p<0.01, ** p<0.05 and * p<0.10.

Various thumb rules explain and analyse if the observed r^2 values are high [29]. According to prior studies, the identified threshold cut-off values for endogenous constructs are 0.2 for ‘weak', 0.50 for ‘moderate' and 0.75 for ‘high'. Figure 2 depicts the loadings of all the marked indicators of the measurement model.

Testing methods and procedure

PLS-SEM is considered an appropriate tool for this research work [29] using the software Smart PLS 4 for data analysis [30]. Among the different weighting schemes that Smart PLS provides for algorithm settings, we have chosen the structural model as a weighing method for conducting the data analysis. Raw data transformation is chosen for facilitating the incorporation of standardized data for indicators [29] to facilitate algorithms convergence, this researcher has chosen the stop criterion of $1 \cdot 10^{-5}$, which is also the threshold value for the purpose. The maximum number of iterations chosen is 300.

There are varying rules of thumb that explain whether r^2 values are high or not [29]. There is no distributional assumption. Therefore, this researcher has conducted a non-parametric test. Accordingly, the non-parametric bootstrapping procedure is invoked. Therefore, this research work has adopted the following bootstrapping routine.

- The total number of valid samples is 385. 5000 bootstrap samples are invoked to run the PLS-SEM algorithm by following the rule of thumb.
- Empirical t-values and theoretical/critical t-values are compared with each other for the two-tailed test. The critical t-value, which is used for comparison, is 1.96.
- To obtain the empirical t-values, the ‘no sign change' option is used.
- Bootstrapping confidence intervals is also duly reported.

Composite reliability, also known as internal consistency reliability, is considered a measure of composite reliability. The threshold value of internal consistency reliability should be equal to or greater than 0.8 [31] which has been established in the present work. For a reflective model, the threshold value of path loadings should be above 0.7 [32]. The threshold value of outer loadings of all indicators is above 0.7 (table 1), indicating that the indicators of all constructs have acceptable levels of outer loading. The Average Variance Extracted (AVE) is a strongly recommended test to measure convergent validity with a threshold value of more than 0.50. AVE values of all constructs of the study are above the threshold value of 0.5 (table 1). Therefore, there exists convergent validity in all exogenous and endogenous latent constructs. PLS is a better way to measure the discriminant validity, where the square of the correlations among the variables has been in contrast with the AVE [33]. Fornell-Lacker's (1981) criterion is the best way to measure the discriminant validity, which is a comparison between the square root of AVE and other latent variables.

The collinearity levels among constructs of the study are tested. Following the Variance Inflated Factors (VIF) guidelines. All predictor variables showed VIF levels below 5.00 (table 1). This suggests that there is no collinearity in the structural model of the study. To calculate the predictive relevance of the model, the study adopted a blindfolding procedure where samples are used repeatedly by the omission of every 7th data point of the data set of endogenous constructs. This procedure is adopted for only those endogenous constructs that have a measurement specification of the reflective type. The blindfolding process calculates the parameter estimates to assess predictive relevance, i.e. q^2. This study has used the cross-validated redundancy method to calculate the q^2 value, which is a gauge of the predictive relevance of the model with a value larger than zero [29]. Suggested to compute Stone-Geisser's q^2 value [34, 35] for understanding the model's predictive relevance. After running the blindfolding procedure, our study arrived at the values of q^2 (table 3). All values of q^2 are above zero, which indicates that the model of this research endeavour has predictive relevance.

RESULTS

Evaluation of measurement and structural model

The evaluation of the reflective model includes a validation of outer loading, composite reliability, Cronbach's alpha, AVE, outer weight and variance inflation are validated in this model (table 1). The Fornell-Lecker criterion [29, 33] is used to measure the discriminant validity (table 2). The discriminant validity values in this reflective construct, i.e. Cultural Intelligence Strategy (CQS) 0.824, Cultural Intelligence Knowledge (CQK) 0.892, Cultural Intelligence Motivation (CQM) 0.858, Cultural Intelligence Behaviour (CQB) 0.846, Multicultural Workforce (MCW) 0.898, Workplace Harmony (WFH) 0.833 shows that the study has established discriminant validity.

The study observed the path value and empirical t-value of all the hypotheses to be above the threshold value of 0.20 and 1.96, respectively, substantiating the validity of all the hypotheses. There are varying rules of thumb that explain whether R^2 values are high or not [29]. Prior research (*Ibid*, 2017) states that the cut-off values of 0.25 are weak, 0.50 are moderate, and 0.75 are treated to be high, respectively, in other studies. All four exogenous constructs explain 89.6% of Workplace Harmony (R^2 = 0.896).

Table 2

DISCRIMINANT VALIDITY (THE FORNELL-LECKER CRITERION)

Criterion	CQS	CQK	CQM	CQB	MCW	WFH
CQS	**0.824**					
CQK	0.795	**0.892**				
CQM	0.541	0.736	**0.858**			
CQB	0.261	0.511	0.715	**0.846**		
MCW	0.167	0.409	0.639	0.799	**0.898**	
WFH	0.128	0.232	0.482	0.694	0.763	**0.833**

Table 3

HYPOTHESIS TESTING AND F^2 AND Q^2 EFFECTS

Relationships	Path coefficient	t-value	Bias-corrected 95% confidence interval	f^2	q^2
$H_{1:}$ Cultural Intelligence Strategies – Multicultural Workforce	0.743***	26.475	(0.728,0.719)	0.412	0.761
$H_{2:}$ Cultural Intelligence Knowledge – Multicultural Workforce	0.744***	30.842	(0.692,0.786)	0.314	0.649
$H_{3:}$ Cultural Intelligence Motivation – Multicultural Workforce	0.358***	10.360	(0.286,0.422)	0.341	0.438
$H_{4:}$ Cultural Intelligence Behaviour – Multicultural Workforce	0.626***	16.743	(0.553,0.701)	0.913	0.589
$H_{5:}$ Cultural Intelligence Strategies – Workplace Harmony	0.311***	18.912	(-0.580,0.590)	0.239	0.368
$H_{6:}$ Cultural Intelligence Knowledge – Workplace Harmony	0.566***	17.634	(0.539,0.521)	0.713	0.839
$H_{7:}$ Cultural Intelligence Motivation – Workplace Harmony	0.477***	29.482	(0.692,0.786)	0.314	0.547
$H_{8:}$ Cultural Intelligence Behaviour – Workplace Harmony	0.674***	27.434	(0.739,0.621)	0.519	0.861
$H_{9:}$ Multicultural Workforce – Workplace Harmony	0.558***	13.736	(0.586,0.242)	0.839	0.787

Note: *** p<0.01, ** p<0.05 and * p<0.10.

Table 4

MEDIATING EFFECT					
Variables	**Direct effect**	**Indirect effect**	**Total effect**	**VAF**	**Mediation**
CQS – MCW-WFH	0.361***	0.468***	0.829***	56.4%	Partial
CQK – MCW-WFH	0.590***	0.240***	0.830***	28.9%	Partial
CQM – MCW-WFH	0.358***	0.470***	0.828***	57.5%	Partial
CQB – MCW-WFH	0.358***	0.470***	0.828***	57.5%	Partial

Note: *** p<0.01, ** p<0.05 and * p<0.10 (two-sided test).

As the prior research suggests, q^2 values show the efficiency with which the path model demonstrates the predictability of values that we originally observe [29]. The q^2 of endogenous construct Workplace Harmony (WFH) is 0.787, which is above zero, indicating the model of this research has predictive relevance. The f^2 effect size of the independent variable was calculated after the calculations relating to the r^2 value, p-values, t-values, and bootstrap confidence intervals. We also calculate the q^2 effect size, which explains the "relative impact of predictive relevance" [29]. The rule of thumb that the prior research advocates, to decide upon the importance of the effect size f^2 and q^2, states that the effect size values of 0.35 have a large effect, 0.15 have a medium effect, and 0.02 have a small effect size, respectively. From the above calculation, the f^2 effect size of the impact of Cultural Intelligence Behaviours (CQB) and Multicultural Workforce (MCW) on Workplace Harmony (WFH) is significant. The q^2 effect size of Cultural Intelligence Behaviours (CQB) on Workplace Harmony (WFH) is high, whereas Multicultural Workforce (MCW) on Workplace Harmony (WFH) has a medium effect. Model fitness is measured with SRMR criteria fit [32]. The greatest fit arises when the SRMR value is zero. A good fitness threshold value is less than 0.08. In this study work the SRMR value is 0.071 indicates good fitness of the model.

Evaluation of mediator analysis

The mediating effects of Multicultural Workforce (MCW) was assessed, to explore the consequences of its intervention in the liaison between exogenous latent variables of Cultural Intelligence viz., Cultural Intelligence Strategy (CQS), Cultural Intelligence Knowledge (CQK), Cultural Intelligence Motivation (CQM) and Cultural Intelligence Behaviour (CQB) with endogenous latent variable, Workplace Harmony (WFH). The theoretical and structural model of the present study conceptualizes the direct effect of all exogenous latent variables on the endogenous latent variable, and it was found to be significant. Further, the study tested whether the direct effect of all exogenous latent variables on endogenous latent variables would be significant after the inclusion of the mediator in the model [29].

Importance performance matrix analysis

The important performance matrix analysis (IPMA) depicts the relative importance and performance of exogenous constructs in their relationship with the endogenous construct. Total effects of exogenous constructs represent their importance, while their index values represent their performance.

Table 5

TOTAL EFFECTS AND INDEX VALUES OF LATENT CONSTRUCTS		
Latent constructs	**Institutional performance**	
	Importance (Total effects)	**Performance (Index values)**
CQS	0.306	84.497
CQK	0.626	92.715
CQM	0.047	85.139
CQB	0.834	91.274
MCW	0.806	81.213
WFH	NA	84.206

Table 6

MULTI-GROUP ANALYSIS				
Variables	**Path**	**Women**	**Location**	**|Δ|**
N		0.566	0.434	
Path relation	CQS – MCW	0.349	0.703	0.83
	CQK – MCW	0.786**	0.625**	0.161**
	CQM – MCW	0.395**	0.211**	0.184**
	CQB – MCW	0.624	0.757	0.133
	MCW – WFH	–0.023	–0.006	0.029
R^2	CQS	0.519	0.495	0.123
	CQK	0.632	0.428**	0.547**
	CQM	0.743	0.391**	0.227**
	CQB	0.895*	0.835*	0.060*
AVE/CR	CQS	0.934/0.739	0.840/0.522	
	CQK	0.946/0.854	0.845/0.660	
	CQM	0.899/0.747	0.818/0.604	
	CQB	0.935/0.706	0.932/0.698	
Total effects	CQS – MCW	0.786	0.703	0.083
	CQK – MCW	0.786**	0.625**	0.161**
	CQM – MCW	0.867***	0.740***	0.127***
	CQB – MCW	0.624	0.757	0.133
	MCW – WFH	–0.023	–0.006	0.017

Note: *** p<0.01, ** p<0.05 and * p<0.10.

IPMA contrasts the total effects, representing the predecessor constructs' importance in shaping a certain target construct, with their average latent variable scores indicating their performance.

IPMA analysis shows that Cultural Intelligence Knowledge (CQK) has a high performance of 92.715 in comparison with the other exogenous latent variables. On the other hand, the total effect of Cultural Intelligence Behaviour (CQB) is 0.834, which is specifically high. In terms of performance, improvement in Cultural Intelligence Behaviour (CQB) would significantly contribute to the performance improvement of Workplace Harmony (WFH) and improvement of Cultural Intelligence Knowledge (CQK) in terms of total effect would overall contribute to the improvement of Workplace Harmony (WFH).

For the demographics data, the cross-table analysis can be used to identify applicable descriptors. It is observed that only women and the location aspect of demographic features show a good fit. The two groups under demographic features are women and the location group. Table 6 shows the results of group-specific PLS-SEM. It also shows their differences. PLS multi-group analysis helps to understand the importance of differences through a double bootstrap routine.

DISCUSSION AND CONCLUSION

This research paper has significant managerial implications. It contributes to our understanding of the empirical validity of the assumptions of the impact of cultural intelligence on the multicultural workforce and workforce harmony. Cultural intelligence behaviour is vital to the success of workplace harmony. The indicator of cultural intelligence behaviour, which propagates workers' willingness to embrace a multicultural workforce, and the indicator that workers need to have an inclusive workforce, ranks the construct at the highest level about its importance. Further, cultural intelligence knowledge is also considered to have maximum influence on its importance and performance for a harmonious workplace. The importance matrix shows that the companies should focus on cultural intelligence knowledge, where the company should focus on sensitising the workers on various cultures, educating them on different cultures, their practices, and the way of life, to enable workers to blend with a multicultural workforce and focus on the assigned tasks. Therefore, decision makers should focus on these aspects to improve workplace harmony. There are numerous research studies in the literature that analyse worker behaviour based on various research methodologies [36–38].

The mediating relationship of multicultural workforce with the exogenous variables and endogenous variables is found to be partial for all four mediations of the study. The indirect effect of the exogenous variables, cultural intelligence strategy, cultural intelligence motivation and cultural intelligence behaviour is higher than the direct effect of these variables on the endogenous variable workplace harmony. This substantiates the importance of the mediator used in the study. So, to facilitate workplace harmony, a multicultural workforce should concentrate on developing strategies that promote cultural intelligence among the workforce, develop multicultural knowledge to be sensitive to different cultural backgrounds, motivate diversity and inclusivity and shape workers' behaviours to be mutually inclusive in the workplace. Therefore, managers should focus on

- Creating a conducive environment where all the workers feel safe to work without diverting their efficiency into non-productive activities.
- Implementing strategies of inclusivity, acceptance and understanding the cultural complexities and taking steps to educate the workers on multicultural aspects.
- Refining the workers' behaviours to maintain a happy and harmonious workplace environment.

The total effects substantiate the path relationship concerning the results of the total effect of PLS-MGA, since it's similar to that of the path relationship. Therefore, this research endeavour has significant managerial implications that retail workplaces need to pay more attention to the individual segment without ignoring the locational segment since there is not much difference in values. This empirical research has a wide scope for future reference. Firstly, the structural model of the future research can take up global indicators and develop a hierarchical model for the study. Secondly, IPMA assumes a linear relationship in the study. Future research can focus on nonlinear IPMA, making the analysis even more useful. There are minor limitations in the present study. The current study uses convenience sampling, which is confined to the readymade garment industry. There is a possibility of missing an appropriate sample from the garment industry. The common source bias is another limitation of the study. This is because the data for dependent and independent variables are collected from the same source. As a result, the data on the independent variable and dependent variable might be influenced and exercised an adverse impact on the study.

REFERENCES

[1] Petrozziello, A.J., Wooding, B., *Borders, buscones, brothels, and bi-national markets: Haitian women negotiate how to get through*, In: Cultural Dynamics, 2013, 25, 2, 183–205

[2] Shanthi, K., *Female labour migration in India: Insights from NSSO data (Vol. 4),* Chennai: Madras School of Economics, 2006)

[3] Deshingkar, P., Sharma, P., Kumar, S., Akter, S., Farrington, J., *Circular migration in Madhya Pradesh: changing patterns and social protection needs*, In: The European Journal of Development Research, 2008, 20, 612–628

[4] Hodges, N., Watchravesringkan, K., Yurchisin, J., Hegland, J., Karpova, E., Marcketti, S., Yan, R.N., *Assessing curriculum designed to foster students' entrepreneurial knowledge and small business skills from a global perspective*, In: Family and Consumer Sciences Research Journal, 2015, 43, 4, 313–327

[5] Reisinger, Y., Dimanche, F., *International tourism*, Routledge, 2010

[6] Earley, P.C., Peterson, R.S., *The elusive cultural chameleon: Cultural intelligence as a new approach to intercultural training for the global manager*, In: Academy of Management Learning & Education, 2004, 3, 1, 100–115

[7] Rockstuhl, T., Seiler, S., Ang, S., Van Dyne, L., Annen, H., *Beyond general intelligence (IQ) and emotional intelligence (EQ): The role of cultural intelligence (CQ) on cross‐border leadership effectiveness in a globalized world*, In: Journal of Social Issues, 2011, 67, 4, 825–840

[8] Earley, P.C., Ang, S., *Cultural intelligence: Individual interactions across cultures*, 2003

[9] Brislin, R., Worthley, R., Macnab, B., *Cultural intelligence: Understanding behaviors that serve people's goals*, In: Group & Organization Management, 2006, 31, 1, 40–55

[10] Ang, S., Van Dyne, L., Koh, C., Ng, K.Y., Templer, K.J., Tay, C., Chandrasekar, N.A., *Cultural intelligence: Its measurement and effects on cultural judgment and decision making, cultural adaptation and task performance*, In: Management and organization review, 2007, 3, 3, 335–371

[11] Thomas, D.C., Lazarova, M.B., Inkson, K., *Global careers: new phenomenon or new perspectives?*, In: Journal of World Business, 2005, 40, 4, 340–347

[12] Thomas, D.C., Elron, E., Stahl, G., Ekelund, B.Z., Ravlin, E.C., Cerdin, J., Poelmans, S., Brislin, R., Pekerti, A., Aycan, Z., Maznevski, M., Au, K., Lazarova, M.B., *Cultural Intelligence: Domain and Assessment*, In: International Journal of Cross Cultural Management, 2008, 8, 2, 123–143

[13] Cooper-Thomas, H.D., Burke, S.E., *Newcomer proactive behavior: Can there be too much of a good thing?*, The Oxford handbook of organizational socialization, 2012, 2, 1–26

[14] Gruman, J.A., Saks, A.M., Zweig, D.I., *Organizational socialization tactics and newcomer proactive behaviors: An integrative study*, In: Journal of Vocational Behavior, 2006, 69, 1, 90–104

[15] Wanberg, C.R., Kammeyer-Mueller, J.D., *Predictors and outcomes of proactivity in the socialization process*, In: Journal of Applied Psychology, 2000, 85, 3, 373

[16] MacNab, B.R., *An experiential approach to cultural intelligence education*, 2012, 1, 66–94

[17] Earley, P.C., Mosakowski, E., *Toward culture intelligence: turning cultural differences into a workplace advantage*, In: Academy of Management Perspectives, 2004, 18, 3, 151–157

[18] Jyoti, J., Kour, S., *Assessing the cultural intelligence and task performance equation: Mediating role of cultural adjustment*, In: Cross Cultural Management, 2015, 22, 2, 236–258

[19] Devine, F., Baum, T., Hearns, N., Devine, A., *Cultural diversity in hospitality work: the Northern Ireland experience*, In: The International Journal of Human Resource Management, 2007, 18, 2, 333–349

[20] Fullwood, R., Rowley, J., Delbridge, R., *Knowledge sharing amongst academics in UK universities*, In: Journal of Knowledge Management, 2013, 17, 1, 123–136

[21] Bhatti, M.A., Alshagawi, M., Zakariya, A., Juhari, A.S., *Do multicultural faculty members perform well in higher educational institutions? Examining the roles of psychological diversity climate, HRM practices and personality traits (big five),* In: European Journal of Training and Development, 2019, 43, 1/2, 166–187

[22] Lum, D., Maznevski, M.L., DiStefano, J.J., *Global leaders are team players: Developing global leaders through membership on global teams*, In: Human Resource Management, 2010, 39, 2–3, 195–208

[23] Hong, L., Page, S.E., *Groups of diverse problem solvers can outperform groups of high-ability problem solvers*, In: Proceedings of the National Academy of Sciences, 2004, 101, 46, 16385–16389

[24] Homan, A.C., Hollenbeck, J.R., Humphrey, S.E., Knippenberg, D.V., Ilgen, D.R., Van Kleef, G.A., *Facing differences with an open mind: Openness to experience, salience of intragroup differences, and performance of diverse work groups*, In: Academy of Management Journal, 2008, 51, 6, 1204–1222

[25] Caligiuri, P., Lazarova, M., *A model for the influence of social interaction and social support on female expatriates' cross-cultural adjustment*, In: International Journal of Human Resource Management, 2002, 13, 5, 761–772

[26] Cox, T.H., Lobel, S.A., McLeod, P.L., *Effects of ethnic group cultural differences on cooperative and competitive behavior on a group task*, In: Academy of Management Journal, 1991, 34, 4, 827–847

[27] Adler, N.J., *Global managers: no longer men alone*, In: International Journal of Human Resource Management, 2002, 13, 5, 743–760

[28] Shore, L.M., Chung-Herrera, B.G., Dean, M.A., Ehrhart, K.H., Jung, D.I., Randel, A.E., Singh, G., *Diversity in organizations: Where are we now and where are we going?*, In: Human Resource Management Review, 2009, 19, 2, 117–133

[29] Hair Jr, J.F., Matthews, L.M., Matthews, R.L., Sarstedt, M., *PLS-SEM or CB-SEM: updated guidelines on which method to use*, In: International Journal of Multivariate Data Analysis, 2017, 1, 2, 107–123

[30] Henseler, J., Ringle, C.M., Sarstedt, M., *A new criterion for assessing discriminant validity in variance-based structural equation modelling*, In: Journal of the Academy of Marketing Science, 2015, 43, 115–135

[31] Daskalakis, S., Mantas, J., *Evaluating the impact of a service-oriented framework for healthcare interoperability*, In: Studies in Health Technology and Informatics, 2008, 136, 285

[32] Henseler, J., Ringle, C.M., Sarstedt, M., *Using partial least squares path modeling in advertising research: basic concepts and recent issues*, In: Handbook of research on international advertising, Edward Elgar Publishing, 2012

[33] Chin, W.W., *The partial least squares approach to structural equation modelling*, In: Modern Methods for Business Research, 1998, 295, 2, 295–336

[34] Geisser, S., *A predictive approach to the random effect model*, In: Biometrika, 1974, 61, 1, 101–107

[35] Stone, M., *Cross-validation and multinomial prediction*, In: Biometrika, 1974, 61, 3, 509–515

[36] Priti, B., Agrawal, R., Mendon, S., Birau, R., Bărbăcioru, I.C., *Framework of SDG leadership among SMEs in South Asian nations-using Interpretive Structural Modelling*, In: Cogent Business & Management, 2023, 10, 3, https://doi.org/10.1080/23311975.2023.2253607

[37] Awais-E-Yazdan, M., Hassan, Z., Spulbar, C., Birau, R., Mushtaq, M., Bărbăcioru, I.C., *Relationship among leadership styles, employee's well-being and employee's safety behavior: an empirical evidence of COVID-19 from the frontline healthcare workers*, In: Economic Research-Ekonomska Istraživanja, 2023, 36, 1, 1–21, https://doi.org/10.1080/1331677X.2023.2173629

[38] Frank, D., Singh, R.R., Harrison, A., Vidya Bai, G., Birau, R., Spulbar, C., Ninulescu, P.V., *Worker saving attitude towards retirement planning: A study on Indian textile industry*, In: Industria Textila, 2023, 74, 5, 610–617, http://doi.org/10.35530/IT.074.05.202316

Authors:

AALIYA ASHRAF[1], NANCY SAHNI[1], RAMONA BIRAU[2], DANIEL FRANK[3], GOKARNA VIDYA BAI[3], SUHAN MENDON[3], LUCIA PALIU-POPA[4], GABRIEL NICOLAE PRICINĂ[5], COSMIN MIHAI PRICINĂ[6]

[1]University School of Business, Chandigarh University, Punjab, India
Mittal School of Business, Lovely Professional University, Punjab, India
e-mail: aaliya123ashraf@gmail.com, nancy.sahni@lpu.co.in

[2]University of Craiova, "Eugeniu Carada" Doctoral School of Economic Sciences, Craiova, Romania

[3]Manipal School of Commerce and Economics, Manipal Academy of Higher Education, Manipal, India
e-mail: daniel.frank@manipal.edu, vidhya.g@manipal.edu, suhan.mendon@manipal.edu

[4]University "Constantin Brancusi" of Târgu Jiu, Faculty of Economic Science, Târgu Jiu, Romania
e-mail: univers_cont@yahoo.com

[5]University of Craiova, Faculty of Social Sciences, Craiova, Dolj, Romania
e-mail: gabrielpricina@gmail.com

[6]University of Craiova, Doctoral School of the Faculty of Law, Craiova, Dolj, Romania
e-mail: pricinamihai@gmail.com

Corresponding author:

RAMONA BIRAU
e-mail: ramona.f.birau@gmail.com

Does ESG performance have an impact on firm value? Evidence from the Chinese textile and garment industry

DOI: 10.35530/IT.076.02.2023126

YIBING SHAO
MENGLIN ZHENG
XIN XU
XIAOFEN JI

ABSTRACT – REZUMAT

Does ESG performance have an impact on firm value? Evidence from the Chinese textile and garment industry

The effect of ESG performance has recently become a challenge, attracting controversy. This study investigates the relationship between ESG performance and firm value in textile and garment companies; moreover, it examines the role of green innovation in the relationship between ESG performance and firm value. We used 673 annual samples of Chinese Shanghai and Shenzhen A-share textile and garment listed companies from 2012 to 2022. Correlation and panel regression analyses were carried out to evaluate possible links between ESG performance as determined by the ESG rating data published by the Sino-Securities Index Information Service (Shanghai) Co., Ltd and market-based measures of firm value. Our main finding reveals that the ESG performance has a significant positive relationship with textile and garment company value; ESG performance can promote firm value by increasing green innovation, and green innovation has a partial intermediary role between ESG performance and firm value. We conducted multiple sensitivity analyses, and our findings are robust, which can provide useful recommendations for firms, investors, and policymakers.

Keywords: *environmental, social responsibility and corporate governance (ESG), circular economy, sustainability, textile industry, garment industry*

Performanța ESG are un impact asupra valorii întreprinderii? Dovezi din industria textilă și de îmbrăcăminte din China

Efectul performanței ESG a devenit recent o provocare care atrage controverse. Acest studiu investighează relația dintre performanța ESG și valoarea întreprinderii în companiile textile și cele de îmbrăcăminte, în plus, examinează rolul inovării ecologice în relația dintre performanța ESG și valoarea întreprinderii. Au fost utilizate 673 de eșantioane anuale de companii chineze de textile și de îmbrăcăminte cotate în Shanghai și Shenzhen A-share din 2012 până în 2022. Au fost efectuate analize de corelație și de regresie în panel pentru a evalua posibilele legături dintre performanța ESG, determinată de datele de rating ESG publicate de Sino-Securities Index Information Service (Shanghai) Co. Ltd și măsurile bazate pe piață ale valorii întreprinderii. Principala noastră constatare arată că performanța ESG are o relație pozitivă semnificativă cu valoarea întreprinderilor din sectorul de textile și de îmbrăcăminte; performanța ESG poate promova valoarea întreprinderii prin creșterea inovării ecologice, iar inovarea ecologică are un rol parțial de intermediar între performanța ESG și valoarea întreprinderii. Am efectuat mai multe analize de sensibilitate, iar constatările noastre sunt solide, ceea ce poate oferi recomandări utile pentru întreprinderi, investitori și factorii de decizie politică.

Cuvinte-cheie*: mediu, responsabilitate socială și guvernanță corporativă (ESG), economie circulară, durabilitate, industria textilă, industria de îmbrăcăminte*

INTRODUCTION

ESG refers to the combination of environmental, social, and governance factors, which expands and enhances the concept of responsible investment. Three constituent elements of ESG have gradually become the most important dimensions the international community considers when measuring enterprises' sustainability. A report published by the Global Alliance for Sustainable Investment in 2023 disclosed that the global ESG investment reached $30 trillion by the end of 2022, representing over a quarter of the global total asset management scale. The rapid growth of ESG investment has prompted the capital market to focus on a company's ESG performance. ESG performance is an assessment tool that urges investors to concentrate on the environmental, social, and corporate governance performance [1]. This means that if historically investors were willing to pay mainly for physical assets such as property, equipment, and machinery, then nowadays the value of the company consists largely of intangible values such as reputation, corporate culture, and customer loyalty. Thus, to gain the favour from the capital market, an increasing number of listed companies disclose their ESG performance by releasing ESG reports. However, from the firm's perspective, one of the key questions is whether the ESG performance makes financial sense or may have an impact on firm value.

Scholars who support the notion contend that ESG performance can offer stakeholders comprehensive and comparable data to address information asymmetries, provide access to resources, and reduce regulatory and reputational risks. On the other hand, other scholars hold the view that ESG performance is ineffective, believing that companies adopt ESG performance to comply with external requirements and gain various benefits, which may not necessarily result in meaningful improvements to their value; instead, it represents institutional retrogression and can mislead stakeholders. These heterogeneous results can be mainly explained by different data, sample, timing, and methodology. Furthermore, the findings of the previous studies lack agreement as they mostly focused on investigating the direct association between ESG performance and firm value rather than exploring some other latent factors influencing their relationship. The mechanism of the relationship between ESG performance and firm value has not been studied in depth.

The textile and garment industry plays a significant role in the economies of some developing countries by providing employment opportunities, contributing to foreign reserves, and empowering women.

However, the textile and garment industry is resource-intensive, especially, a growing demand for fast fashion products relying on cheap textile production, frequent cloth consumption, and short-lived garment usage exacerbate environmental pollution. According to a range of estimations, the textile and garment industry produces up to 10% of CO_2 emissions, which is the second largest polluter in the world. Regarding the social aspect, outsourcing production raises people's awareness of safety issues and labour exploitation in textile and garment factories. These situations have brought the textile and garment industry under pressure to adopt sustainable practices for reducing the depletion of finite natural resources. To this end, many textile and garment enterprises are introducing sustainability into their developmental strategies to promote the harmonization of corporate and social values with high-quality economic development. The textile and garment industry is one of the key sectors in the Chinese economy. China's 15th national congress targets a commitment of "strive to peak China's carbon dioxide emissions by 2030, achieving carbon neutrality by 2060", later in 2021, "carbon peak and neutrality" was also written into the government work report.

To achieve the industry's carbon reduction goals, China's textile and garment industry is continuously exploring models and paths of sustainable production. The impact of the ESG performance in the textile and garment industry on sustainable development draws scholarly attention. Li [2] proposed that the ESG cost-sharing contract significantly improves the textile and garment supply chain's ESG performance, with customers' sustainable awareness increasing. Furthermore, such contracts are instrumental in enhancing the aggregate ESG environmental performance of the textile and garment supply chain, elevating profits for both manufacturers and retailers and alleviating the impact of fluctuating demand on supply chain participants. Liu [3] introduces a data-driven ESG assessment approach using blockchain technology and quantitatively compares the ESG performance of 71 textiles and garment listed companies in Hong Kong.

In the context of sustainable development, green innovation has attracted increasing attention owing to its contributions to the conservation of resources, environmental protection, and financial performance creation. as the core of enabling corporate green transformation, green innovation is generally considered to be an innovation model consisting of improved products, processes or management to achieve environmental sustainability.

In light of this, we will empirically investigate whether and how ESG performance affects textile and garment firm value in China. Our study attempts to answer the following questions: (1) Can ESG performance effectively promote textile and garment firm value? (2) Can ESG performance promote green innovation in textile and garment firms? (3) What is the role of green innovation in the relationship between ESG performance and firm value?

Our study makes a clear contribution to the existing literature in two ways. Firstly, we examine ESG performance on firm value in the Chinese textile and garment industry, which provides the most recent evidence for the role of ESG performance in improving firm value, expanding and enriching the literature on the ESG economic consequences and factors affecting firm value. Secondly, we uncover how ESG performance influences textile and garment firms' value. We introduce green innovation as a mediating variable of the relationship between ESG performance and firm value, which provides a new foothold for relevant research. We find that ESG performance can improve firm value by promoting green innovation. Further, the green innovation has a partial intermediary role in the association between ESG performance and firm value.

The remainder of the paper is organized as follows. The 2nd section provides a review of the related literature and develops the hypothesis. The 3rd section describes the data and modelling framework. The 4th section analyses the results and discusses. The last section provides concluding remarks, practical implications and the limitations of this research.

LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

ESG performance and firm value

Stakeholder theory puts forward the idea that successful companies can align the interests of all stakeholders and build trust relationships with diverse stakeholders, which is important to the financial success of a firm [4, 5]. Engaging in socially and environmentally responsible activities, textile and garment companies can convey to their stakeholders that they are not focused solely on their self-interest. This can result in the building of a positive social reputation, attraction and retention of high-quality employees, increasing employee morale and productivity, and enhancement of goodwill and trust with key stakeholders. Additionally, the legitimacy theory requires firms to voluntarily extend and report their efforts for the welfare of society, as these have positive implications for their financial performance through increasing positive image or getting legitimacy in the eyes of stakeholders. Such practices can help build a positive social reputation, increase product demand and profitability. Based on these arguments, it is reasonable to expect that high ESG performance may have better firm value.

Hypothesis 1: ESG performance has a positive and significant impact on the value of textile and garment firms.

ESG performance and green innovation

Green innovation, characterized by technological innovation through environmental protection, bridges the gap between environmental improvement and economic development. ESG performance might impose a positive influence on corporate green innovation activities by alleviating information asymmetries and reducing financial constraints while simultaneously conveying the manager's attitudes towards green investment to external stakeholders [6]. First, according to agency theory, in the absence of effective supervision and incentives, managers tend to show a strong preference for enjoying a quiet life since their efforts are difficult to observe, which will lead to a low willingness among managers to engage in green innovation. ESG performance contributes to increased corporate information transparency, which can help shareholders monitor corporate green innovation more effectively [7–9]. Comprehensive and varied information used in ESG performance can effectively mitigate the misleading effect of corporate strategic disclosure. Thus, ESG performance information can help investors enhance their ability to monitor the managers and promote corporate green innovation. Second, owing to the long investment cycle, high risk of failure, low comparability and low innovation predictability. Green innovation must be supplemented with sufficient financial support to address market failure problems. The availability of funds plays a vital role in green innovation. ESG performance is an important means of redressing information asymmetry between stakeholders and companies. Under the premise of agency theory in the capital market, companies can distinguish themselves from competitors by disclosing high-quality ESG performance information to access stakeholder resource support. Therefore, we expect high ESG performance to have a positive impact on green innovation.

Hypothesis 2: ESG performance has a positive and significant impact on textile and garment firms' green innovation.

Green innovation and firm value

Failure to opt for and implement the green innovation strategy may have adverse consequences for firms, which may lead to the loss of affluent resources, competitive advantage, potential customers and eventually a decrease in firm value. First, green Innovation helps firms to reduce the use of raw materials, emission of greenhouse gases and adverse effects on the environment through sustainable industrial processes [10]. Firms apply green innovation not only to reduce environmental pollution, but also to increase the efficiency of other aspects of the firm, such as production methods and energy utilization, which eventually increases firm value [11]. Consequently, greater firm value is considered the output of green innovation [12]. Second, green innovation implementation in firms through the development of green technology and low-cost eco-products may also create a sustainable, positive image and good reputation in society. Social responsibility-sensitive consumers' satisfaction with low-cost and eco-friendly products also increases the market share of products and improves the firm value [13]. Therefore, we propose the following hypothesis.

Hypothesis 3: Green innovation has a positive and significant impact on textile and garment firm value.

ESG performance and firm value: The mediating role of green innovation

Porter's hypothesis suggests that appropriate environmental regulation can generate external pressure to induce firms to pay attention to resource efficiency and technological innovation. Intense pressure from the regulators and increasing awareness of consumers lead firms to change their conventional production methods to sustainable and innovative processes, also known as green innovation. In line with the resource-based view, we argue that green innovation is an important missing variable, which may help resolve the issue of inconclusive findings regarding the association between ESG performance and firm value. We propose the following hypotheses for the mediating models.

Hypothesis 4: ESG performance promotes textile and garment firm value by increasing green innovation.

RESEARCH METHODOLOGY

Sample selection and data sources

We utilized a panel dataset consisting of 673 annual samples from China's Shanghai and Shenzhen A-share textile and garment listed companies from 2012 to 2022. The financial data were collected from the China Stock Market and Accounting Research (CSMAR) database, which provides the fundamental characteristics of assets, debt, IPO time, and industry information. To ensure the reliability of the research samples, we performed the following data processing principles: (1) Exclude Special Treatment (ST) and Particular Transfer (PT) samples during the research period. (2) Exclude samples with missing values. A common practice in financial studies is to minorize the extreme values of all variables of interest before estimating a regression model to deal with outlier observations. Therefore, all the variables were minorized at the 1 and 99 % levels to avoid the influence of extreme observations.

Variable

Explanatory variable

Evaluating the ESG performance of listed companies has become an important aspect of assessing their sustainable competitiveness. However, corporate social responsibility (CSR) reports may be limited and misleading due to factors such as greenwashing behaviour. Voluntary disclosure of ESG information may also result in selective reporting by companies. In contrast, ESG rating agencies, such as Bloomberg, can provide more comprehensive and reliable ESG-related information for measuring a company's ESG performance. In this study, we utilized the ESG rating data published by the Sino-Securities Index Information Service (Shanghai) Co. Ltd. The Sino-Securities Index ESG rating system is based on the core connotation and development experience of ESG, taking into account the specific circumstances of the Chinese capital market. The system uses data from various sources, including firms' public disclosure data, periodic reports, firms' social responsibility reports and sustainable development reports, government and relevant regulatory authorities' websites, and media reports, to construct a three-tier indicator system. The system assigns a nine-level C-AAA rating based on a company's total ESG score, with higher scores representing better ESG performance. For empirical analysis, we assign the nine grades of C-AAA as 1-9, respectively.

Explained variable

The primary purpose of this research is to investigate the influence of ESG performance on firm value. To achieve this objective, we employed Tobin's Q as a proxy for firm value, as it has been widely used in prior studies in this area. Tobin's Q is a metric that encompasses both short-term and long-term financial performance, and it is defined as the ratio of a company's market value to its replacement value. Firms with high Tobin's Q, or a ratio greater than 1, are typically considered to have favourable investment opportunities or strong management performance. Additionally, Tobin's Q reflects the economic sources of future cash flows, which serve as the foundation for a company's value.

Mediating variable

We utilized green innovation as a mediating variable to further explore the causal path through which ESG performance affects firm value. Prior research has employed the questionnaire methodology or R&D expenditures to quantify green innovation. However, these methods may suffer from biases and subjectivity owing to the personal beliefs of respondents. Recent literature suggests that patent-based variables are a more reliable measure of innovation output. Therefore, we use the number of green patents granted to a firm each year as a proxy for corporate green innovation. Considering the significant variation in patent counts among firms, we apply natural logarithm processing to the patent indicator.

Control variables

After reviewing the current literature, we incorporated various control variables that could potentially influence textile and garment firm value. First, we use firm size (SIZE) as a control variable, as larger firms typically possess better market conditions and more resources to enhance firm value. Second, we included firm profitability (ROA) as a control variable, as high profitability signals favourable corporate prospects and investors tend to attribute more value to firms with high profitability. Third, we controlled for the sales growth rate (SG), as a firm with strong growth potential is an attractive target for investors. Additionally, we also controlled for firm financial leverage (LEV) and the age of the firm (AGE). Furthermore, we incorporated time fixed effects into the model to control for any macroeconomic environment and other unaccounted for time-varying factors that may affect firm value. A summary of the variables is provided in table 1.

Mathematical modelling

Benchmark model

To evaluate the influence of ESG performance on textile and garment firm value, the following fixed-effect panel econometric model has been developed based on theoretical analysis and research hypotheses presented in the previous section:

$$TQ_{i,t} = a_0 + a_1 ESG_{i,t} + \sum control_{i,t} + \delta_t + e_{i,t} \qquad (1)$$

In the metrological model (1), the subscripts i and t represent a textile and garment company i and annual t, respectively. $ESG_{i,t}$ represents the ESG performance of the i^{th} sample firm in the t year. $TQ_{i,t}$ represents the t year firm value of the i^{th} sample company, and $control_{i,t}$ are the variables used to control for other factors that may affect the value of the firm. Model (1) also includes year fixed effects to eliminate the effects of the macroeconomic environment, δ_t is the time fixed effect, and $e_{i,t}$ is the residual term with a normal distribution, a_0 denotes the constant term. Coefficient a_1 is used to measure the effect of ESG performance on firm value, and if it is significantly positive, it indicates that ESG performance can significantly improve the firm value.

Mediating effect model

We adopt green innovation as the mediating variable to further explore the path mechanism of ESG performance influencing firms' value. By employing the mediation effect model proposed by Baron and Kenny, we establish the recursive equation formulas 2 and 3, where $GI_{i,t}$ is the mediating variable: green innovation, and the meanings of δ_t, $e_{i,t}$ are consistent

Table 1

THE SUMMARY OF THE VARIABLES		
Variable	**Definition**	**Description/Formula**
TQ	Tobin's Q	(Equity Market Value + Liabilities Market Value) / (Equity Book Value + Liabilities Book Value)
ESG	ESG performance	ESG rating data published by Sino-Securities Index Information Service (Shanghai) Co.Ltd.
GI	Green innovation	The green patent application count plus 1, followed by the logarithm
SIZE	Firm size	Book value of total assets by logarithm
ROA	Return on assets	The ratio of current net profit to total assets
LEV	Leverage	The ratio of total liabilities to total assets
SG	Sales growth	The ratio of sales in year (t) to sales in year (t – 1)
AGE	Age	Natural log of the number of days since the first listing
Year FE		The year fixed effect

in Model 1. If the coefficient β of ESG in model 2 is significant, and the coefficient γ of the mediator in the model (3) is significant, the mediating effect exists.

$$GI_{i,t} = \beta_0 + \beta_1 ESG_{i,t} + \sum control_{i,t} + \delta_t + e_{i,t} \qquad (2)$$

$$TQ_{i,t} = \gamma_0 + \gamma_1 ESG_{i,t} + \gamma_2 GI_{i,t} + \sum control_{i,t} + \delta_t + e_{i,t} \qquad (3)$$

MAIN ANALYSES

Descriptive statistics

Table 2 reports descriptive statistical results for the main variables. As seen from the table, Tobin's Q has a mean of 2.43 and a median of 2.53. SIZE has a mean of 21.53 and ranges from 25.53 to 19.27, indicating that our sample includes large as well as small firms in terms of sales and assets. SG varies from 77.07 to –2.53, with a median of 4.05. The average ROA for the year is 0.17, with a maximum of 0.25 and a minimum of 0.10, indicating significant variation. The mean and median of ESG are 3.90 and 4, respectively, indicating that the ESG performance of the sample firms is generally between CCC-B; the minimum ESG rating is 1, indicating that some textile and garment listed companies have poor ESG performance. GI is a dependent variable used in this paper. Its mean is 0.41, with a standard deviation of 0.65, indicating great variations in green innovation among our observations.

Correlation result

Checking multicollinearity is important as its existence undermines the statistical significance of a predictor or increases the variance of the coefficient estimates, which reduces the reliability. Table 3 reports Pearson's correlation matrix for checking whether two variables are associated or vary with each other. None of the statistics has a higher value than 0.3, and the correlation coefficient between ESG and each control variable is small, indicating that the regression model is less susceptible to multicollinearity. Multicollinearity is further endorsed by the Variance Inflation Factor (VIF) test. If the VIF is higher than 10, severe multicollinearity problems might occur. However, in our data, no VIF exceeds 2.22, so multicollinearity should not affect our results. Moreover, the correlation between firm value (TQ) and ESG performance (ESG) is positive and statistically significant. Hence, providing some initial support to our hypotheses.

Empirical result

We present the regression result in table 4, column (1) shows a univariate regression without any control variables, and the coefficient estimate of ESG is positive and significant. Column (2) adds other control variables. In column (1), benchmark regression shows

Table 2

VARIABLES DESCRIPTIVE STATISTICS						
Variable	**Observations**	**Mean**	**Median**	**St.Dev**	**Min**	**Max**
TQ	673	2.43	2.53	1.86	0.76	8.03
ESG	673	3.90	4.00	3.93	1.00	7.00
GI	673	0.41	0.11	0.65	0.00	4.89
SIZE	673	21.53	21.17	1.05	19.27	25.53
ROA	673	0.17	0.19	0.32	0.10	0.25
LEV	673	0.61	0.60	0.31	0.02	0.91
AGE	673	2.99	3.05	0.29	1.60	3.40
SG	673	8.48	4.05	18.67	-2.53	77.07

Table 3

CORRELATION MATRIX						
Variable	**TQ**	**ESG**	**SIZE**	**ROA**	**LEV**	**AGE**
TQ	1	0.27**	0.11*	–0.13***	0.51***	0.12**
ESG	0.27**	1	0.18***	0.31***	0.16**	0.07***
GI	0.11*	0.18***	1	0.08***	–0.11***	0.13**
SIZE	–0.13***	0.30***	0.08***	1	–0.27***	0.28*
ROA	0.51***	0.16**	–0.11***	–0.27***	1	–0.22**
LEV	0.12**	0.07***	0.13**	0.28*	–0.22**	1
AGE	0.18***	0.11**	0.16**	0.27*	0.14**	0.06*
SG	0.22***	0.08*	0.01***	0.12***	0.24***	0.11**
VIF	—	1.77	1.05	1.95	2.13	1.79

that the coefficient on ESG is 0.29 with $t = 6.05$, significantly positive at the 1% level, indicating that the improvement of the ESG performance significantly promotes the value of the textile and garment firm. Column (2) shows that the coefficient of ESG is still significantly positively correlated at the 5% level after adding control variables such as ROA and LEV to the regression, indicating that firm value has been significantly improved with the deepening of ESG performance; thus, hypothesis 1 was tested.

Mechanism analysis

This study wants to explore the underlying mechanisms of ESG performance on firm value and determine whether there is a causal chain of "corporate ESG performance – enhancement of green innovation – improvement of firm value". We use a stepwise method to test the mediating effect, and the results are presented in table 4, columns (3) and (4) examine the mediating effect of green innovation. Column (3) shows the regression results, where the green innovation is the dependent variable. The coefficient of ESG is significantly positive, indicating that the higher the ESG level of the company, the greater the green innovation of the firm. This further proves the effectiveness of ESG performance: better-performing companies are more willing to increase the quantity of green innovation, and hypothesis 2 is tested. Column (4) shows the regression results of including the mediating variable in the model. The coefficient of GI is significantly positive at the 5% level and the coefficient of ESG is significantly positive at the 1% level as well. This implies that ESG performance can effectively enhance green innovation, thus improving the firm value. Therefore, hypotheses 3 and 4 are supported.

Robustness checks

Endogeneity test

Benchmark regression shows that ESG performance is positively correlated with firm value, but this may be the result of companies with higher value being more willing and able to improve their ESG performance, which brings about a reverse causality problem. The reverse causality problem is alleviated by lagging explanatory variables. Since the ESG performance in the lag period is not easily affected by the negative impact of the current firm value, we use the ESG performance with a lag of one period and two periods as the explanatory variables to re-regress the model. Columns (1) – (2) of table 5 report the corresponding regression results, which show that the conclusions of this paper remain robust.

Measure the replacement test

It is necessary to test whether the results of the benchmark regression will have different results owing to the definition of the dependent variable. In addition to Tobin's Q, we use alternative measures of firm value to examine the robustness of the results. The measure is the market-to-book ratio, which is frequently used as a proxy of Tobin's Q [14, 15]. Market-to-book ratio is the total market value of equity divided by the total book value of equity. We re-examine the relationship between ESG performance and firm value, and regression results are listed in table 5, column (3). It can be seen from the results that the ESG coefficient is significantly positive, indicating that the benchmark regression results have not fundamentally changed even if the dependent variable is changed, supporting hypothesis 1.

Placebo test

To verify that the empirical results of this study are caused by ESG performance as opposed to other factors, we construct a random value of ESG performance to conduct placebo tests. If the true performance of ESG does affect firm value, then the randomly rated ESG performance will not affect firm value similarly. The regression results are presented in table 5. In column (4), showing that the coefficient of random ESG is insignificantly different from zero. This result is in contrast to those shown in table 4, indicating that our main results pass the placebo test.

CONCLUSIONS AND POLICY IMPLICATIONS

The primary findings of our analysis can be succinctly summarized as follows: (1) ESG performance plays a critical role in augmenting the value of textile and garment firms. (2) The essential mechanism through which ESG performance exerts a positive

Table 4

EMPIRICAL ANALYSIS RESULTS				
Variable	**Firm value**	**Firm value**	**Green innovation**	**Firm value**
	(1)	**(2)**	**(3)**	**(4)**
ESG	0.29^{***}(6.05)	0.30^{**}(3.67)	0.10^{*}(3.18)	0.13^{***}(7.38)
GI				0.13^{**}(5.93)
SIZE		-0.47^{***}(–9.73)	0.66^{***}(11.23)	0.05^{***}(7.02)
ROA		0.51^{***}(7.93)	–0.12(–1.68)	0.10^{**}(3.98)
LEV		0.03*(2.78)	-0.10^{*}(–3.01)	–0.21(–0.89)
SG		0.22^{**}(3.39)	0.36^{***}(5.37)	0.27^{***}(6.19)
AGE		0.05(1.08)	0.02(1.67)	0.12^{*}(2.01)
Constant	3.43^{***}(13.56)	3.82^{***}(25.29)	0.80^{***}(7.90)	4.04^{***}(16.87)
Year FE	Yes	Yes	Yes	Yes
Observations	673	673	673	673
R2	0.48	0.51	0.42	0.53

Table 5

RESULT OF ROBUSTNESS CHECKS				
Variable	**Firm value**		**Measure replacement**	**Placebo test**
	Lagged explanatory variable			
	(1)	**(2)**	**(3)**	**(4)**
ESG	**0.31^{***} (4.77)**	**0.25^{***} (6.18)**	**0.43^{***} (6.27)**	
Random ESG				0.05 (0.63)
Constant	1.89^{***} (5.38)	2.12^{**}(1.76)	3.02^{***}(16.21)	2.65^{**}(2.08)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	601	538	673	673
R^2	0.53	0.51	0.45	0.31

impact is by promoting green innovation. Results demonstrate that ESG performance is positively correlated with green innovation, implying that increased green innovation may serve as the medium through which ESG performance influences firm value. The data suggest that higher firm value is attributable to the enhancement of the firm's green innovation, specifically through a causal chain of events: "better corporate ESG performance-enhancement of textile and garment firm's green innovation-improvement of firm value".

Based on the empirical findings presented, several significant inferences and policy implications can be drawn. Firstly, textile and garment enterprises must heighten their awareness of ESG and proactively improve their ESG performance to enhance their competitiveness in the market and gain favour from investors. Secondly, ESG performance can be utilized to address the issue of information asymmetry, and financial resources should be allocated to support initiatives that promote energy efficiency, emissions reduction, and social responsibility. Lastly, government regulators must actively promote the improvement of ESG information disclosure and accelerate the standardization of ESG evaluation criteria, while also encouraging textile and garment enterprises to engage in green technology innovation.

This study has certain limitations that warrant further investigation in the future. Firstly, the sample employed in this research is from the Chinese market, which restricts the generalizability of the findings. While robustness tests have been carried out to mitigate this limitation, the study may still be susceptible to selection bias. Therefore, future research must utilize more advanced econometric techniques to address this issue. Secondly, the ESG performance examined in this study is at the aggregate level, which limits the ability to assess its impact on firm value or green innovation at a more granular level. Subsequent studies could attempt to obtain separate performance for environmental, social, and governance factors to explore these effects in greater detail.

ACKNOWLEDGEMENTS

This work is supported by Science Foundation of Zhejiang Sci-Tech University (ZSTU) under Grant no. 22192334-Y.

REFERENCES

[1] Chen, L., et al., *ESG disclosure and technological innovation capabilities of the Chinese listed companies,* In: Research in International Business and Finance, 2023, 65

[2] Li, L., Liu, X., Hu, M., *Textile and apparel supply chain coordination under ESG-related cost-sharing contract based on stochastic demand,* In: Journal of Cleaner Production, 2024, 437

[3] Liu, X., et al., *Data-driven ESG assessment for blockchain services: A comparative study in textiles and apparel industry,* In: Resources, Conservation and Recycling, 2023, 190

[4] Maqbool, S., Zameer, M.N., *Corporate social responsibility and financial performance: An empirical analysis of Indian banks,* In: Future Business Journal, 2018, 4, 1, 84–93

[5] Ghoul, S.E., Guedhami, O., Kim, Y., *Country-level institutions, firm value, and the role of corporate social responsibility initiatives,* In: Journal of International Business Studies, 2017, 48, 3, 360–385

[6] Tan, Y., Zhu, Z., *The effect of ESG rating events on corporate green innovation in China: The mediating role of financial constraints and managers' environmental awareness,* In: Technology in Society, 2022, 68

[7] Boone, A.L., White, J.T., *The effect of institutional ownership on firm transparency and information production,* In: Journal of Financial Economics, 2015, 117, 3, 508–533

[8] Frydman, C., Wang, B., *The Impact of Salience on Investor Behavior: Evidence from a Natural Experiment,* In: The Journal of Finance, 2019, 75, 1, 229–276

[9] Porumb, V.A., et al., *Expanded Auditor's Report Disclosures and Loan Contracting,* In: Contemporary Accounting Research, 2021, 38, 4, 3214–3253

[10] Horváthová, E., *The impact of environmental performance on firm performance: Short-term costs and long-term benefits?* In: Ecological Economics, 2012, 84, 91–97

[11] Eiadat, Y., et al., *Green and competitive? An empirical test of the mediating role of environmental innovation strategy,* In: Journal of World Business, 2008, 43, 2, 131–145

[12] Glavas, A., Mish, J., *Resources and Capabilities of Triple Bottom Line Firms: Going Over Old or Breaking New Ground?,* In: Journal of Business Ethics, 2014, 127, 3, 623–642

[13] Ghisetti, C., Marzucchi, A., Montresor, S., *The open eco-innovation mode. An empirical investigation of eleven European countries,* In: Research Policy, 2015, 44, 5, 1080–1093

[14] Galema, R., Plantinga, A., Scholtens, B., *The stocks at stake: Return and risk in socially responsible investment,* In: Journal of Banking & Finance, 2008, 32, 12, 2646-2654

[15] Edmans, A., *Does the stock market fully value intangibles? Employee satisfaction and equity prices,* In: Journal of Financial Economics, 2011, 101, 3, 621–640

Authors:

YIBING SHAO[1], MENGLIN ZHENG[2], XIN XU[3], XIAOFEN JI[1]

[1]School of International Education, Zhejiang Sci-Tech University, Zhejiang, China
e-mail: syb@zstu.edu.cn

[2]JNBY Clothing Co., Ltd, Hangzhou, Zhejiang, China
e-mail: zhengmenglin@jnby.com

[3]Shanghai Youfan Information Technology Co., Ltd, Hangzhou, Zhejiang, China
e-mail: feiniao1989@hotmail.com

Corresponding author:

XIAOFEN JI
e-mail: xiaofenji@zstu.edu.cn

Study on the adaptability of cellulose diacetate tow for tobacco to the type of curling machine

DOI: 10.35530/IT.076.02.202446

LI ZHANG
HAOXUAN SHI
ZONG CHEN
JIANXING HUANG
JIAHUI GAO
YIQUN LI

ABSTRACT – REZUMAT

Study on the adaptability of cellulose diacetate tow for tobacco to the type of curling machine

The raw material of cigarette filters is cellulose diacetate slurry, and potentially harmful substances such as acetone are used during production. To improve cigarette filters' filtering effectiveness, increase cellulose diacetate filaments' utilisation rate, and reduce environmental pollution during production, this study aims to investigate the effects of cellulose diacetate tow specifications and crimping machine models on tow formation quality. In this paper, the correlation between the specification of cellulose acetate tow, crimping machine models, and the resulting tow quality is determined to guide the selection of crimping machines for practical production. To tackle the challenges of large sample sizes and high experimental costs, a multidimensional sampling method is developed. Utilizing a learning-based approach, we identify a robust nonlinear relationship among these three factors and validate the relationship by using historical production data. Our findings reveal a significant nonlinear correlation between the crimping machine model and both single and total deniers. Through two regression adjustments, a reasonable degree of regression fitting for the relationships among the three factors is achieved. The experimental results indicate that the selection of the crimping machine is positively correlated with the number of filaments in the bundle and the pressure on the rollers, while it is negatively correlated with the cross-sectional area of the filaments. Additionally, a production guidance model, which relates the crimping machine model to the specifications of cellulose acetate tow, is established.

Keywords: *curling machine, cellulose diacetate, orthogonal experimental design, Latin hypercube sampling, logistic regression*

Studiu privind adaptabilitatea filamentului din diacetat de celuloză pentru tutun la tipul de mașină de sertizare

Materia primă a filtrelor pentru țigări este suspensia de diacetat de celuloză, iar în timpul procesului de producție sunt utilizate substanțe potențial nocive, cum ar fi acetona. Pentru a îmbunătăți eficiența de filtrare a filtrelor de țigări, pentru a crește rata de utilizare a filamentelor de acetat de celuloză și a reduce poluarea mediului în timpul producției, acest studiu urmărește să investigheze efectele specificațiilor filamentelor de acetat de celuloză și ale modelelor de mașini de sertizare asupra calității formării filamentelor. În această lucrare, se determină corelația dintre specificațiile filamentelor de acetat de celuloză, modelele de mașini de sertizare și calitatea filamentelor rezultate pentru a ghida selecția mașinilor de sertizare pentru producția practică. Pentru a face față provocărilor legate de dimensiunea mare a eșantioanelor și de costurile experimentale ridicate, este dezvoltată o metodă de eșantionare multidimensională. Utilizând o abordare bazată pe învățare, identificăm o relație neliniară robustă între acești trei factori și validăm relația prin utilizarea datelor istorice de producție. Constatările noastre relevă o corelație neliniară semnificativă între modelul mașinii de sertizare și denierul unic și cel total. Prin două ajustări ale regresiei, se obține un grad rezonabil de ajustare a regresiei pentru relațiile dintre cei trei factori. Rezultatele experimentale indică faptul că selectarea mașinii de sertizare este corelată pozitiv cu numărul de filamente din fascicul și cu presiunea exercitată asupra rolelor, în timp ce este corelată negativ cu aria secțiunii transversale a filamentelor. În plus, este stabilit un model de ghidare pentru producție, care leagă modelul mașinii de sertizare cu specificațiile filamentului de acetat de celuloză.

Cuvinte-cheie*: mașină de sertizare, diacetat de celuloză, design experimental ortogonal, prelevare de probe cu hipercub latin, regresie logistică*

INTRODUCTION

Cellulose acetate fibres, known for their excellent adsorption properties [1] and substantial surface area, can effectively capture harmful substances in cigarette smoke. These fibres are primarily derived from cellulose acetate, which is the main component of cigarette filters [2, 3]. The preparation of cellulose acetate fibres involves the production of cellulose acetate slurry, which is then extruded through a spinneret with a defined cross-sectional shape and directed into a duct. After exposure to heated air within the duct, the slurry transforms into filaments with specific plasticity. The preparation process involves the use of hazardous chemicals, such as acetone. In the long-term production processes, leaks and other issues can arise, potentially impacting the environment and posing health risks to those involved. Additionally, cellulose diacetate can take several years or even decades to degrade in natural environments [4, 5]. Therefore, improving the quality of filament formation and increasing product utilization can reduce the environmental impact indirectly.

In the production of cellulose acetate fibre tows, the filaments exiting the duct are treated with oil on oiling wheels. This process helps protect the filaments in subsequent stages by reducing friction, providing lubrication, cleaning, and cooling. When the slurry is sprayed through nozzles of varying diameters, it creates filaments with different cross-sections, resulting in different single-fibre specifications, commonly referred to as 'single denier' in practical production. Different specifications of the total filament bundle, depending on the number of converging ducts and variations in spray nozzle models, combine to form different total fibre specifications, known as 'total denier' in practical production.

Once the specifications for single and total fibres are established, physical processes such as stretching and squeezing occur through a crimping machine. This results in the formation of large and small curling waves, which shape the filament tows and determine their overall quality. Extensive experimental research has been conducted on the compatibility between cellulose acetate tows for smoking and crimping machines, as well as on the width of the filaments before they enter the crimping machine [6].

To improve the curling process of cellulose acetate fibres for smoking [7], we established the relationship between the specifications of filament curling and different types of crimping machines. A guiding model has been developed to assist in selecting crimping machines based on the specifications of single and total denier. Under optimal conditions for filament quality, this model establishes the relationship between single and total deniers, and crimping machine types. In other words, for specific specifications and types of single and total deniers, the regression model developed in this study provides recommendations for suitable crimping machine models, offering significant reference value.

Experimental considerations

Cigarette filters are typically manufactured from cellulose acetate tows [8], which undergo a series of processing steps. The crimping process of the filament bundle is a central and crucial technology in the production of cigarette filters. This process often employs a crimping machine to process the preliminarily formed filament tow [9]. Horizontal stuffing box curling machines consist of upper and lower pressure rollers and a stuffing box [10]. The rotating rollers are responsible for both stretching and rolling the filament bundle, while in the stuffing box, the fibres deform and curl due to mutual compression and the pressure applied by the stuffing box plate. The rollers of the crimping machine play a significant role in determining the final shaping pattern of cellulose acetate tows through their effects on the rolling and stretching of the filaments.

This study aims to achieve optimal matching between cigarette cellulose acetate tow specifications and crimping machine models. It develops a robust nonlinear model to relate fibre specifications to crimping machine types. Given the extensive range of fibre specifications, a full-sample experiment would be cost-prohibitive. Therefore, an orthogonal experimental design and a Latin hypercube sampling scheme are employed to select representative samples from the experimental population, thereby reducing both the complexity and cost of the experiment. Additionally, to better align with practical production and avoid sampling in areas irrelevant to actual production, commonly used fibre specifications are employed as the base library for experimental selection. Biased treatments are applied to the specimens within this base library to enrich the sample space and enhance the trend data of model variations at the sampling points. In the experiment, sampling models are established using production data from a real company. 70% of the randomly extracted data from the constructed dataset is used for model training, while the remaining 30% is allocated to validate the accuracy of the trained model.

The quality of cellulose acetate tows can be assessed from several perspectives, including the stability of curling for fibres with the same specifications, the amount of fibre fly produced during subsequent processing, the tensile strength of the fibres, and the size and distribution of the curling waves. However, these evaluation metrics are influenced by factors such as the fibre tow specifications and the oiling process, making it challenging to normalize them under varying conditions and isolate the impact of a single variable on fibre tow quality. Therefore, considering the combined influence of these factors, we use a weighted comprehensive evaluation score as the final criterion for selecting curling machines.

The final evaluation criteria for the fibre tows can be obtained from the relevant data in table 1.

Finally, the original data model is processed using logistic regression to build an initial adaptation model. By evaluating different specifications, scores for the crimping machines are generated, and the model with the highest score is selected. The training data is then updated, and the model is retrained and re-evaluated. The model's fitting accuracy is validated using the test set. This comprehensive approach aims to account for various influencing factors, incorporate bias treatment, and iteratively refine the model to ensure the accurate evaluation and selection of crimping machines under different conditions.

PRELIMINARIES

In this section, we will introduce several key methods, including Latin hypercube sampling (LHS) [11], orthogonal experimental design, and logistic regression modelling.

Table 1

SPINNING PRODUCTION QUALITY INSPECTION INFORMATION			
Indicators	**Equipment**	**Control range**	**Common methods**
Beating evaluation	Beating machine	Individual item < 3 Total score < 5	Beating
Fly test	Fly machine	< 90 mg/30 min	Weighing method
Line density test for crimped fibre tows	Total denier testing station	Target value: ± 0.1 ktex	Weighing method
Fibre bundle moisture test	Rapid moisture meter	5.7 ± 1.0%	Moisture meter method
Crimping energy test	Tensile tester	Target value: ± 35.0 g cm/cm	Tensile tester method
Break strength test	Tensile tester	≥ 18 N/ktex	Tensile tester method
Whiteness	Whiteness meter	≤ 8.0 B	Instrumental method
Fibre bundle crimp count measurement	Single fibre denier meter	Target value: ± 4	Instrumental method

Latin hypercube sampling

LHS is a method based on the principles of mathematical random theory, notable for its features of stratification, randomness, and disorder, which has been widely used in practical engineering. This sampling technique effectively mitigates the collapse of sample points [12]. These characteristics ensure that, while covering the entire feasible space through random sampling, the collected sample space avoids excessive clustering. Additionally, it guarantees edge sampling within the total space, thus preventing distortion of the sample space.

To investigate this, we compared Monte Carlo random sampling and Latin hypercube sampling for sampling from a standard normal distribution, as shown in figure 1, *a*. Both methods maintain the distribution pattern of the original data, with denser sampling in areas of higher probability density and sparser sampling in areas of lower probability density. However, Monte Carlo random sampling tends to lose samples at the distribution edges (as indicated by the sparse red points in the intervals [–4, –2] and [2, 4] in figure 1, which diminishes the representativeness of the overall distribution. In contrast, Latin hypercube sampling effectively avoids this issue.

In the present experimental data, the results of Latin hypercube sampling for the distribution of single denier are depicted in figure 1, *b* and *c*.

Orthogonal experimental

Orthogonal experimental design [13] is a method used to study the effects of multiple factors at different levels. Based on Galois theory [14], it selects representative combinations of factor levels from a fully matched set of experiments to identify the optimal level combinations. Typically, high-order interactions between factors are minimal, with first-order interactions (interactions between two factors) being the primary focus. The orthogonal design ensures that all possible two-factor combinations at different levels are represented in the orthogonal table, addressing first-order interactions. This approach maintains experimental representativeness while reducing complexity.

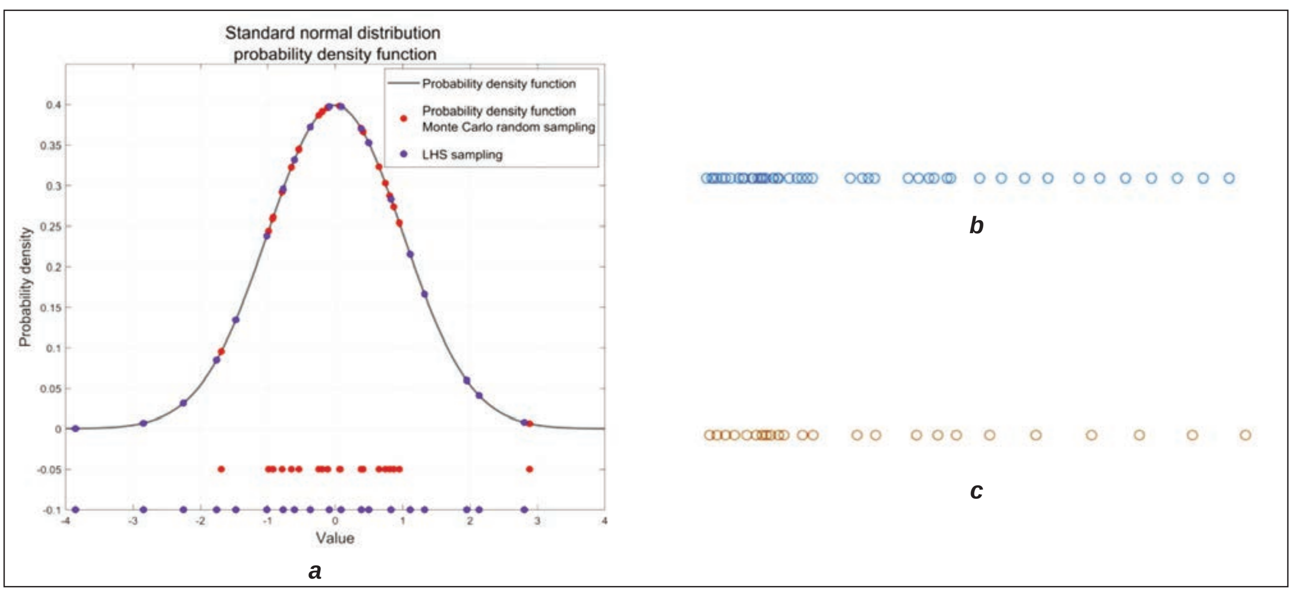


Fig. 1. Image of: *a* – the comparative schematic diagram between Monte Carlo sampling and LHS under the standard normal distribution; *b* and *c* – the demonstration of the LHS on the original data and sampled data

The fundamental requirement of orthogonal experimental design is to maintain orthogonality among various factors. Hence, it is necessary to ensure:

1. For any pair of distinct factors (*A,B*), it is essential to fulfil the requirement of interaction

$$AB = 0 \tag{1}$$

2. The sum across different levels of the same factor should meet the requirement

$$A_1 + A_2 + A_3 + \dots A_k = 0 \tag{2}$$

Thus, ensuring the independence of mutual influences among different factors.

Logistic regression

Logistic regression [15–18] is a widely used algorithm in machine learning. It starts with the assumption that the data follows a logistic distribution. Using maximum likelihood estimation, the algorithm determines the error values of the parameters.

Optimization methods such as gradient descent, Newton's method [19], and others are employed to minimize the loss function by identifying the parameter values that yield the smallest error.

Logistic regression can be viewed as a classification method. The associated logistic distribution is a continuous probability distribution, characterized by its probability distribution function (CDF) and probability density function (PDF), defined as follows,

$$\begin{aligned} F(x) &= P(X \leq x) = \frac{1}{1 + e^{-(x-\mu)/\gamma}} \\ f(x) &= F(X \leq x) = \frac{e^{-(x-\mu)/\gamma}}{\gamma(1 + e^{-(x-\mu)/2})^2} \end{aligned} \tag{3}$$

When the probability corresponding to an event exceeds a specific threshold, the event is classified as one type; otherwise, it is classified as another type. The logistic distribution is a continuous probability distribution characterized by its location and scale parameters. The shape of the logistic distribution is similar to that of the normal distribution, but features longer tails. This characteristic makes the logistic distribution suitable for modelling data distributions with longer tails and higher peaks compared to the normal distribution. The sigmoid function commonly used in deep learning is a special case of the logistic distribution function, mapping any real-valued number into a value between 0 and 1.

EXPERIMENTAL DESIGN

Theoretical analysis

In the experimental study conducted in this research, the matching between the specifications of cellulose acetate fibre tows and the crimping machine is primarily influenced by both the single denier and the total number of fibres. The specification of a total deniers is determined by the combined effects of the spinneret and the number of spinneret holes, as described by the following formula:

$$N = \alpha(k,n) \cdot n \tag{4}$$

where, *N* represents the total denier, $\alpha(\cdot)$ is the constraint function, *k*, *m*, and *n* denote the type of spray, positions, and single denier in the spinneret, respectively.

The selection of the spinneret model is constrained by the limitation, which can only correspond to a specific range of single denier specifications. The three factors of single denier, spinneret, and the number of positions cannot form a completely orthogonal design. To address this, we map the spinneret to the single filament, taking the mapping results $\mathcal{S}$ and the number of positions $\mathcal{T}$ as the factors for orthogonal experimental design. Consequently, design a two-factor $(\mathcal{S}, \mathcal{T})$ orthogonal experimental table with 35 levels and 27 levels, respectively.

However, since this experiment involves only two factors, each with numerous levels, using a single orthogonal experimental table for modelling would still require a lot of experiments, failing to demonstrate the advantages of orthogonal experimental design in reducing experimental complexity. To achieve a better design for the experimental setup with two factors and multiple levels in this study, we adopted the concept of "blocking". Utilizing LHS, extracted samples with lower levels from factors $\mathcal{S}$ and $\mathcal{T}$, resulting in an orthogonal experimental table *L*64 with 2 factors and 8 levels. This process was repeated three times, excluding duplicated sampling points. The resulting baseline orthogonal experimental table is shown in figure 2, *a*, where the horizontal axis $\mathcal{S}$ represents the full mapping combination of single denier and total deniers after applying the constraint function $\alpha(\cdot)$, the vertical axis $\mathcal{T}$ represents the part number. In figure 2, *b*, X_i represents the designed fibre specifications, Y_i represents the curling machine model, $Y_{i,j}$ represents the curling machine model library obtained after bias processing by the preliminary model, $Q_{i,j}$ represents the quality score of the corresponding fibre after passing through the corresponding curling machine, R_L represents the logistic regression model, *M* represents the final 'fibre tows-curling machine' matching model obtained.

Taking the obtained data from the orthogonal experimental table, reverse mapping it to the set of positions ($\mathcal{T}$) and mapping set ($\mathcal{T}$) to single denier specifications, we form the training set *X*, which includes the number of positions *m* and single denier specifications *n*.

Using the existing pairing relationship between single denier, total deniers, and curling machine in Nanxian Company's current production, we establish a logistic regression model R_L. The model takes single denier and total deniers as inputs X_0, and predicts the type of curling machine used in actual production as the output Y_0. We have modelled the existing data to develop a preliminary model M_0 for pairing single filament specifications, total denier, and curling machine types.

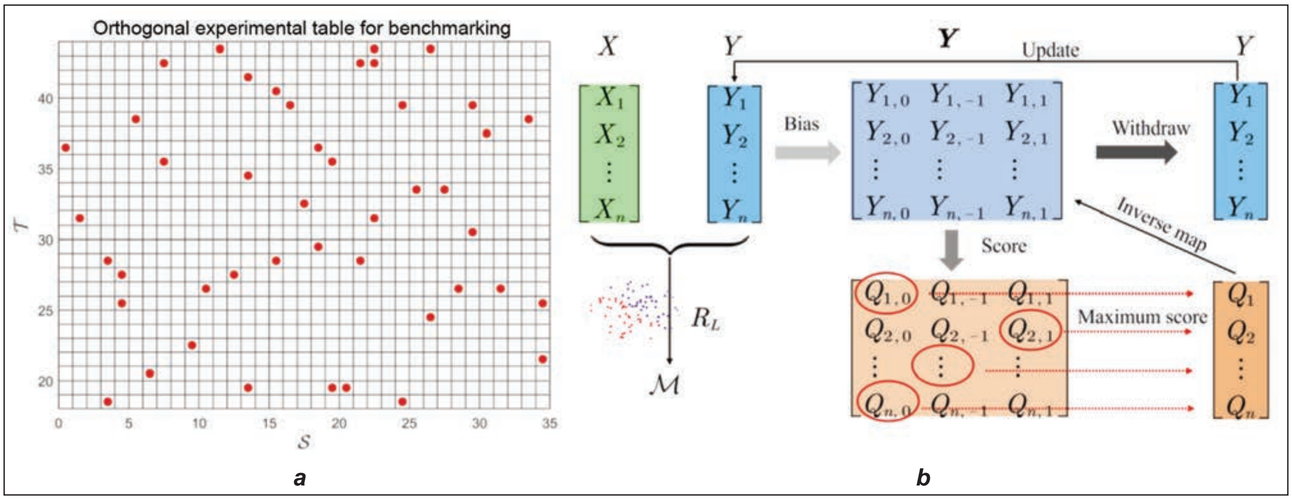


Fig. 2. Images of: *a* – orthogonal experimental table for benchmarking; *b* – update of the Logistic Regression Model

For the obtained training set X, apply the model M_0 to find the matching curling machine model in the training set Y. For each training input X_i and training output Y_i, a bias is applied to Y_i as follows:

$$Y_i \leftarrow [Y_{i,0}, Y_{i,-1}, Y_{i,1}] \quad (5)$$

Through the obtained relationship (X, Y), i.e., the experimental matching relationship between single denier, total denier X_i and curling machine Y_i, physical experiments are conducted by the technical department of NanXian Company. This resulted in semi-finished filament tows after curling, and the quality of the filament tows was evaluated and scored as $Q_{i,*}$.

For each training input X_i, a set of curling machine types Y_i and the corresponding fibre quality scores $Q_{i,*}$ can be obtained. By searching for the highest fibre quality score and its corresponding curling machine type Y_i, the original logistic regression model can be updated. Subsequently, the updated single denier, total deniers and curling machine matching model M is retrained. The flowchart is illustrated in figure 2, *b*.

Design of evaluation indicators

Through testing and analysis of the final selected experimental fibre tows in terms of curl stability, filter rod stability, flying ashes, number of curls in the fibre, breaking strength, etc., an evaluation of the final quality of fibre curling is conducted. This evaluation aims to refine the initial curling machine model, M_0.

The scoring will primarily consider suction resistance stability (suction resistance CV), accounting for 80%, curling stability accounting for 10%, fibre fly and number of curls, each contributing 5% to the overall evaluation. The final fibre curling score, denoted as Q, will be generated based on these factors.

The design flow chart of the overall experiment is shown in figure 3, *a*.

Table 2

SPECIFICATION FOR SUCTION RESISTANCE STABILITY TESTING		
Norm	**Value**	**Unit**
Conventional Filter Rod Circumference	24.2	mm
Circumference of small and medium branch filter rods	19.9	mm
Circumference of large and medium branch filter rods	22.0	mm
Fine branch filter rod circumference	16.9	mm

EXPERIMENT AND THEORETICAL ANALYSIS

Experiment result

According to the experimental design, the data was modelled using the proposed approach, and the classification performance on the test set is illustrated in figure 3, *b*. The characteristics of single denier, total deniers, etc., in the figure have been subjected to biasing for confidentiality reasons.

The scatter plot displays the specifications of single denier and total deniers in production. The colour of the scatter points indicates the corresponding curling machine. Curling machine F covers a relatively extensive region across the phase plane. Curling machine E is primarily located in areas with low single denier characteristics and high total deniers characteristics, forming the boundary between machines E and F. Curling machine B, in comparison to machine F, shows a slightly lower ratio of total deniers characteristics to single denier characteristics. Curling machine H is predominantly found in regions with higher single denier characteristics.

In the test set, the comparison between predicted models for the curling machine types and the actual true values is presented in table 3. And the accuracy of the testing reached a precision of 88.889%.

Theoretical analysis

The physical characteristics of the fibres are essentially consistent. Therefore, it can be inferred that the

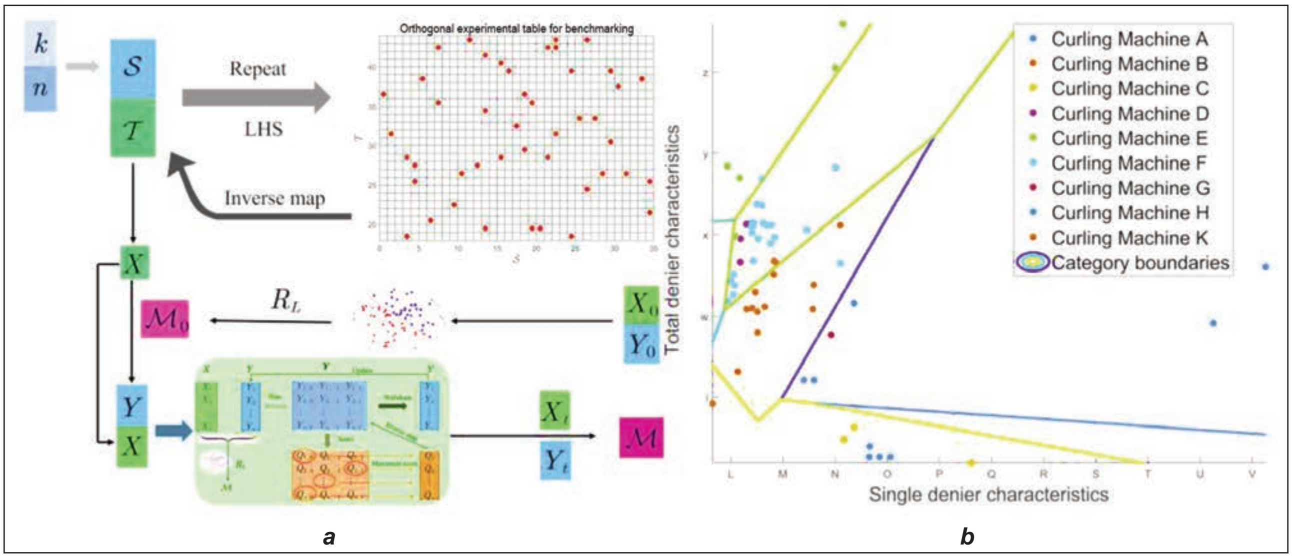


Fig. 3. Images of: *a* – Comprehensive flowchart of experimental design; *b* – Regression and classification model diagram

Table 3

MODEL TEST SET COMPARISON																		
Predict	F	B	F	**D**	F	F	B	F	F	F	B	**C**	E	**G**	B	H	A	K
True	F	B	F	**F**	F	F	B	F	F	F	B	**H**	E	**A**	B	H	A	K

pressure exerted on the unit pressed surface (line) of a single denier, when it undergoes curling due to the rolling and pressing of the crimping machine, should be approximately the same. In other words, there should be a linear relationship between the roller pressure and the roller wheel width. The ratio of the roller pressure to the roller wheel width, and similarly, the ratio of the roller pressure to the cross-sectional area of a single denier, should be constant for the single denier pressure.

Through analysis and verification of experimental data, the relationship between roller pressure and roller wheel width of the curling machine is shown in figure 4, *a*, and the variation of single denier pressure obtained from data of each fibre tow is shown in figure 4, *b*.

It can be observed that the single denier pressure does not remain constant but instead exhibits a certain trend of change, contrary to our initial speculation. However, the specifications of the denier tows entering the crimping machine are also influenced by the number of fibres. Therefore, we infer that there is a functional relationship between the roller pressure and the number of fibres.

The force on the plastic deformation of a single denier is consistent, and there are gaps between single denier and total deniers as they enter the curling machine, there should be a corresponding functional relationship between the force and the number of fibres. This function is directly affected by the specifications and quantity of tows. That is, there is a strong coupling relationship between roller pressure and the tows. Based on this, we analyse and verify the relationship, as shown in figure 4, *c*.

There is a strong linear coupling relationship between the single denier pressure and the quantity

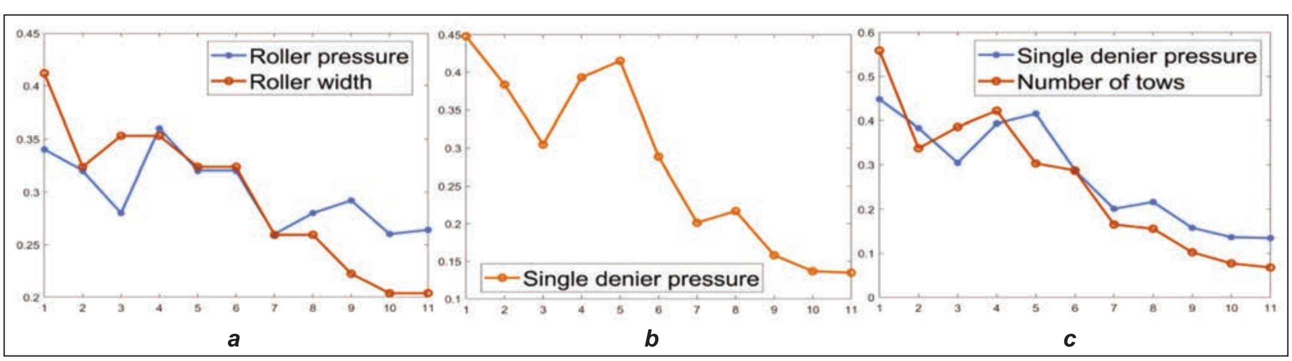


Fig. 4. Graphs of: *a* – the relationship between the curling machine roller pressure and the roller width, with the fibres number on the horizontal axis and the normalized data value on the vertical axis; *b* – the ratio of roller pressure to the cross-sectional area of a single denier-the variation of single-strand pressure with fibre specifications; *c* – the relationship between single-denier pressure and the specifications of the number of tows

of fibre tows. Considering the impact of measurement errors and random factors, it can be approximated that there is a positive correlation between them. Based on this observation, we can proceed with theoretical analysis and modelling of the relationship between fibre specifications and the type of crimping machine.

Definition 1. (*Roll pressure P_{roll}*). *The ratio between the rolling force F_{roll} and the width of the rolling element W_{roll} is defined as the rolling pressure*

$$P_{roll} = \frac{F_{roll}}{W_{roll}}.$$

Definition 2. (*Fibre pressure P_s*). *The ratio between the rolling pressure P_{roll} and the cross-sectional area of a single denier S_a is denoted as the fibre pressure*

$$P_s = \frac{F_{roll}}{S_a}.$$

The selection of the curling machine is denoted as M, the rolling force as F_{roll}, the cross-sectional area of a single denier as S_a, and the number of tows as N. The relationship among these variables can be expressed as follows:

$$\frac{\frac{F_{roll}}{M}}{S_a} \cdot N = C \tag{6}$$

where, C is a constant coefficient.

The selection of the curling machine corresponds to the choice of the rolling element width model, and there exists a proportional relationship between the cross-sectional area of a single denier S_a and the diameter of the single denier D_s expressed as:

$$S_a = C_1 D_s \tag{7}$$

where, C_1 represents the linear coefficient between the cross-section area of the denier per fibre.

The relationship between the total deniers D_t and the cross-sectional area S_a can be expressed as:

$$D_t = C_2 C_1 S_a N \tag{8}$$

Therefore, the relationship between the curling machine M and the diameter of a single denier D_s, as well as the total deniers D_t can be expressed as:

$$M = \frac{C C_1^3 D_s^2}{\frac{D_t}{C_2} F_{roll}} \tag{9}$$

The relationship between the curling machine, the width of the rolling element, the number of tows, the rolling force, and the cross-sectional area of a single denier can be expressed as:

$$M \propto W_{roll} \propto N \frac{F_{roll}}{CS_a} \tag{10}$$

DISCUSSION AND CONCLUSION

In this study, we developed a matching model by analysing the relationships between single denier, total denier, and crimping machines in practical production. Building on this model, we refined it by adjusting the selection criteria and validating these adjustments through experimentation. The updated training model improved upon the original, leading to the final matching model, with regression results shown in figure 3, *b*. The experimental design revealed a significant nonlinear relationship between the type of crimping machine and the specifications of both single and total deniers. Figure 3, *b* illustrates the fundamental distribution, with axes representing inputs (single denier and total deniers) and colours representing outputs (the type of crimping machine). After two rounds of training corrections, the classification relationships for the original data are depicted by the enclosed data points in figure 3, *b*. And the final model's performance on the test set is summarized in table 3.

The basic relationships between the data revealed significant non-linearity and instances where input data were closely situated at extreme operating points. Despite the proximity of the input data, variations in the selected crimping machine were observed. This is illustrated in the dense enclosure region in the top-left corner of figure 3, *b*, which includes two additional crimping machine types within the region for crimping machine F. Both the training data and actual production data indicated that crimping machine F was the predominant choice, covering nearly the entire range of single and total deniers. In contrast, the other five crimping machine types were distributed sporadically, with significantly lower occurrences and probabilities compared to crimping machine F. This uneven distribution presented considerable challenges for modelling and regression of these less common crimping machine types.

In this study, we developed a theoretical reference model based on experimental data to link fibre tows with crimping machines. We constructed a matching model to guide the selection of crimping machines based on fibre specifications. This model helps identify suitable crimping machine specifications within a narrower range, enhances the quality of fibre crimping, significantly reduces the number of required experiments, and lowers production costs.

Additionally, it provides preliminary guidance for further exploration of the fibre crimping mechanism. Future experimental improvements will focus on expanding the model's adaptability to less common crimping machine types, enabling it to better accommodate a broader range of single denier, total deniers, and crimping machine types.

REFERENCES

[1] Shujie, Z., Xiangping, S., Jun, C., et al., *Property and application of cellulose acetate fibre*, In: J. Tianjin Polytech. Univ., 2015, 34, 02, 38–42

[2] Zhang, D., *Advances in filament yarn spinning of textiles and polymers*, Elsevier, 2014

[3] Wang, *Study on the structure and properties of acetate fibre*, 2010

[4] Yadav, N., Hakkarainen, M., *Degradable or not? Cellulose acetate as a model for complicated interplay between structure, environment and degradation*, In: Chemosphere, 2011, 265, 128731

[5] Serbruyns, L., Van de Perre, D., Hölter, D., *Biodegradability of cellulose diacetate in aqueous environments*, In: J. Polym. Environ., 2024, 32, 3, 1326–1341

[6] Yuan, T., Xu, W., Wang, D., *Research on the input width of the cellulose diacetate tow before entering the crimping machine*, In: Synth. Fibre China, 2022, 51, 08, 17–20, https://doi.org/10.16090/j.cnki.hcxw.2022.08.006

[7] Zhanping, Y., *Discussion on crimp process of acetate tows*, In: Tob. Sci. Technol., 2001, 09, 9–12

[8] Zhang, L., Effects of the structure and properties of the cellulose fibre on microwave treatment and its aplications, PhD Thesis, Donghua University, 2008

[9] Cairui, L., Hong, L., Tao, L., Xiaolong, J., *Study on spinnability and related indexes of cellulose diacetate tow*, In: Synth. Fibre China, 2023, 52, 08, 30–34, https://doi.org/10.16090/j.cnki.hcxw.2023.08.023

[10] Nan, Y., *Horizontal stuffing box type curling machine working principle and the main factors affecting the curling number analysis*, In: Text. Mach., 2014, 08, 88–91

[11] Loh, W.-L., On Latin hypercube sampling, In: Ann. Stat., 1996, 24, 5, 2058–2080

[12] Longfei, Y., et al., *Probabilistic Evaluation of Short-Circuit Currents Based on Latin Hypercube Sampling*, In: 2021 IEEE Sustainable Power and Energy Conference (iSPEC), 2021, 1529–1534

[13] Kempthorne, O., *The design and analysis of experiments*, LWW, 1952, 73

[14] Artin, E., Milgram, A.N., *Galois theory*, Courier Corporation, 1998, 2

[15] LaValley, M.P., *Logistic regression*, In: Circulation, 2008, 117, 18, 2395–2399

[16] James, G., Witten, D., Hastie, T., Tibshirani, R., et al., *An introduction to statistical learning*, Springer, 2013, 112

[17] Baştanlar, Y., Özuysal, M., *Introduction to machine learning*, In: MiRNomics MicroRNA Biol. Comput. Anal., 2014, 105–128

[18] Liming, J., Xingwang, X., Zirong, Y., *A classification model of diesel engine operating conditions based on logistics regression*, In: SMALL Intern. Combust. ENGINE Veh. Tech., 2023, 52, 02, 6–9 and 20

[19] Kress, R., *Numerical analysis*, Springer Science & Business Media, 2012, 181

Authors:

LI ZHANG[1], HAOXUAN SHI[1], ZONG CHEN[2], JIANXING HUANG[1], JIAHUI GAO[2], YIQUN LI[2,3]

[1]Fibre and Novel Tobacco Materials Research Department, Nantong Cellulose Fibres Co., Ltd. Zhongxiu Road, Nantong, 226008, Jiangsu, China
e-mail: zhangli@ncfcinfo.com, nantonghjx@sina.com

[2]Huazhong University of Science and Technology, The State Key Laboratory of Intelligent Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Luoyu Road, Wuhan, 430074, Hubei, China
e-mail: M202170539@hust.edu.cn (Zong Chen), M202170655@hust.edu.cn (Jiahui Gao), liyiqun@hust.edu.cn (Yiqun Li)

[3]Research Center for Intelligent Fibre Devices and Equipment and State Key Laboratory of New Textile Materials and Advanced Processing, Huazhong University of Science and Technology, Wuhan 430074, China
e-mail: liyiqun@hust.edu.cn (Yiqun Li)

Corresponding author:

HAOXUAN SHI
e-mail: 11240@ncfcinfo.com

Methylene blue removal capabilities of activated carbon doped nanofibres

DOI: 10.35530/IT.076.02.202457

GAMZE D. TETIK
RAGIPHAN OZTURAN
MURAT ERCAN

ABSTRACT – REZUMAT

Methylene blue removal capabilities of activated carbon doped nanofibres

The importance of adsorbents in wastewater treatment is related to their pollutant removal efficiency. The performance in the treatment process depends on the surface area, morphology, and chemical structure of the adsorbents. Since these properties can be controlled in both nanofibres and activated carbon, activated carbon (AC) doped nanofibres were used to remove methylene blue (MB) from the aqueous medium in this study. For this purpose, AC was synthesized from human hair by chemical activation and characterized. By this means, AC possessing 561 m^2/g Brunauer-Emmet-Teller (BET) surface area and 6.5% ash content was obtained. Thermogravimetric analysis of the AC showed that approximately. 50% of the initial weight decomposed at 750°C. The synthesized AC was doped into the silk fibroin (SF) electrospinning solution at the ratios of 1% and 5% (w/v). Scanning electron microscope and energy dispersive X-ray analyses, and BET surface area measurements were conducted for characterization. Finally, batch adsorption tests were performed under different conditions, assisted with an ultrasonic bath. According to the test results, 5% AC-doped nanofibre web with 15 mg of adsorbent amount exhibited the best performance among nanofibre webs with an adsorption amount of 262.3 mg/g. This value was achieved at pH 12, 50°C, and an ultrasonic bath-assisted process duration of 10 min. The overall results showed that the AC synthesized from human hair-doped SF nanofibre webs has the potential to remove MB from textile wastewater.

Keywords: *activated carbon, adsorption, electrospinning, nanofibre, methylene blue, wastewater*

Proprietăți de eliminare a albastrului de metilen din nanofibre dopate cu carbon activ

Importanța adsorbanților în tratarea apelor reziduale este legată de eficiența lor de eliminare a poluanților. Performanța în procesul de tratare depinde de suprafața, morfologia și structura chimică a adsorbanților. Deoarece aceste proprietăți pot fi controlate atât în nanofibre, cât și în cărbunele activ, nanofibrele dopate cu cărbune activ (CA) au fost utilizate în acest studiu pentru a îndepărta albastrul de metilen (MB) din mediul apos. În acest scop, AC a fost sintetizat din păr uman prin activare chimică și caracterizat. Prin acest mijloc, s-a obținut AC care posedă o suprafață Brunauer-Emmet-Teller (BET) de 561 m^2/g și un conținut de cenușă de 6,5%. Analiza termogravimetrică a CA a arătat că aprox. 50% din greutatea inițială s-a descompus la 750°C. AC sintetizat a fost dopat în soluția de electrofilare a fibroinei de mătase (SF) în proporții de 1% și 5% (w/v). Pentru caracterizare au fost efectuate analize la microscopul electronic cu baleiaj și cu raze X cu dispersie de energie și măsurători ale suprafeței BET. În cele din urmă, au fost efectuate teste de adsorbție pe loturi în diferite condiții de asistență cu baie cu ultrasunete. Conform rezultatelor testelor, vălul de nanofibre dopat cu 5% AC cu o cantitate de adsorbant de 15 mg a prezentat cea mai bună performanță dintre vălurile de nanofibre cu o cantitate de adsorbție de 262,3 mg/g. Această valoare a fost obținută la pH 12, 50°C și o durată a procesului asistat de baie cu ultrasunete de 10 min. Rezultatele generale au arătat că AC sintetizat din păr uman dopat cu nanofibre SF are potențialul de a elimina MB din apele reziduale textile.

Cuvinte-cheie*: cărbune activ, adsorbție, electrofilare, nanofibre, albastru de metilen, ape reziduale*

INTRODUCTION

The rise in demand for industrial products increases the use of various chemicals consumed during the production of these products, and sometimes causes these chemicals to be released into natural environments uncontrollably and in a way that harms the environment. The negative effects of the textile industry in terms of harmful chemicals released into the environment are undeniable. As the effluent discharged after domestic use or industrial processes is defined as wastewater [1], textile wastewater contains phosphates, organic dyes or heavy metals [2]. These substances harm living creatures as well as the environment. For this reason, the treatment of wastewater appears to be a very important issue. Currently, wastewater treatment is controlled by various international or national laws and regulations, and it is not possible to release wastewater into the environment without reducing the amount of harmful chemicals below a certain level. Physical, biological, and/or chemical processes are utilized to reduce the chemicals contained in the wastewater to specified values [3]. The removal of dissolved impurities from textile wastewater is often achieved by chemical or physical adsorption. The principle of adsorption is based on the accumulation of substances to be removed in a fluid environment on solid adsorbents through chemical or physical interactions [4]. While in physical adsorption, the chemicals to be removed (adsorbates) and the surface atoms of solid adsorbents interact via van der Waals forces or electrostatic attraction forces, in chemical adsorption, surface atoms of adsorbates and adsorbents form chemical bonds [5, 6]. Activated carbon, silica, clays, metal oxides, and polymer-based materials can be used as adsorbents in both chemical and physical adsorption [7, 8].

It is known that there is a significant use of dyestuffs in the textile industry. These coloured substances cause some hazards and environmental problems. Approximately 10–15% of the dyestuffs are discharged as waste. One of the hazardous dyestuffs frequently encountered in textile wastewater is methylene blue (MB), also called methylthioninium chloride. The MB, a compound with a heterocyclic aromatic structure, creates a dark blue colour when dissolved in water. To protect both water bodies and aquatic ecosystems, this toxic component should be removed from wastewater [9, 10]. Since it is important to remove MB, which damages the habitat by making it difficult to transfer sunlight in waterbodies and causes the formation of single oxygen, from textile wastewater [11–14], the MB was chosen as the adsorbate in this study.

Activated carbon (AC), which can be produced from all raw materials containing at least 40–50% carbon by a (physical or chemical) activation treatment following the carbonization process, is an indispensable product for the adsorption process. The high surface area makes activated carbon significant for adsorption. In carbonization, an attempt is made to obtain the main skeleton from the structure, in which moisture and volatile substances are removed. Oxidation occurs in the activation process. Besides, the pore structure formed in the previous stage is developed through controlling parameters [15]. In this way, a product with a high specific surface area and increased adsorbate binding points is obtained. Commercial ACs, with specific surface areas of up to 1000 m^2/g, are highly preferred adsorbents in the removal of undesirable substances from wastewater due to their performance. However, its high cost poses a problem for its widespread use [16]. The use of different wastes as raw materials in activated carbon synthesis has recently started to attract attention. In studies carried out to date, textile waste [17, 18], tea waste [19], coffee waste [20], and municipal waste [21] are the wastes used in the synthesis of AC. Moreover, there are studies in which human hair is used as a raw material. In a study, which chemical activation chosen for synthesis, activated carbon with a surface area of ~36 m^2/g is obtained [22]. In another study, AC from human hair waste is used in the adsorption of reactive violet and acid green 4G from aqueous solutions [23]. This study focused on the selection of human hair, which has a carbon content of 45% [24], as a waste raw material to reduce the cost of activated carbon.

The properties developed by the production of materials at the nanoscale have led to the design and production of remarkable nanoscale products for environmental applications as well as in many application areas [25]. Nanofibre webs that are composed of nanosized fibres are utilized in various areas such as filtration, separation, sensor applications, and adsorption. Their small unit structure sizes make them effective in these applications. The reduction of the unit structure to the nanoscale results in an increase in the number of regions that will be active in adsorption, thus increasing the possibility of interaction between the nanofibrous web acting as an adsorbent and the molecules of the adsorbate. Nanofibres suitable for adsorption purposes can be obtained using different raw materials with the electrospinning method, which allows nanofibre production with simple equipment. Carbon and various polymers such as poly(acrylic acid), poly(styrene) or cellulose acetate have been tested in numerous studies to remove MB in aqueous media. The adsorption amounts varying between 40–400 mg/g have been obtained in various studies [26–29]. The maximum adsorption capacity of ~72 mg/g has been reached in a study examining MB adsorption with nanofibres formed with AC obtained from poly(acrylonitrile) [30]. There is no effective study in the literature involving the adsorption of MB by activated carbon-doped nanofibre webs. In this study, it was aimed to investigate the removal efficiency of MB from the aqueous medium by taking advantage of both the high surface areas and high adsorption capacities of nanofibres and activated carbon in a cost-effective way. In this regard, the results obtained are expected to make significant contributions to the literature.

MATERIALS AND METHODS

The hair used to produce activated carbon (AC) in the study was purchased commercially (in the form of a raw human hair wig). Human hair contains a high amount of carbon, and it is a no-cost waste material with easy availability. Silk fibroin (SF) was chosen as the polymer into which activated carbon is doped. Silk was supplied in filament form from a local company (Bursa, Türkiye) and silk fibroin was obtained according to the procedure specified in the literature [31]. Briefly, silk was degummed through boiling in 0.05% sodium carbonate aqueous solution for 30 min three times. After rinsing and drying, aqueous SF solutions were prepared by dissolving SF in Ajisawa solution ($CaCl_2$/distilled water/ethanol with molar ratios of 1:8:2). The dialysis process was performed in SnakeSkin® dialysis tubings (Thermo Scientific, IL, USA) at +4°C for three days to obtain a SF aqueous solution free from neutral salts. Then the solutions were cast, and the SF films were obtained by drying at room temperature. Medical syringes and needle tips used in electrospinning were obtained from a local company. Ethanol (with a 0.79 g/cm^3 density and ACS grade), formic acid (with 98% purity), and methylene blue (possessing a solubility of 50 g/l, with a 373.9 g/mol molecular weight, and 400–600 kg/m^3 bulk density) were purchased from Merck (Germany). Sodium carbonate (in powder form, with a purity of ≥99.5% and ACS reagent), calcium chloride (in powder form), sodium hydroxide (in pellet form, ACS reagent, and with ≥97.0% purity), hydrochloric acid (ACS reagent and 37%), sulfuric acid (with 95–97% purity) were provided from Sigma Aldrich (Germany). Distilled water was used in all experiments.

AC Synthesis

The hair was subjected to a cleaning process to make it ready for synthesis. For this purpose, hairs were soaked in 70% (v/v) ethanol at room temperature for 20 minutes, and the process was repeated three times. After the final process of rinsing with distilled water, it was filtered using filter paper and then dried in an oven at 60°C. The dried hair was cut into a length of approximately. 1.0–1.5 cm with the help of scissors to facilitate the subsequent procedures.

The chemical activation method was chosen to synthesize the AC. The chemical agent used for activation was sulfuric acid. The hair was saturated with sulfuric acid by keeping it in a 20% (v/v) sulfuric acid solution for 1 h. The impregnation ratio, the ratio between the AC raw material and the chemical agent, was 1:4. Since the saturated hair should be dry before the carbonization process, the hair was dried for 24 hours in an oven set at 60°C.

A furnace (Protherm MOS 160/8, Ankara, Türkiye) was used for the carbonization process of the chemically activated and fully dried hair. To ensure that the atmosphere inside the furnace chamber is inert, the high-purity argon gas tube is tightly connected to the furnace chamber inlet. The flow rate was adjusted to approximately. 0.5 L/min with the regulator on the tube. The temperatures that can be selected according to the raw material generally vary between 500°C and 900°C [32]. In this study, 650°C was chosen as the maximum carbonization temperature. It is known that higher carbonization temperature reduces efficiency [33]. The temperature was increased from room temperature (20°C) to 650°C in 210 min with a heating rate of 3°C/min. The waiting time was set to 2 hours. After this period, the furnace was allowed to cool by itself, and the argon gas flow continued during the cooling process.

The samples taken out of the chamber were first washed with 0.5 M HCl to remove residual chemicals from them. Then they were washed with hot and cold distilled water, respectively. The drying was performed in an oven at 60°C for 24 hours. The synthesized AC was used in dry powder form for characterization and production of AC-doped nanofibre webs.

Fabrication of AC doped SF nanofibre webs

Silk fibroin is attractive due to its high biocompatibility, good thermal stability, and high mechanical strength, as well as the presence of various amino acid groups that provide great advantages for the adsorption of adsorbates [34]. Moreover, it is one of the easiest polymers to electrospin. Electrospinning is a method that allows the manufacture of nano-scaled fibres from a wide variety of materials. Additives can be easily incorporated into nanofibre webs by adding to electrospinning polymer solutions. In this study, 15% (w/v) SF/formic acid solutions were prepared. The AC was doped to these solutions in ratios of 1%, 5% and 10% (w/v). SF nanofibres without AC were also fabricated to use as control webs (blank) in adsorption tests. Although electrospinning was tried with all these solutions, no jet formation was observed with 10% (w/v) AC-doped solution. Samples doped with 1% and 5% (w/v) AC were fabricated by electrospinning for 5 hours. The samples are coded according to the amount of AC they contain. Nanofibre webs fabricated using SF solution without AC, SF solution doped with 1% (w/v) AC, and SF solution doped with 5% (w/v) AC are coded as 0ACSF, 1ACSF, and 5ACSF, respectively.

The 20–24 kV applied voltage, 0.24 mL/h flow rate, and 20 cm distance were the electrospinning process parameters. A 20 mL eccentric plastic syringe and a flattened 21G metal needle tip were used for solution feeding via a syringe pump (New Era Ne-1000, USA). A high voltage power supply (Gamma High Voltage Research Inc., USA) was used, and an aluminium foil-coated fixed plate was the grounded collector. Nanofibre spinning was performed at room temperature (20 ± 2°C) and 30 ± 5% relative humidity.

Characterization tests

Scanning electron microscopy (SEM, LEO 1430 VP) analyses were performed to determine the morphology of synthesized AC and nanofibre webs. The AC sample was analysed by directly sticking it on double-sided carbon tapes. On the other hand, nanofibre web samples were coated with gold for 30 s before analysis. The accelerating voltage applied in the analyses was 20 kV. The magnifications are 500 and 5000X for AC, and 2500 and 10000X for nanofibre web samples. In addition, EDX analyses were performed on the AC and the nanofibre web samples to determine elemental components. The mean diameters of the nanofibre web samples were calculated with Image-J Measurement Software by measuring 50 nanofibres' diameters from each SEM image.

Thermogravimetric analysis (TGA) of the synthesized AC was conducted by TG/DSC (Differential Scanning Calorimetry) analyser (Netzsch STA 449F3, Germany). The thermogram of the AC was recorded between 25°C and 750°C with a heating rate of 10°C/min, under a nitrogen atmosphere and using an AL_2O_3 crucible with a 10 mg AC sample.

In addition, the amount of ash in the synthesized AC was determined according to ASTM-D 2866-94.

1 g of activated carbon was placed in porcelain crucibles (50×25 mm, Isolab) and brought to constant weight at 650°C. Again, the samples placed in the muffle furnace (ELF 11/6B, Carbolite, England) at

650°C were burned for about 6 hours to reach constant weight. Then, they were cooled to room temperature in the desiccator. An analytical balance with an accuracy of 0.1 mg was used during the measurements (Radwag, Poland). The amount of ash was calculated by equation 1:

$$Ash\ content(\%) = \frac{(B - C)}{(A - C)} \cdot 100 \qquad (1)$$

where, A is the "crucible weight + AC amount at the beginning of the process", B is the "crucible weight + AC amount at the end of the process", and C is the "crucible weight".

Since the surface area of AC and nanofibre webs is of great importance in the adsorption process, BET surface area measurement was performed with a Micrometrics Gemini 2360 model (USA) computer-equipped device. The specific surface area measurement was based on the nitrogen (N_2) gas adsorption technique in a liquid nitrogen environment at –198°C. The device sensitivity was 0.01 m^2/g.

Batch adsorption tests were carried out to determine the potential of AC-doped SF nanofibre webs to be used as adsorbents. For this purpose, the highest absorbance wavelength of the MB was detected by a UV-visible spectrophotometer (Biochrom Libra S70, UK). Scanning was performed by considering distilled water as a blank. The highest absorbance was recorded at 670 nm by the results stated in the literature [11]. All subsequent absorbance measurements were performed at 670 nm. The MB solution with a concentration of 100 mg/l was prepared, and 8 sets of dilutions were made to obtain a calibration curve. The MB removal percent from aqueous solutions was determined using the equation derived from the calibration curve of MB ($y = 0.1348x – 0.0013$ with a R^2 of 0.9971).

Since the adsorption process is affected by parameters such as stirring type, stirring speed, adsorbent amount or process duration, several parameters were chosen for the determination of the maximum MB removal percentage. In this study, ultrasonic bath-assisted adsorption tests were performed. All tests were carried out in an ultrasonic bath (Elmasonic Easy 100 H, Elma, Germany). The ultrasonic frequency of the device was 37 kHz, and the effective ultrasonic power was 150 W. Three process durations of 2, 6, and 10 minutes, two temperatures of 30 and 50°C, and three amounts of adsorbent as 5, 10, and 15 mg, were tested. The pH values were selected as pH 5 and pH 12 to test acidic and basic aqueous media. All tests were carried out in 50 ml of MB aqueous solution with an initial concentration of 100 mg/l, and pH adjustment was made with either HCl or NaOH.

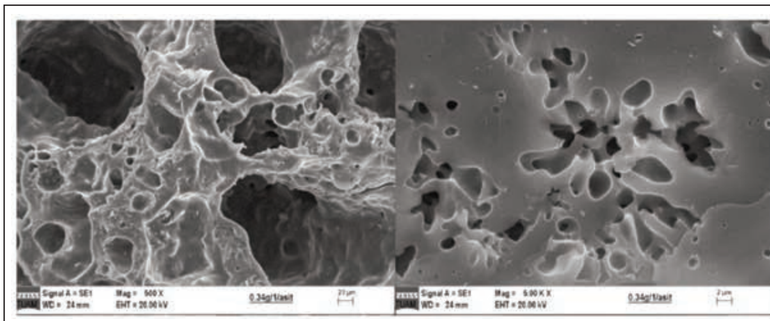
The mean of the absorbance values of the activated carbon-free (0ACSF) nanofibre web samples in pure water at 670 nm was subtracted from all absorbances recorded with the MB aqueous solution. The obtained absorbance values were converted to concentration based on the calibration curve, and the adsorption amount, Q (in mg/g), was calculated using equation 2:

$$Q = \frac{V(C_i - C_f)}{W} \qquad (2)$$

Where V is the volume of the MB aqueous solution (medium) in L, C_i and C_f are the initial and final MB concentrations in mg/l, respectively, and W is the weight of the adsorbent nanofibre web in g. Mean Q values of triplicate measurements are given.

RESULTS AND DISCUSSIONS

Synthesizing AC from low-cost or no-cost materials has attracted attention in recent years. Since the adsorption capability of AC is high due to its characteristic properties, researchers focus on cost reduction research by selecting suitable raw materials. Human hair is one of these suitable materials with high carbon content. The SEM images of the AC synthesized by chemical activation and carbonization process are seen in figure 1, *a* and *b*. Pores with radii smaller than 0.4 nm, pores between 0.4–1 nm, pores between 1–25 nm, and pores with 25 nm and above are called sub-micropores, micropores, mesopores, and macropores, respectively [35]. When the SEM images are examined, a highly porous structure with cavities is observed, and the pores are on a macro scale. The cavities seen on the SEM images of the AC may serve as functional sites for the adsorption of the agent that is desired to be adsorbed. Moreover, according to the International Union of Pure and



EDX

Element	Series	Net	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	28994	27.48	27.45	40.09
Nitrogen	K series	3229	18.44	18.42	23.07
Oxygen	K series	5551	22.95	22.92	25.13
Sulfur	K series	35584	6.17	6.16	3.37
Chlorine	K series	36231	7.14	7.13	3.53
Zinc	K series	14800	17.93	17.91	4.81

Total: 100.0

a *b* *c*

Fig. 1. Details of: *a* – 0.5KX SEM image; *b* – 5KX SEM image; *c* – EDX analysis result of the synthesized AC

Applied Chemistry's (IUPAC) porous solid materials classification, the AC synthesized was classified as a macroporous solid having pore sizes higher than 50 nm [36]. The SEM-EDX analysis result of the AC is given in figure 1, *c*. When the elemental content analysis of the synthesized AC was examined, 40% carbon content and 25% oxygen content were seen. The results are consistent with the studies in the literature. The carbon and oxygen content of the AC derived from human hair was found to be 49.8% and 30.3%, respectively, in another study [37].

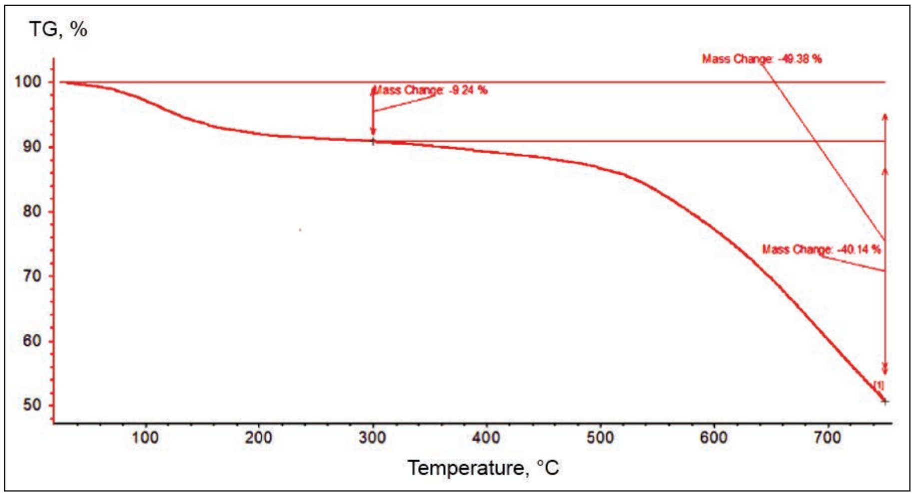


Fig. 2. Thermogram of the AC

According to the BET surface area analysis, the specific surface area of the AC synthesized was 561 m^2/g. that can be stated as a reasonable value when compared with commercial ACs. Since the higher surface area means an enhancement in the adsorption capability [38], the surface area value of the AC synthesized is important in terms of effectiveness.

The ash content of the synthesized AC was experimentally calculated, and 6.5 ± 0.4% ash content was determined. It is necessary for ACs to have low ash content to exhibit high efficiency. This is the main disadvantage of ACs obtained from human hair.

Thermal behaviour of the synthesized AC was investigated with TGA from 25°C to 750°C. Decomposition of the AC was divided into two stages (figure 2). The first stage, which is between 25–300°C, corresponds to the slow pyrolysis and the second stage, which is between 300–750°C, corresponds to the fast pyrolysis step. In the first (slow) stage, 9.24% of the initial mass was lost due to the volatilization of volatile compounds and vaporization of moisture. The higher mass loss (approx. 40%) occurred in the fast decomposition stage up to 750°C. The TGA results proved the high thermal stability of the synthesized AC.

Electrospinning is one of the most preferred methods to get nanofibre webs using versatile polymers and materials for numerous applications. The simple equipment, composed of a high voltage power supply, a syringe pump, and a grounded collector, allows for the production of nanofibres by adjusting process and solution parameters. Silk fibroin (SF) is a challenging polymer for electrospinning because of its easy electrospinnability. Besides, it preserves its thermal stability up to 250°C [39]. In this study, beadles and uniform nanofibre morphologies are obtained from SF and AC-doped SF. The SEM images of the nanofibre webs electrospun without AC, with 1% and 5% AC are given in figure 3. The mean diameters of SF nanofibres without AC, SF nanofibres containing 1% and 5% AC were measured as 263 ± 68 nm, 276 ± 69 nm, and 283 ± 75 nm, respectively. As all the process parameters were kept constant during electrospinning, the mean nanofibre diameter increased with increasing AC content.

According to the SEM-EDX analysis results carbon content of the 0ACSF, 1ACSF, and 5ACSF was determined as 36.91%, 40.80%, and 41.12%, respectively. Increases in both fibre diameters and carbon content were observed with an increase in the AC amount involved. This is the sign of successful incorporation of the AC into the SF nanofibres.

The surface area enhancement of a nanofibre web is related to the nano-scaled unit structure (fibres possessing diameters in nm). The BET surface areas of 0ACSF, 1ACSF, and 5ACSF nanofibre webs were found to be 35.43 m^2/g, 42.38 m^2/g, and 43.58 m^2/g, respectively. These values are slightly different from each other. These little changes in the values are the results of morphological similarities. There was only a 20 nm difference observed (263–283 nm) between the fibre diameters of nanofibre webs. Additionally, there are studies in the literature stating similar surface area values with similar nanofibre diameters [40]. Furthermore, there are publications in the literature regarding nanofibre web applications with similar BET surface area values used for MB adsorption [41].

Since the isoelectronic point of silk fibroin is around 4.2–4.5, two pH values were chosen in this study, one slightly higher than this point (pH 5) and the other an alkaline value (pH 12). Results of batch adsorption tests performed at pH 5 and pH 12 are given in figures 4 and 5, respectively. The adsorption amounts observed at pH 12 were higher than the amounts observed at pH 5. The maximum adsorption amounts recorded were 190.5 mg/g and 262.3 mg/g at pH 5 and pH 12, respectively. SF has a net negative charge in alkaline medium (at about pH 12) [42]. Therefore, batch adsorption tests at this pH value resulted in higher adsorption amounts than at pH 5 due to the increased interactions between the adsorbent – AC doped SF nanofibres – and the adsorbate-MB, a cationic dye. Furthermore, the sample 5ACSF gave the highest adsorption amount results in all

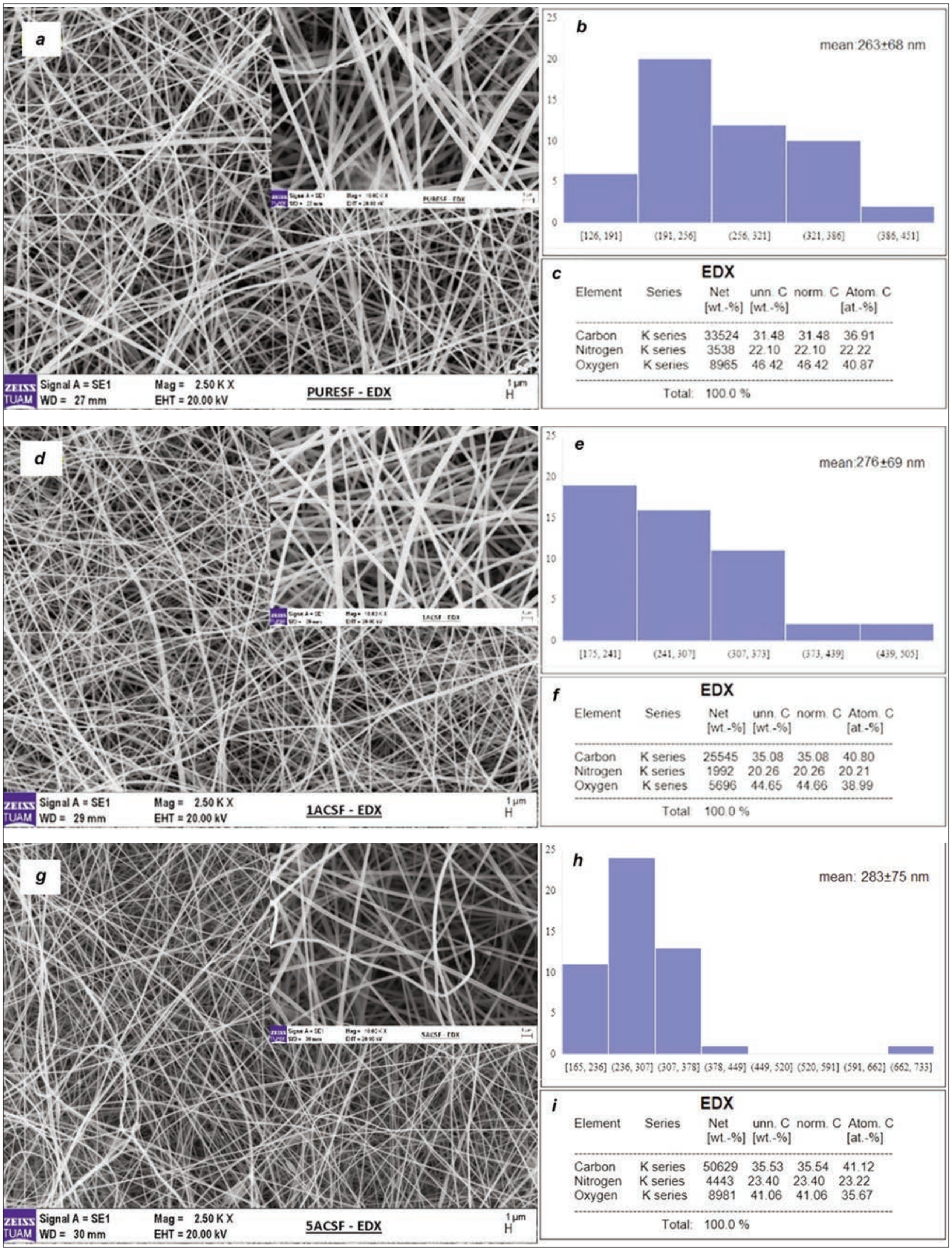


Fig. 3. SEM images (with 2.5KX and 10KX magnification), histograms of nanofibre diameters, and EDX analyses results of: *a, b, c* – 0ACSF; *d, e, f* – 1ACSF; *g, h, i* – 5ACSF

parameters tested. This can be attributed to the adsorption enhancement ability of the AC encountered at high pH values [43].

The adsorbent amount affected the adsorption capacity positively. Increasing the adsorbent amount allows more MB in the aqueous medium to be accumulated by adsorption. This is why among the 5, 10, and 15 mg adsorbent amounts, the highest values were obtained with 15 mg.

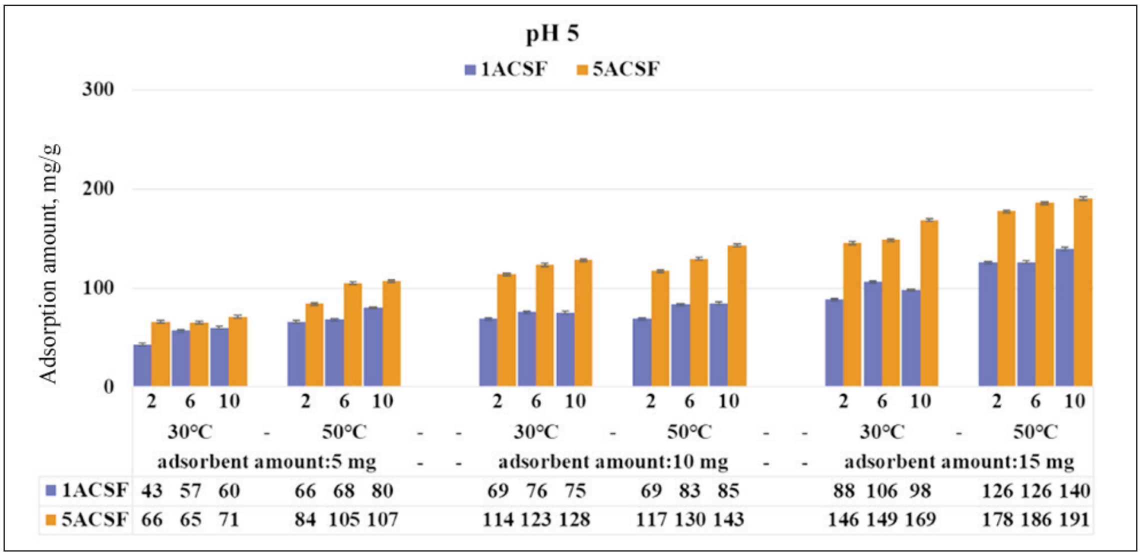


Fig. 4. Adsorption amounts of 1ACSF and 5 ACSF nanofibre webs according to the process parameters at pH 5

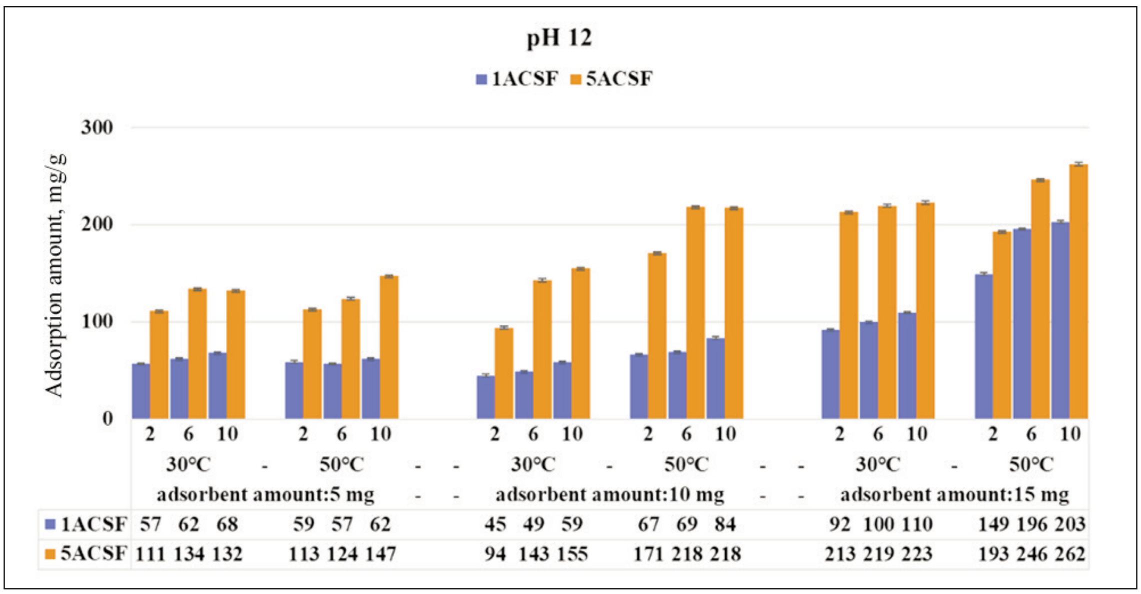


Fig. 5. Adsorption amounts of 1ACSF and 5 ACSF nanofibre webs according to the process parameters at pH 12

According to the batch adsorption test results, as the applied temperature increases, the adsorption amount increases too. Since temperature increases the mobility of molecules in physical or chemical processes, it is an expected phenomenon that adsorption efficiency increases with increasing temperature. In the literature, various temperature ranges have been studied in batch adsorption tests. In this study, two temperatures were selected as low (30°C) and high (50°C). The findings in the literature indicate that temperature appears to be a parameter that improves adsorption [27]. Moreover, the MB adsorption on the SF nanofibres is an endothermic adsorption process [44].

Increasing the processing time means extending the application time of the ultrasonic frequency applied during adsorption. Time extension improves adsorption because it also causes molecular mobility.

Moreover, significant differences between the adsorption amounts of 1ACSF and 5ACSF were observed. As the amount of AC doped increased, the adsorption amount increased. It was revealed that the AC with a higher surface area added to the nanofibres made a considerable contribution to the adsorption phenomenon.

CONCLUSIONS

The results obtained from the study can be summarized as follows: Human hair is a suitable raw material for the synthesis of AC. Chemical activation was chosen for the synthesis of AC from human hair, and macro-porous structured AC with a surface area value of 561 m^2/g was obtained. TGA of the AC denoted that ~9.24% and ~50% mass losses were observed at 300°C and 750°C, respectively. The 1% and 5% AC-doped SF nanofibre webs were produced.

The fibres had a regular morphology and no beads. The mean diameters of SF nanofibres without AC, SF nanofibres containing 1% and 5% AC were measured as 263±68 nm, 276±69 nm, and 283±75 nm, respectively. An increase in diameter was observed with the addition of activated carbon. The BET surface areas of nanofibre webs were found to be 35.43 m^2/g, 42.38 m^2/g, and 43.58 m^2/g for 0ACSF, 1ACSF, and 5ACSF, respectively. BET surface area values were very close to each other, and these values are considerable for adsorption. According to the results of the batch adsorption tests, a maximum of 262 mg/g adsorption amount was recorded with the 5% AC doped nanofibre web at 50°C, pH 12 and with the highest amount of adsorbent (15 mg).

The purpose of all these tests was to demonstrate the usability of activated carbon-doped nanofibres in adsorption. Thus, in the study, it has been shown that it is possible to obtain enhanced adsorption properties by the combined effect of activated carbon obtained from a waste (zero-cost) material like human hair and nanofibres, which are very attractive in wastewater treatment due to their high surface areas. Additionally, ultrasonic vibrations created by the ultrasonic bath where the adsorption media is placed aided the adsorption process and shortened the adsorption duration. Moreover, future studies may include the production of nanofibres by low-cost or recycled polymers.

REFERENCES

[1] Sall, N., Sadique, C.M.Z., Gawde, P., Qureshi, S., Bhadauriya, S.S., *Drain waste water cleaner*, In: Glob J Res Eng: J Gen Eng., 2016, 16, 1, 16–20

[2] Andrade, C.J., Andrade, L.M., *Microalgae for bioremediation of textile wastewater: An overview*, In: MOJ Food Process Technol., 2018, 6, 5, 432–433, https://doi.org/10.15406/mojfpt.2018.06.00200

[3] Kumar, P.S., Saravanan, A., *Sustainable wastewater treatments in the textile sector*, In: Muthu SS, editor. The Textile Institute Book Series Sustainable fibres and textiles., Woodhead Publishing, 2017, 323–346, https://doi.org/10.1016/B978-0-08-102041-8.00011-1

[4] Lameire, N.H., De Vriese, A.S., *Adsorption techniques and the use of sorbents*, In: Contrib Nephrol., 2001, 133, https://doi.org/10.1159/000060121

[5] Suzuki, M., *Adsorption engineering*, Tokyo: Kodansha Ltd and Elsevier Science Publishers, 1990

[6] Deaconu, M., Senin, R., Stoica, R., Athanasiu, A., Crudu, M., Opriou, L., et al., *Adsorption decolorization technique of textile/leather – dye containing effluents*, In: Int J Waste Resour., 2016, 6, 2, 1000212, https://doi.org/10.4172/2252-5211.1000212

[7] Dutta, S., Gupta, B., Srivastava, S.K., Gupta, A.K., *Recent advances on the removal of dyes from wastewater using various adsorbents: A critical review*, In: Mater Adv., 2021, 2, 14, 4497–4531, https://doi.org/10.1039/D1MA00354B

[8] Srebrenkoska, V., Zhezhova, S., Risteski, S., Golomeova, S., *Methods for waste waters treatment in textile industry*, In: International Scientific Conference, 2014 Nov 21–22, Gabrovo, Bulgaria

[9] Ravulapalli, S., Kunta, R., *Effective removal of methylene blue, a hazardous dye from industrial effluents using active carbon of F.infectoria plant*, In: Int J Environ Sci Technol., 2019, 16, https://doi.org/10.1007/s13762-018-2147-3

[10] Mohammad, N., Atassi, Y., *TiO2/PLLA Electrospun nanofibres membranes for efficient removal of methylene blue using sunlight*, In: J Polym Environ., 2021, 29, 2, https://doi.org/10.1007/s10924-020-01895-5

[11] Mahmoud, M.E., Abdelwahab, M.S., *Fabricated and functionalized magnetite/phenylenediamine/cellulose acetate nanocomposite for adsorptive removal of methylene blue*, In: Int J Biol Macromol., 2019, 128, https://doi.org/10.1016/j.ijbiomac.2019.01.102

[12] Melgoza, D., Hernández-Ramírez, A., Peralta-Hernández, J.M., *Comparative efficiencies of the decolourisation of Methylene Blue using Fenton's and photo Fenton's reactions*, In: Photochem Photobiol Sci., 2009, 8, 5, https://doi.org/10.1039/b817287k

[13] Khan, I., Saeed, K., Zekker, I., Zhang, B., Hendi, A.H., Ahmad, A., et al., *Review on methylene blue: Its properties, uses, toxicity and photodegradation*, In: Water, 2022, 14, 242, 1–33, https://doi.org/10.3390/w14020242

[14] Polat, S., Bellıtürk, K., Metınoğlu, M., *Evaluation of agricultural fields in terms of soil productivity and environmental health in the industrial zone*, In: MKU J Agric Sci., 2019, 24, 222–231

[15] Zhu, R., Yu, Q., Li, M., Zhao, H., Jin, S., Huang, Y., et al., *Analysis of factors influencing pore structure development of agricultural and forestry waste-derived activated carbon for adsorption application in gas and liquid phases: A review*, In: J Environ Chem Eng., 2021, 9, 5, 105905, https://doi.org/10.1016/j.jece.2021.105905

[16] Dias, J.M., Alvim-Ferraz, M.C., Almeida, M.F., Rivera-Utrilla, J., Sánchez-Polo, M. *Waste materials for activated carbon preparation and their use in aqueous-phase treatment: A review*, In: J Environ Manage, 2007, 85, 4, 833–846, https://doi.org/10.1016/j.jenvman.2007.07.031

[17] Mia, M.S., Yao, P., Zhu, X., Zhang, J., Xing, T., Chen, G., *Removal of heavy metals from aqueous solutions by modified waste silk*, In: Text Res J., 2022, 92, 11–12, 1952–1965, https://doi.org/10.1177/00405175221076026

[18] Wanassi, B., Hariz, I.B., Ghimbeu, C.M., Vaulot, C., Hassen, M.B., Jeguirim, M., *Carbonaceous adsorbents derived from textile cotton waste for the removal of Alizarin S dye from aqueous effluent: kinetic and equilibrium studies*, In: Environ Sci Pollut Res., 2017, 24, 10041–10055, https://doi.org/10.1007/s11356-017-8410-1

[19] Peng, C., Yan, X., Wang, R., Lang, J., Ou, Y., Xue, Q., *Promising activated carbons derived from waste tea-leaves and their application in high performance supercapacitors electrodes*, In: Electrochim Acta, 2013, 87, 401–408, https://doi.org/10.1016/j.electacta.2012.09.082

[20] Figueroa Campos, G.A., Perez, J.P.H., Block, I., Sagu, S.T., Saravia Celis, P., Taubert, A., et al., *Preparation of activated carbons from spent coffee grounds and coffee parchment and assessment of their adsorbent efficiency*, In: Processes, 2021, 9, 1396, https://doi.org/10.3390/pr9081396

[21] Nagano, S., Tamon, H., Adzumi, T., Nakagawa, K., Suzuki, T., *Activated carbon from municipal waste*, In: Carbon, 2000, 38, 6, 915–920, https://doi.org/10.1016/S0008-6223(99)00208-0

[22] Bal Altuntaş, D., Nevruzoğlu, V., Dokumacı, M., Cam, Ş., *Synthesis and characterization of activated carbon produced from waste human hair mass using chemical activation*, In: Carbon Lett., 2020, 30, 307–313, https://doi.org/10.1007/s42823-019-00099-9

[23] Lansari, I., Benguella, B., Kruchinina, N., Nistratov, A., *Adsorption of textile dyes from aqueous solution using activated carbon from human hair*, In: Reac Kinet Mech Cat., 2022, 135, 1891–1903, https://doi.org/10.1007/s11144-022-02224-8

[24] Chakraborty, I., Lai, S.N., Wu, M.C., Lin, H.Y., Li, C., Wu, J.M., et al., *Charge trapping with α-Fe2O3 nanoparticles accompanied by human hair towards an enriched triboelectric series and a sustainable circular bioeconomy*, In: Mater Horiz., 2021, 8, 11, 3149–3162, https://doi.org/10.1039/D1MH00919B

[25] Pokropivny, V., Lohmus, R., Hussainova, I., Pokropivny, A., Vlassov, S., *Introduction to nanomaterials and nanotechnology*, 1st ed. Tartu, Estonia: Tartu University Press, 2007

[26] Aluigi, A., Rombaldoni, F., Tonetti, C., Jannoke, L., *Study of Methylene Blue adsorption on keratin nanofibrous membranes*, In: J Hazard Mater., 2014, 268, 156–165, https://doi.org/10.1016/j.jhazmat.2014.01.012

[27] Fendi, W.J., Naser, J., *Adsorption isotherms study of methylene blue dye on membranes from electrospun nanofibers*, In: Orient J Chem., 2018, 34, 6, 2884–2894, https://doi.org/10.13005/ojc/340628

[28] Nie, D., Wang, P., Zang, C., Zhang, G., Li, S., Liu, R., et al., *Preparation of ZnO-incorporated porous carbon nanofibres and adsorption performance investigation on methylene blue*, In: ACS Omega, 2022, 7, 2, 2198–2204, https://doi.org/10.1021/acsomega.1c05729

[29] Moradi, E., Ebrahimzadeh, H., Mehrani, Z., Asgharinezhad, A.A., *The efficient removal of methylene blue from water samples using three-dimensional poly (vinyl alcohol)/starch nanofibre membrane as a green nanosorbent*, In: Environ Sci Pollut Res., 2019, 26, 34, 35071–35081, https://doi.org/10.1007/s11356-019-06400-7

[30] Ibupoto, A.S., Qureshi, U.A., Ahmed, F., Khatri, Z., Khatri, M., Maqsood, M., et al., *Reusable carbon nanofibres for efficient removal of methylene blue from aqueous solution*, In: Chem Eng Res Des., 2018, 136, 744–752, https://doi.org/10.1016/j.cherd.2018.06.035

[31] Doğan, G., Başal, G., Bayraktar, O., Özyildiz, F., Uzel, A., Erdoğan, İ., *Bioactive sheath/core nanofibres containing olive leaf extract*, In: Microsc Res Tech, 2016, 79, 1, 38–49, https://doi.org/10.1002/jemt.22603

[32] Karacan, F., Ozden, U., Karacan, S., *Optimization of manufacturing conditions for activated carbon from Turkish lignite by chemical activation using response surface methodology*, In: App Therm Eng., 2007, 27, 7, 1212–1218, https://doi.org/10.1016/J.Applthermaleng.2006.02.046

[33] Li, W., Yang, K., Peng, J., Zhang, L., Guo, S., et al., *Effects of carbonization temperatures on characteristics of porosity in coconut shell chars and activated carbons derived from carbonized coconut shell chars*, In: Ind Crops Prod., 2008, 28, 2, 190–198, https://doi.org/10.1016/j.indcrop.2008.02.012

[34] Martis, L.J., Parushuram, N., Sangappa, Y., *Preparation, characterization, and methylene blue dye adsorption study of silk fibroin–graphene oxide nanocomposites*, In: Environ Sci: Adv., 2022, 1, 285–296, https://doi.org/10.1039/d1va00047k

[35] Çabukçu, S., *Removal of methylene blue from aqueous solutions with zick hydroxide coated activated carbon*, Sakarya: Sakarya University, 2021

[36] ALOthman, Z.A., *A Review: Fundamental Aspects of Silicate Mesoporous Materials*, In: Mater., 2012, 5, 12, 2874–2902, https://doi.org/10.3390/ma5122874

[37] Dubey, P., Maheshwari, P.H., Sundriyal, S., *Human hair-derived porous activated carbon as an efficient matrix for conductive polypyrrole for hybrid supercapacitors*, In: Energ Fuel., 2022, 36, 13218−13228, https://doi.org/10.1021/acs.energyfuels.2c01926

[38] Yang, L., Qin, M., Zhang, G., Yang, J., Yang, J., Zhao, J., *Progress of sensitive materials in chemiresistive sensors for detecting chemical warfare agent simulants: A review*, In: Rev Anal Chem., 2023, 42, 20220052, https://doi.org/10.1515/revac-2022-0052

[39] Sobajo, C., Behzad, F., Yuan, X.F., Bayat, A., *Silk: A potential medium for tissue engineering*, In: Eplasty, 2008, 8, 438–446

[40] He, T., Ma, H., Zhou, Z., Xu, W., Ren, F., Shi, Z., et al., *Preparation of ZnS-Fluoropolymer nanocomposites and its photocatalytic degradation of methylene blue*, In: Polym Degrad Stab., 2009, 94, 12, https://doi.org/10.1016/j.polymdegradstab.2009.08.012

[41] Duhan, M., Kaur, R., *Phytic acid doped polyaniline nanofibres: An advanced adsorbent for methylene blue dye*, In: Environ Nanotechnol Monit Manag., 2019, 12, https://doi.org/10.1016/j.enmm.2019.100248

[42] Wang, X., Kim, H.J., Xu, P., Matsumoto, A., Kaplan, D.L., *Biomaterial coatings by stepwise deposition of silk fibroin*, In: Langmuir, 2005, 21, 24, 11335–11341, https://doi.org/10.1021/la051862m. PMID: 16285808

[43] Do, T.H., Dung, N.Q., Chu, M.N., Van Kiet, D., Ngan, T.T.K., Van Tan, L., *Study on methylene blue adsorption of activated carbon made from Moringa oleifera leaf*, In: Mater Today:Proc., 2021, 38, 3405–3413, https://doi.org/10.1016/j.matpr.2020.10.834

[44] Xing, X., Zhang, X., Feng, Y., Yang, X., *Adsorption of methylene blue dye on feather keratin/silk fibroin porous aerogels*, In: J Taiwan Inst Chem Eng., 2023, 105298, https://doi.org/10.1016/j.jtice.2023.105298

Authors:

GAMZE D. TETIK[1], RAGIPHAN OZTURAN[2], MURAT ERCAN[2]

[1]Uşak University, Engineering and Natural Sciences Faculty, Department of Nanotechnology Engineering, 64200, Uşak, Türkiye

[2]Uşak University, Graduate Education Institute, Department of Materials Science and Nanotechnology Engineering, 64200, Uşak, Türkiye
e-mail: rgphnztrn@hotmail.com, murt359@gmail.com

Corresponding author:

GAMZE D. TETIK
e-mail: gamze.tetik@usak.edu.tr

Investigation of electrical and surface properties of spunbond nonwoven fabrics coated with graphene oxide and formed PVDF nano fibres via electrospinning on IT

DOI: 10.35530/IT.076.02.202456

GUL OZKAN
MUSTAFA SABRI OZEN
GULTEKIN NERGIS DEMIREL

ABSTRACT – REZUMAT

Investigation of electrical and surface properties of spunbond nonwoven fabrics coated with graphene oxide and formed PVDF nano fibres via electrospinning on IT

Graphene oxide (GO) and Polyvinylidene fluoride (PVDF) are among the primary materials constituting the basis of conductivity and sensor research. In this study, PVDF and GO-filled PVDF nanofibers were formed by the electrospinning method on the polyester spunbond nonwoven fabric coated with aqueous graphene oxide dispersion via the dip coating method. The graphene oxide dip-coated spunbond nonwoven fabric as a substrate was used. Then, nanofiber surfaces with PVDF and GO-filled PVDF were formed by the electrospinning method onto GO-coated and reduced nonwoven fabrics. Polymer solutions were prepared as pure PVDF with 0.5 wt% – 1 wt% – 2 wt% GO. The chemical reduction operation by using Vitamin C and rosehip extract powder to nonwoven spunbond fabric coated with graphene oxide and forming GO-filled PVDF nanofibers on it, was processed. Characterization analyses of nonwoven spunbond fabric samples were performed by using XRD, FTIR, and SEM. To determine the functional properties, electrical resistance, water contact angle, and mechanical strength measurement results were evaluated. The use of nature- and human-friendly reducing agents in the present study is in alignment with the principle of sustainability.

Keywords: *graphene oxide, polyvinylidene fluoride, electrospinning, spunbond nonwoven fabric, sensor*

Investigarea proprietăților electrice și de suprafață ale nețesutelor consolidate la filare chimică acoperite cu oxid de grafen și nanofibre PVDF formate prin electrofilare pe IT

Oxidul de grafen (GO) și fluorura de poliviniliden (PVDF) se numără printre materialele primare care constituie baza cercetării conductivității și a senzorilor. În acest studiu, nanofibrele PVDF și PVDF umplute cu oxid de grafen au fost formate prin metoda de electrofilare pe materialul nețesut consolidat la filarea chimică din poliester acoperit cu dispersie apoasă de oxid de grafen prin metoda de acoperire prin imersie. Materialul nețesut consolidat la filarea chimică acoperit cu oxid de grafen prin imersie a fost utilizat ca substrat. Apoi, suprafețele de nanofibre cu PVDF și PVDF umplute cu oxid de grafen au fost formate prin electrofilare pe nețesute acoperite cu oxid de grafen și reduse. Soluțiile polimerice au fost preparate ca PVDF pur cu o greutate de 0,5% – 1% – 2% din greutatea oxidului de grafen. A fost prelucrată operația de reducere chimică prin utilizarea vitaminei C și a pulberii de extract de măceșe la materialul nețesut consolidat la filarea chimică acoperit cu oxid de grafen și s-au format nanofibre PVDF umplute cu oxid de grafen pe aceasta. Analizele de caracterizare a probelor nețesute consolidate la filarea chimică au fost efectuate prin utilizarea XRD, FTIR și SEM. Pentru a determina proprietățile funcționale, au fost evaluate rezultatele măsurătorilor privind rezistența electrică, unghiul de contact cu apa și rezistența mecanică. Utilizarea agenților de reducere prietenoși cu natura și omul în studiul de față este în concordanță cu principiul durabilității.

Cuvinte-cheie*: oxid de grafen, fluorură de poliviniliden, electrofilare, nețesut consolidat la filarea chimică, senzor*

INTRODUCTION

Smart textiles are defined as textile materials, unlike traditional textile materials, that can sense these stimuli coming from external sources such as temperature, pressure, elongation, moisture, radiation, light, pH or pressure change, electricity, vibration, noise, sound waves, magnetic field, mechanical action, chemical interaction, etc. and react to these warnings by generating a response [1]. Smart textiles that can sense, actuate, generate/store energy/power, and communicate have gained importance in the textile and clothing industry in recent years. Smart materials are classified into three categories such as passive, active, and very smart textiles. Passive smart textiles only sense the environmental conditions or the users. Active smart textiles can sense and react to stimuli coming from the environment. The very smart materials can sense, react to, and adapt to external conditions or stimuli [2]. In the production of smart textile materials, conductive fibers, shape memory fibers, photochromic fibers, temperature-sensitive fibers, pH-responsive gel fibers, healthy smart fibers, and piezo/tribo-electric materials have been used [3].

There are a lot of components in smart textile materials, like actuators, resistors, capacitors, inductors, antennas, interconnections, power supply, data processing, and sensors. Conductive materials are required to make these electrical parts or elements. Conductivity is a very crucial and desirable property of smart textile materials. Textile materials having conductive properties during polymerization, fiber spinning, and fabric production can be produced. The conductivity properties of any fabric with a coating or printing process can be achieved. Copper/silver wires, stainless steel fibers, silver-coated polyamide fibers, carbon-suffused nylon fibers, conductive bicomponent sheath/core type (conductive sheath) polyester fibers, and graphene are some of the conductive textile materials. In addition to these, carbon black, carbon nanotubes, graphene, and conductive polymers such as polyaniline and polyvinylidene fluoride (PVDF) can be included in the polymer melt during fiber spinning to manufacture electrically conductive composite fiber or yarn [4]. Among all conductive materials, graphene, which has a higher specific surface area, high electrical and thermal conductivity, and excellent mechanical properties, has special importance and great potential as a smart material component. Although graphene is a very expensive material, chemically modified graphene materials (CMG) such as graphene oxide (GO) and reduced graphene oxide (RGO) can be obtained cheaply on a large scale [5]. First, graphite is converted to graphene oxide, and then graphene oxide is reduced by a chemical reduction process, and graphene production is carried out. The chemical method of graphene synthesis stands out as the most favorable, being particularly suited for laboratory studies. In synthesis with the chemical method, first, new bonds are formed between the carbon atoms of the graphite via oxidation, and the carbon layers are separated. With the subsequent reduction process, the bonds between the distant carbon layers are broken down, and sheets of single or multiple layers of carbon are extracted. The resulting structure, known as graphene [6], is commonly obtained using the layer separation method, epitaxial growth, the silicon-carbon method, or Hummer's method [7]. When graphite is oxidized, graphene oxide (GO) results in a material with fewer electrical properties than graphite or graphene [6, 8]. To restore and enhance conductivity, GO sheets must be reduced chemically, thermally, or electrochemically [9]. The material obtained after undergoing the reduction process is called reduced graphene oxide. Concerning graphene and its derivatives in textiles, applications include flexible wearable electronic textiles (fibers, yarns, and fabrics) [10], information transfer, providing communication, heating, reacting to impact, protecting people and sensitive electronic devices against electromagnetic waves and electrostatic discharges, medical textiles [11], conductive nano textiles and nano-optoelectronics [12]. At the same time, graphene-based materials are also widely utilized in strain and pressure sensors due to their excellent flexibility and good electrical conductivity [13].

The word piezoelectric is derived from the ancient Greek words for "pressure" and "electric" [14]. In 1969, Kawai discovered very high piezo activity in polarized fluoropolymers [15]. Among fluoropolymers, polyvinylidene fluoride (PVDF) is one of the most widely known and used polymers, with one of the strongest piezoelectric effects [14]. Properties of the PVDF polymer include the possibility of functioning in a frequency range of 0.001 to 109 Hz and 10–8 to 106 psi (lb/in^2) pressure range, as well as high voltage, elasticity, dielectric resistance, and strength [14]. After PVDF polymers are polarized, they can maintain their polar structure at room temperature for an extended period; however, their polar structure and piezoelectric properties deteriorate with increasing temperature [16]. Piezoelectric materials produce electrical signals when subjected to load and strain. The amplitude and frequency of the generated signal are directly proportional to the mechanical deformation [13]. PVDF is used in the production of sensors thanks to its piezoelectric properties, creating a current when exposed to mechanical effects or undergoing mechanical change due to the effects of currents [17]. Abbasipour et al. [14] studied the piezoelectric effect by adding graphene oxide, graphene, and halloysite nanotube materials of various morphologies and concentrations to PVDF polymer. They reported that the β phase ratios of nanofiber PVDF mats prepared using the electrospinning method were up to 49% higher in GO-doped nanofibers compared to undoped mats. Abolhasani et al. [15] prepared graphene-PVDF composite nanofiber mats, employing the technique of electrospinning using different graphene contents. They observed that the addition of a small amount of graphene (0.1% by weight) significantly increased the β-phase formation and open circuit voltage of the nanofibers. However, increasing the graphene content reduced the electrical output voltage of randomly oriented nanofibers. They reported that the PVDF/graphene nanogenerator that was produced could fully synchronize finger movement and that the electricity generated could light a commercial LED for 30 seconds.

In the literature, it was seen that numerous studies have been performed on the coating of textile surfaces with GO. In most of these scientific studies, woven or knitted fabrics were coated with GO using various methods, after which the GO was reduced and its properties examined. Although most studies on PVDF have employed the electrospinning method, it was realized that, thus far, no study has been conducted in which both the GO coating and GO-doped PVDF polymer solution were used on a nonwoven fabric. In addition, many different reducing agents have been utilized in the literature. The important and remarkable side of our study is that the substances chosen and used as reducing agents were both natural and human & and environmentally friendly. Our study aimed to produce GO-filled PVDF nanofibers by the electrospinning method on GO-coated polyester spunbond nonwoven fabric, to examine their properties and to proffer suggestions regarding novel areas of use by the resulting functional properties of the nonwoven fabrics developed.

EXPERIMENTAL

Materials

All chemicals were of analytical reagent grade and used without further purification. Graphite flakes, acetone, dimethylformamide (DMF), and Vitamin C (L-ascorbic acid) were purchased from Sigma Aldrich (USD). Sulfuric acid (H_2SO_4, 95–98%), potassium permanganate ($KMnO_4$), and ethanol were purchased from Isolab (Türkiye). Hydrogen peroxide (H_2O_2, 35%), phosphoric acid (H_3PO_4), and hydrochloric acid (HCl, 37%) were purchased from Merck (Germany). Water-soluble rosehip extract powder (Rosa canina) was purchased from Naturalya Chemistry (Türkiye). Distilled water was used throughout the experiments. The polyester spunbond nonwoven fabric with a basis weight of 25 g/m^2 was used as the substrate fabric. PVDF (M_w = 244000, Solef® 1000 series) was provided by Solvay (Holland).

Synthesis of GO

Graphene oxide was synthesized from flake graphite by the improved Hummers' method according to the Gültekin et al. [18]. Briefly, a 9:1 mixture of concentrated H_2SO_4/H_3PO_4 (360:40 ml) was added to a mixture of graphite flakes (3 g) and $KMnO_4$ (18 g). The reaction was then heated to 50°C and stirred for 12 h. The reaction was then cooled to room temperature and poured onto ice (400 ml) with 35% H_2O_2 (6 ml). The resulting suspension was washed by repeated centrifugation (each at 8000 rpm for 30 min), first with 400 ml of 1 M HCl and 200 mL of ethanol (×2), then with distilled water until a pH of 4–5 was achieved. The obtained solid product was dried overnight in an oven at 60°C.

Coating of nonwoven fabric

2g/l GO aqueous dispersion was prepared with the obtained graphene oxide. As-obtained 100% polyester nonwoven fabrics were dip-coated with the prepared GO aqueous dispersion and became ready for the electrospinning process. The bath ratio for dip coating was determined as 1:20. The nonwoven fabric was dipped into GO dispersion for 30 min at ambient conditions. Then, the fabric was dried in an oven at 60°C.

Electrospinning

The pure polymer solution was prepared with 10 wt% PVDF in a 3:2 ratio (DMF/Acetone) by using a magnetic stirrer at 50°C. For the preparation of GO-doped PVDF solution, GO ratios were determined and prepared as 0.5 wt%, 1 wt%, and 2 wt%. The electrospinning parameters for the production of neat and GO-doped PVDF nanofibers were set as 12 cm collector-nozzle distance, 200 rpm collector rotation speed, 2 ml/h feeding rate, and 27 kV applied voltage.

Reduction of graphene oxide

The nature-friendly reducing agents determined for the reduction process of the nanofibrous structure obtained on the nonwoven fabric were Vitamin C (L-ascorbic acid) and Rosehip powder extract. For the reduction process with Vitamin C, a 0.2 M aqueous Vitamin C solution was prepared. For the reduction process with rosehip extract, 10 wt% aqueous rosehip extract solution was prepared with 0.5 wt% Vitamin C. After the electrospinning process, the nanofiber samples were reduced with Vitamin C for 90 minutes at 95°C and with rosehip extract solution for 5 hours at 95°C. After reduction, the samples were washed with gradual washing with distilled water and dried in the oven for 60 min.

Characterization

The X-ray diffraction (Shimadzu, LabX XRD 6100) spectra were performed with a Cu Kα (λ=1.5406 Å) radiation source with a θ-2θ range of 5° – 70°. Measurements were made at 40 kV voltage and 30 mA current values. An attenuated total reflection Fourier transform infrared spectrometer (ATR-FTIR, Perkin Elmer Spectrum Two) was used at 400–4000 cm^{-1}. Scanning electron microscopy (TESCAN, VEGA 3) was employed to observe the morphology of GO and RGO-filled PVDF nanofibers, GO, and RGO-coated nonwoven fabrics. The surfaces of the samples were coated with a gold/palladium mixture on the (Quarum, SC7620) for 165 seconds before analysis. Diameters of the electrospun nanofibers were analyzed from the SEM images using ImageJ software.

Tensile strength measurements of nanofiber surfaces were made with the Instron 4411 device. Tensile strength test conditions were set at 30 mm/min test speed and 10 mm to 50 mm sample dimensions. Measurements were performed and reported in both vertical and horizontal directions. The surface electrical resistivity of the samples was measured with a 4-point probe. The setup consists of a sourcemeter (Keithley 2450 Sourcemeter) and a four-point probe station (Everbeing Int'l Corp). The water contact angle measurement of nonwoven and nanofiber samples was measured by using a contact angle meter (CAM 100, KSV Instruments).

RESULT AND DISCUSSION

FTIR Analysis

The FTIR has been used to analyze the coating and reduction of GO nanosheets on the polyester nonwoven fabric surface, and also, to analyze the structural transformation of the crystalline phases within the PVDF nanofiber. Figure 1, *a* shows the FTIR analysis of GO, RGO-R, and RGO-C coated polyester nonwoven fabric. The peaks at 722 cm^{-1}, 871 cm^{-1}, and 1408 cm^{-1} are attributed to the C-H bond in the aromatic group, the peaks at 1711 cm^{-1} and 1238 cm^{-1} were assigned to C=O and C-O stretching vibrations of aromatic ester and ester, respectively [19, 20]. The

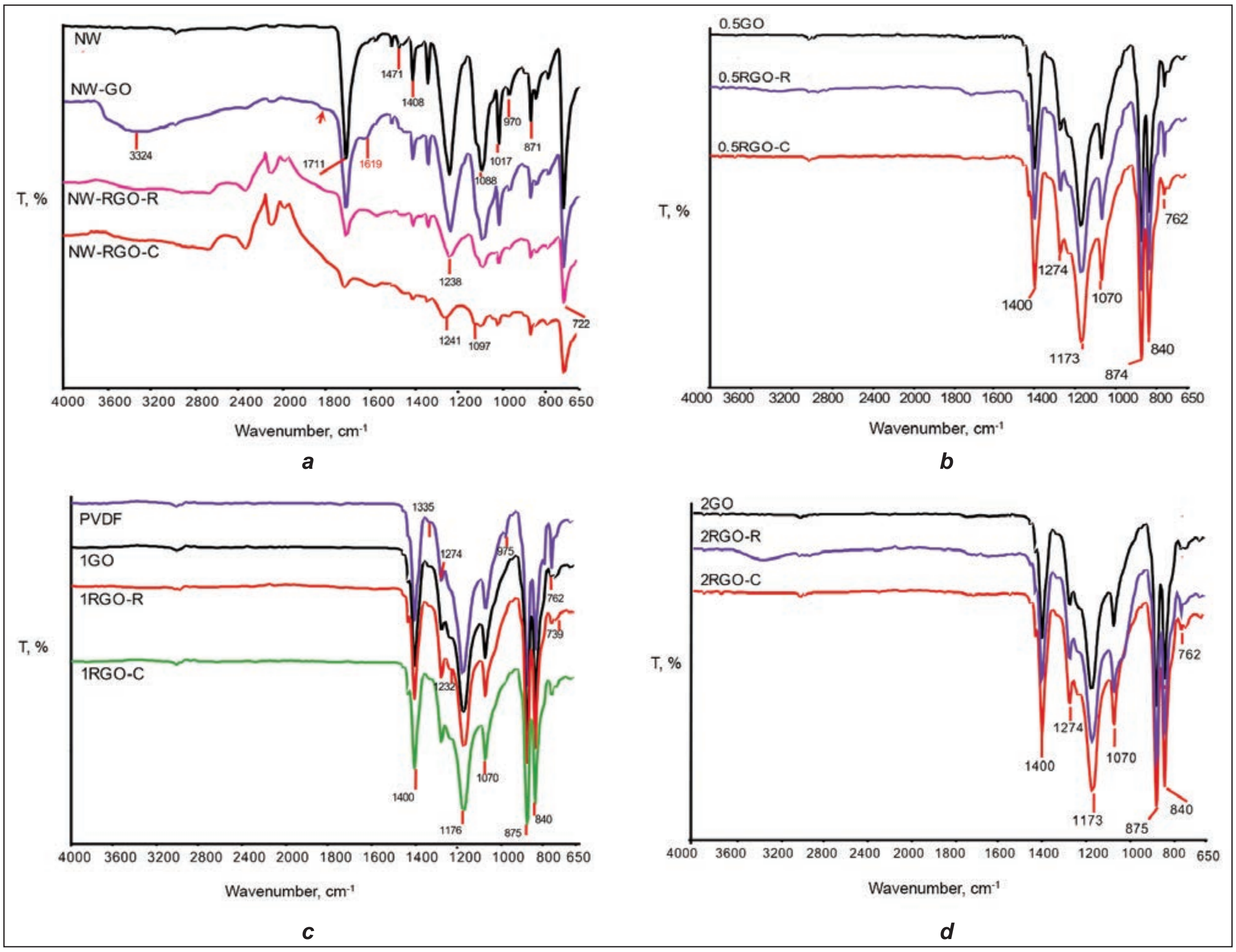


Fig. 1. FTIR spectra of: *a* – neat nonwoven fabric, GO-coated nonwoven fabric, reduced samples with rosehip and Vitamin C; *b* – electrospun neat PVDF nanofibers, 1 wt% GO-PVDF and reduced GO-PVDF composite nanofibers; *c* – electrospun neat PVDF nanofibers, 1 wt% GO-PVDF and reduced GO-PVDF composite nanofibers; *d* – electrospun neat PVDF nanofibers, 2 wt% GO-PVDF and reduced GO-PVDF composite nanofibers

C-O stretching of glycol was seen at 1017 cm$^{-1,}$ and benzene in-plane vibrations were found at 970 cm^{-1}. The peak at 1088 cm^{-1} represents the ester C=O stretching vibration [21]. After the GO coating process, a broad peak between 3600–2800 cm^{-1} shows O-H stretching vibrations of carboxylic acid can be attributed to the water molecules and alcohol groups in GO. The new peak appeared at 1619 cm$^{-1,}$ corresponding to the C°C stretches from the unoxidized graphitic domain [22]. After the reduction of GO, the broad peak between 3600–2800 cm^{-1} disappeared, and the intensity of the sharp peaks decreased

The FT-IR spectra of electrospun neat PVDF nanofibers, 1 wt% GO-PVDF, and reduced GO-PVDF composite nanofibers are shown in figure 1, *b*. For the neat PVDF nanofibers, the characteristic vibrational peaks are observed at 764 cm^{-1}, 796 cm^{-1}, and 975 cm^{-1}, which correspond to the nonpolar α-phase. The peaks at 1274 and 1232 cm^{-1} confirm the nucleation of the polar β-phase and the semipolar γ-phase, respectively. For the 1GO nanofiber, all α-peaks disappeared, and the peaks corresponding to the electroactive β- and γ-phases became stronger. The peak at 840 cm^{-1} for the 1GO nanofibers is more intense than neat PVDF, which indicates the specific electrostatic interaction between the π- π-π-electron cloud and the oxygen-containing functional groups (carbonyl and carboxylic groups) in GO and the $-CH_2/-CF_2$ dipoles of PVDF [23]. Among the five crystalline phases (a, b, g, d, and e) of the PVDF, the stable non-polar phase is the most common crystalline phase, which can be easily obtained from melting crystallization and has no electroactivity. The polar b phase and g phase PVDF crystal have higher electroactivity than the a phase and different methods are used to convert the a phase to the b phase or g phase and enhance the piezoelectricity of PVDF [24]. The piezoelectric property is dependent on the β-phase's amount of the PVDF polymer or its total crystallinity [14]. FTIR is commonly used to identify the b crystalline phases in a polymer by the following equation:

$$F(\beta) = \frac{X_\beta}{X_\alpha + X_\beta} = \frac{A_\beta}{\left(K_\beta / K_\alpha\right) A_\alpha + A_\beta} \qquad (1)$$

where K_α and K_β are the absorption coefficients at the particular wavenumber. K_α is 6.1×10^4 cm^2/mol and K_β is 7.7×10^4 cm^2/mol. X_α and X_β are mass

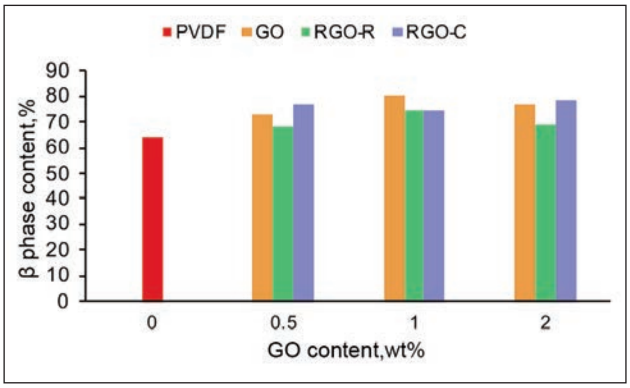


Fig. 2. The calculated b phase content of the electrospun PVDF nanofibers as a function of GO filler amount

fractions of α and β crystalline phases. $A_β$ and $A_β$ are the area of absorption bands at 762 and 840 cm^{-1} [25]. The values of $F_β$ for the electrospun PVDF nanofibers are given in figure 2. The β-phase fraction for the neat PVDF nanofiber is obtained as 64%. The β-phase content increased with the addition of GO nanosheets. The highest β-phase content is obtained with the 1GO sample as 80%. According to the result, it can be said that the amount of β phase was increased by about 25% by the incorporation of GO to PVDF nanofibers. Moreover, the amount of the β phase showed a slight decrease after the reduction of GO with rosehip powder extract and Vitamin C. Although the reduction process of GO decreases the amount of β phase, it is still more than the neat PVDF nanofiber. The highest β-phase content for the reduced samples is obtained at 2RGO-C as 79% which is higher than that of the neat PVDF nanofiber about 23%. The use of GO as a nanofiller in the PVDF nanofibers provided effective dipole polarization and facilitated the nucleation of β phase crystals due to the enhanced dipole-dipole forces. The attachment of PVDF chains to the GO sheets was caused by the interaction between CF_2 in PVDF and the –C=O and COOH groups of the GO (hydrophilic interaction) [14]. The peaks at 840 and 762 cm^{-1} are used to investigate the improved β-phase development and α-phase suppression. The relative ratio of the peak intensities of these two absorption bands for neat PVDF is 2.2, while the highest value of 5.0 was obtained for the composite nanofiber with 1 wt.% of GO. The higher value of the 1GO sample confirms the development β-crystalline phase because of strong Van der Waals interactions between the highly electronegative fluorine on the PVDF chains and the free electron pairs on the GO oxygen atoms. [26]. The relative ratio of the peak intensities for 1RGO-R and 1RGO-C nanofibers is 3.85 and 3.81, respectively. The decrease in the amount of β phase and the relatithe ve ratio of relative intensities after the reduction of GO can be explained by the removal of the oxygen-containing functional groups which provide the interaction between PVDF and GO. The disruption of hydrophilic interaction caused the less amount of β phase.

XRD Analysis

The crystalline structure of electrospun PVDF nanofibers was characterized by XRD patterns. Figure 3 presents the XRD patterns of PVDF, 1GO, 1RGO-R, and 1RGO-C nanofibers. PVDF electrospun nanofiber shows characteristic peaks at 2θ = 18.6° and 20.2° associated with the reflections of α (020) and β ((200), (110)) polymorphs, respectively. The molecular chains of PVDF are uniaxially stretched by the high electrical forces during the electrospinning process, and the electroactive phase formation in the pure PVDF nanofibers takes place. It can be observed that in the sample containing 1 wt% GO, the α peak at 2θ = 18.6° changed to a β characteristic shoulder peak at 20.6°. The characteristic peak of the α phase diminishes, while a new crystallization peak corresponding to the (020) and (110) reflections of the β phase appears at 20.6°, indicating the existence of the β phase. The transformation from α to β phase in the fibers electrospun with GO benefits from the stretching and in situ poling during electrospinning. The incorporation of GO as a nanofiller improves the β-phase crystallinity. Also, a slight increase in the intensity of the β-phase is attributed to the interaction between the carbonyl groups present in the GO and the CF_2 segments in PVDF [27]. After the reduction process with rosehip extract powder and Vitamin C, the characteristic α phase appeared. This is possibly caused by an insufficient amount of carbonyl groups of RGO to nucleate enough PVDF chains into the required trans-trans (TT) conformation of the β-phase [28]. However, it can be seen that after the reduction process, the PVDF nanofibers are still enriched with β-phase compared to the neat PVDF nanofibers. As a result, the analysis of the XRD spectra of the electrospun nanofibers is in line with the analysis of the FTIR spectra.

SEM Analysis

Surface morphology of polyester nonwoven fabric with and without GO and after reduction of GO was characterized by scanning electron microscopy. SEM images of polyester nonwoven fabric coated with GO and RGO are given in figure 4. In figure 4, *a*, the presence of GO nanosheets between and around the polyester fibers confirms the coating process of GO nanosheets from the aqueous dispersion. In figures 4, *b* and *c*, the presence of nanosheets after the reduction of GO with rosehip powder extract and Vitamin C, respectively, can be observed.

The surface morphologies of the neat PVDF and the GO-filled PVDF nanofibrous structures were examined by scanning electron microscopy and are given in figure 5. In figure 5, *a*, the surface of the PVDF nanofibers is smooth and uniform. However, it can also be seen that the beaded nanofibers were

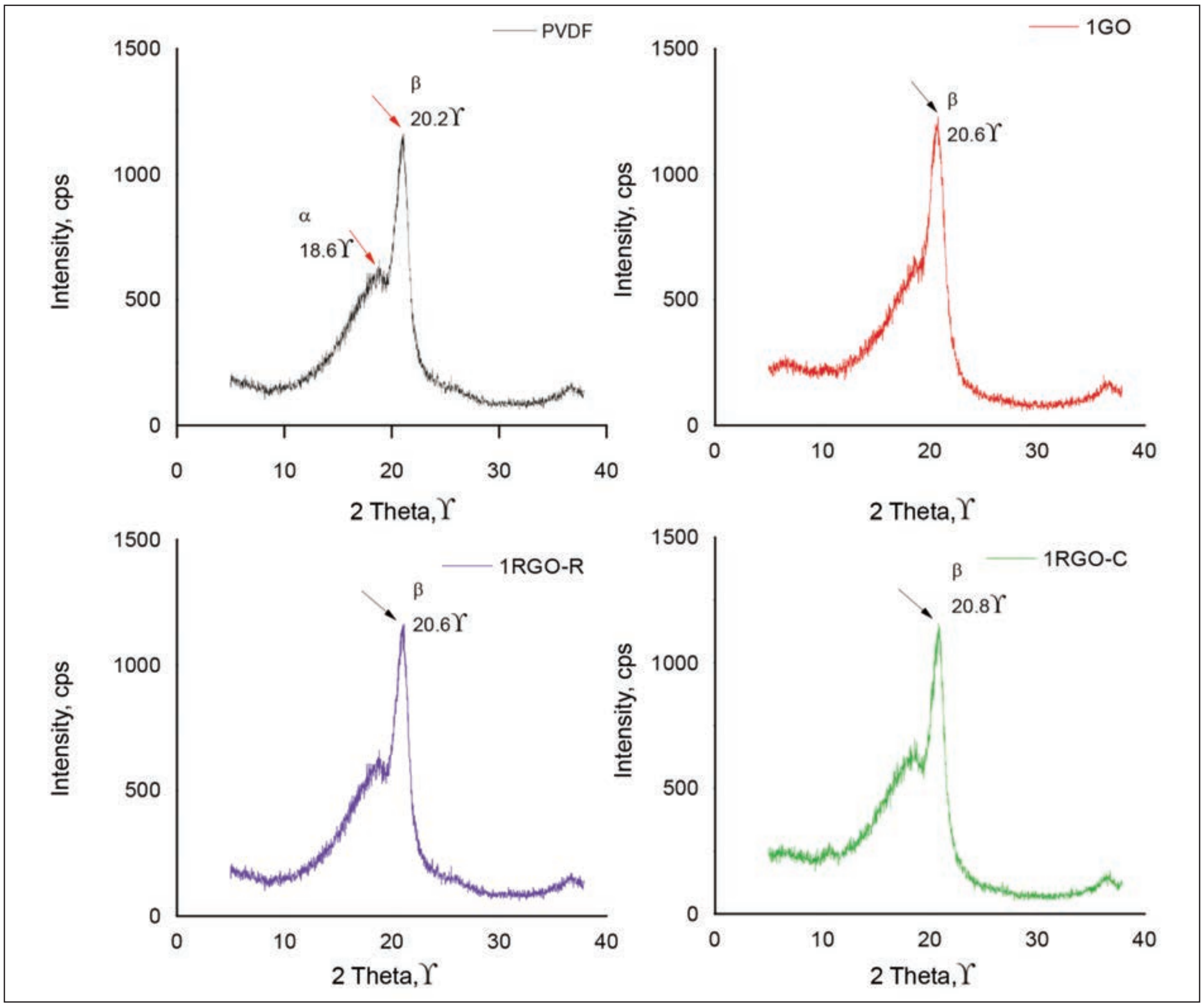


Fig. 3. XRD spectra of electrospun PVDF nanofibers with/without GO and after the chemical reduction process by rosehip extract powder and Vitamin C

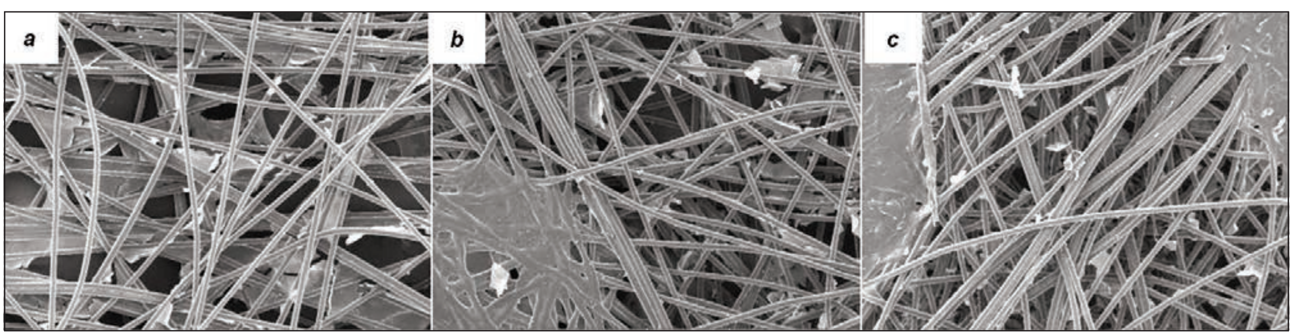


Fig. 4. SEM images (200x) of nonwoven fabric: *a* – coated with GO; *b* – reduced with rosehip powder extract; *c* – reduced with Vitamin C

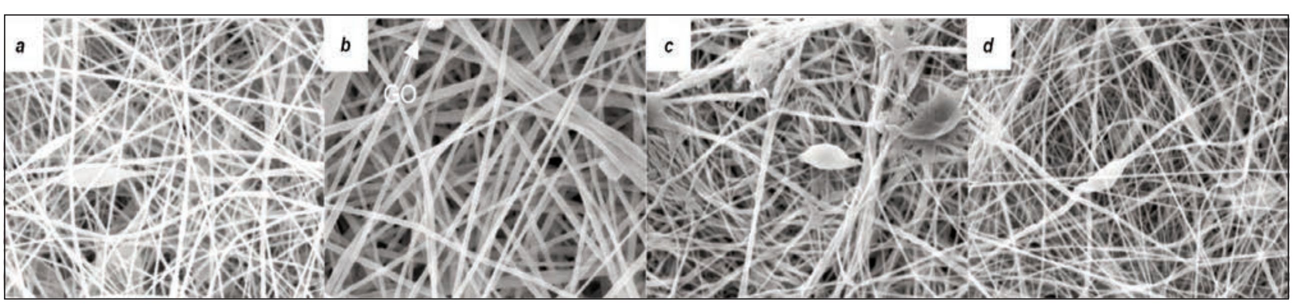


Fig. 5. SEM images (10kx) of: *a* – electrospun PVDF nanofibers: *b* – with GO; *c* – reduced with rosehip powder extract; *d* – reduced with Vitamin C

formed. With the addition of 1 wt% GO to the PVDF polymer solution, the nanofibers were obtained without bead formation. After the chemical reduction process of the GO-filled PVDF nanofibers by using Vitamin C and rosehip extract, the nanofibers maintained the original fibrous morphology, with the partial destruction of uniformity, resulting in the nanofibers sticking together, caused by the applied heat during the reduction process. Also, some defects, such as large beads or agglomerated GO/RGO nanosheets, can be seen in the images. Moreover, the results show the stability of the PVDF nanofibrous structure in aqueous solution at 95°C for a certain time.

The average diameter of nanofibers was measured and given in figure 6. It is seen that the diameter of the neat PVDF nanofibers was obtained as 230±26 nm. At the same time, the 1 wt% GO added PVDF nanofibers were obtained as 251±21 nm. The result suggests that the GO-added PVDF nanofibers have larger diameters than the neat PVDF nanofibers. However, the diameter of the nanofibers showed a dramatic decrease after the reduction process with Vitamin C and rosehip extract powder. The reason for the decrease in the diameter of the nanofibers after the chemical reduction process could be the removal of oxygen-containing functionalities located on the surface and the edges of the GO nanosheets, thus, the decrease in the interplanar distance of the nanosheets results in the finer nanofibrous structure.

The surface morphologies of neat PVDF and GO-filled PVDF nanofibrous structures were examined by scanning electron microscopy and are given in figure 4. In figure 4, *a*, the surface of the PVDF nanofibers is smooth and uniform. However, it can also be seen that the beaded nanofibers were formed. With the addition of 1 wt% GO to the PVDF polymer solution, the nanofibers were obtained without bead formation. After the chemical reduction process of GO-filled PVDF nanofibers by using Vitamin C and rosehip extract, the uniformity of nanofibers was destroyed and the applied heat during the reduction process caused the nanofibers to stick together. Also, some defects, such as large beads or agglomerated GO/RGO nanosheets, can be seen from the images. The average diameter of nanofibers was measured and given in figure 5. It is seen that the diameter of neat PVDF nanofibers was obtained as 230±0.026 nm, while the 1 wt% GO added PVDF nanofibers were obtained as 386±0.047 nm. The result suggests that the GO added PVDF nanofibers have larger diameters than the neat PVDF nanofibers. However, the diameter of the nanofibers showed a dramatic decrease after the reduction process with Vitamin C and rosehip extract powder.

Tensile strength measurements

The mechanical performance of neat PVDF, before and after reduction of GO-filled PVDF nanofiber surfaces, was analyzed using a universal tensile tester, and the results are presented in figure 7. The tensile

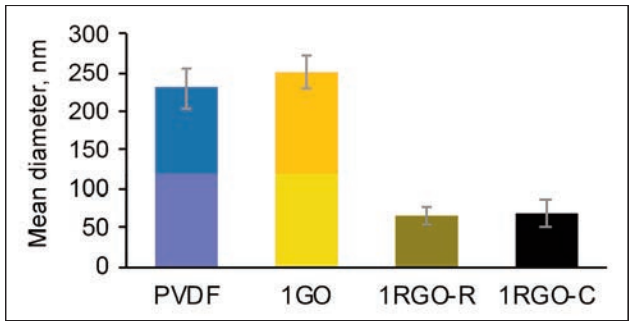


Fig. 6. Average nanofiber diameter of electrospun neat PVDF, GO, and RGO-filled PVDF nanofibers

strength properties of nanofiber samples were tested both in the machine direction and the cross direction. The results were evaluated in terms of elongation and tensile strength.

The elongation and tensile strength of neat PVDF nanofibers were higher in the machine direction than in the cross direction. The elongation and tensile strength values of the neat PVDF nanofiber in the machine and cross directions were obtained as 107%, 1.5 MPa, and 92%, 1.4 MPa, respectively. With the addition of 0.5 wt.% of GO to the PVDF polymer solution, the mechanical performance of the nanofibrous structure increased prominently. When the GO filler content was increased to 1 wt.%, the highest mechanical performance in both directions was recorded. The elongation and tensile strength of the nanofiber containing 1 wt% GO increased by approximately 107% and 333% in the machine direction, and 139% and 436% in the cross direction, respectively, compared to those of the neat PVDF nanofiber. The results indicated the enhancement of the mechanical properties of GO-filled PVDF nanofibers. Besides, when the 2 wt% GO filler content was achieved, the mechanical performance of the nanofiber decreased, except for the tensile strength in both directions, compared to that of the neat PVDF nanofiber. Therefore, it can be inferred that the strength of the nanofibers increased without reducing the stretchability of the nanofibers at a certain amount of GO filler loading.

After the reduction of GO-filled PVDF nanofibers by using two different nature-based reducing agents, namely Vitamin C and rosehip extract powder, the mechanical performance of the RGO-filled PVDF nanofibers decreased compared to the GO-filled PVDF nanofibers. The reduction of GO-filled PVDF nanofibers with Vitamin C aqueous solution resulted in lower elongation values in both directions compared to those of the neat PVDF and GO-filled PVDF nanofibers. The elongation and tensile strength of Vitamin C-reduced nanofiber (RGO-C) samples increased with the increasing amount of GO nanosheets. The highest results were obtained with 2 wt% GO-filled PVDF nanofiber samples reduced with Vitamin C in both directions. The tensile strength of Vitamin C-reduced nanofiber samples was

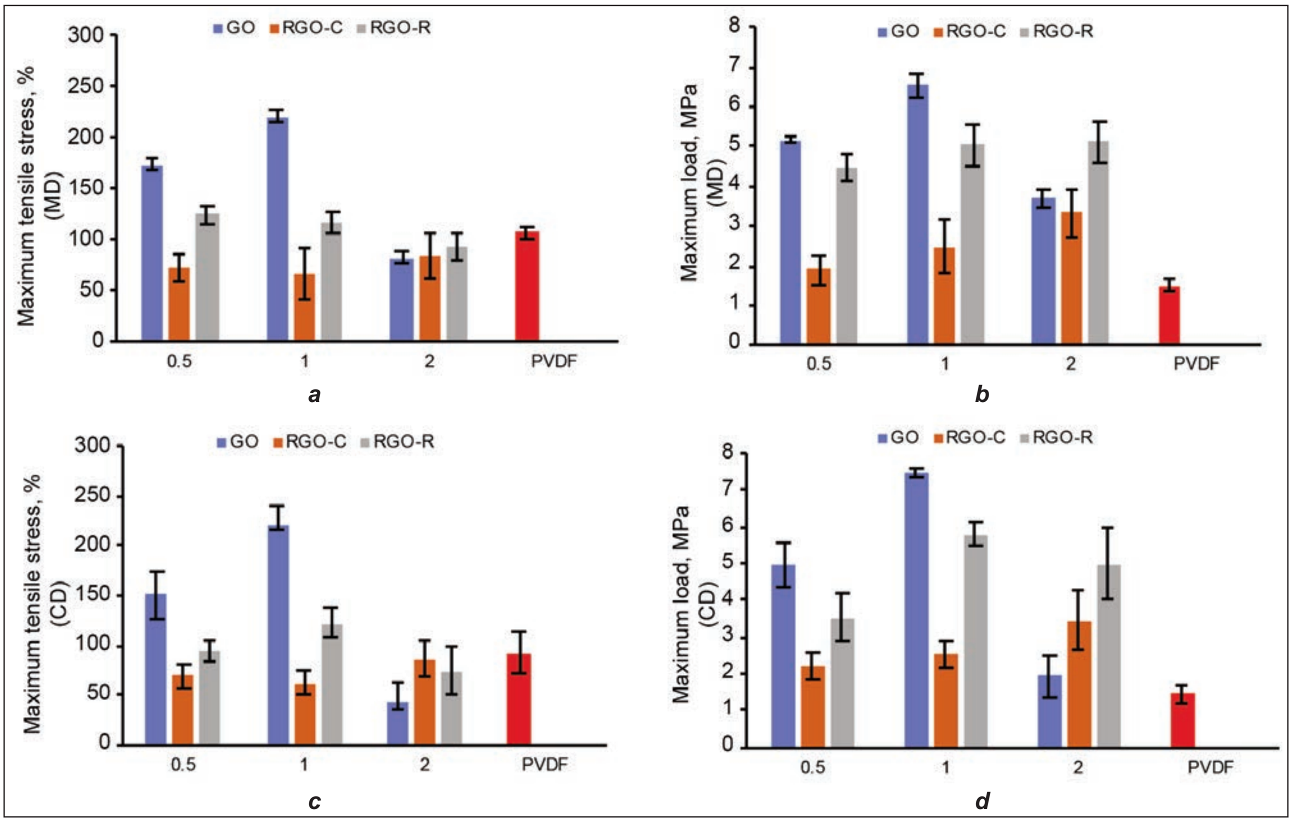


Fig. 7. Mechanical properties of PVDF nanofibers as a function of filler content, elongation (%) and tensile strength values of samples in the: *a* and *b* – machine direction; *c* and *d* – cross direction

obtained as 3.3 MPa and 3.4 MPa in the machine direction and the cross direction, respectively, which was higher than that of the neat PVDF nanofibers in both directions by about 120% and 143%, respectively. The reduction of GO-filled PVDF nanofibers with the aqueous solution of rosehip extract powder resulted in higher elongation and tensile strength values compared to those of Vitamin C-reduced (RGO-C) samples. The tensile strength of the rosehip extract-reduced (RGO-R) nanofibers increased with the increasing amount of GO nanosheets. The highest tensile strength was obtained as 5.1 MPa with a 2 wt% GO-filled PVDF nanofiber sample reduced with rosehip extract in the machine direction. On the other hand, the highest tensile strength was obtained as 5.8 MPa with a 1 wt% GO-filled PVDF nanofiber sample reduced with rosehip extract in the cross direction.

Electrical resistivity

The electrical surface resistivity of the polyester spunbond nonwoven fabric coated with GO and the GO-coated nonwoven fabrics after reduction by using Vitamin C and rosehip extract powder was measured. The obtained results are given in table 1. The electrical surface resistivity of polyester nonwoven fabric was obtained as $1.94 \cdot 10^6$ kW, indicating the electrical insulating property. The GO coating of polyester nonwoven fabric did not change the electrical surface resistivity value. The GO nanosheets present an electrically insulating character because of the presence of oxygenated functional groups. On the other hand, the reduced samples show relatively lower electrical resistivity. The reduction of GO-coated polyester nonwoven fabric with rosehip extract powder decreased the electrical surface resistivity to $7.06 \cdot 10^3$ kW. Moreover, the lowest value was obtained with Vitamin C-reduced GO-coated nonwoven fabric as $5.57 \cdot 10^2$ kW. It can be understood that the reduction of GO with Vitamin C and rosehip extract powder turned the electrically insulating GO into the electrically conductive RGO.

Table 1

SURFACE ELECTRICAL RESISTIVITY MEASUREMENTS OF NONWOVEN SAMPLES

Sample	Surface electrical resistivity (kW)
NW	$1.94 \cdot 10^6$
NW-GO	$1.70 \cdot 10^6$
NW-RGO-R	$7.06 \cdot 10^3$
NW-RGO-C	$5.57 \cdot 10^2$

The electrical resistivity of the PVDF, GO, RGO-R, and RGO-C nanofibers was measured as $1.70 \cdot 10^6$ kΩ. The results did not show any change with the change of the filler content and the reducing agent.

Water Contact Angle

The water contact angle measurements were made separately for all samples and given in tables 2 and 3 along with corresponding droplet images, for

Table 2

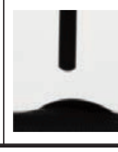
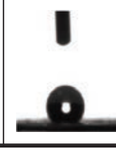
WATER CONTACT ANGLE MEASUREMENT RESULTS AND DROPLET IMAGES OF ELECTROSPUN NANOFIBERS									
Water contact angle (°) and droplet images									
PVDF	0.5%			1%			2%		
	GO	RGO-C	RGO-R	GO	RGO-C	RGO-R	GO	RGO-C	RGO-R
121.1	129.8	124.2	61.2	128.8	124.5	28.2	124.1	119.3	26.8
									

Table 3

WATER CONTACT ANGLE RESULTS (°) AND DROPLET IMAGES OF GO-COATED AND RGO-COATED NONWOVEN FABRICS			
Water contact angle (°) and droplet images			
NW	NW-GO	NW-RGO-C	NW-RGO-R
108.6	90.6	94.1	48.1
			

nanofibers and nonwoven fabrics, respectively. From table 2, it can be understood that the neat PVDF nanofiber was hydrophobic due to having a water contact angle higher than 90°. With the addition of a small amount of GO to the nanofibrous structure, the water contact angle shows a slight increase. The increase in GO concentration in the PVDF polymer matrix does not affect the water contact angle of the nanofibers. The highest water contact angle was obtained as 129.8° with the GO-filled PVDF nanofiber containing 0.5 wt% filler. Although the water contact angle values of the nanofibers tend to decrease with the increase of GO content, the resulting values still indicate hydrophobicity. The reduction of GO-filled PVDF nanofibers with Vitamin C (RGO-C) retained the hydrophobicity. On the contrary, the water contact angle of the RGO-R samples decreased dramatically to values lower than 90°, indicating hydrophilicity.

Water contact angle results and corresponding droplet images of GO and RGO-coated nonwoven fabric samples are given in table 3. Since all nonwoven fabrics are coated in the same way, one measurement is taken as a reference measurement for all GO-coated nonwoven fabrics. The water contact angle of the polyester nonwoven fabric was measured as 108.6°. When the water contact angle values of nonwoven surfaces are examined, it is seen that the GO-coated nonwoven fabric can be considered hydrophobic due to the water contact angle obtained as 90°. However, a slight decrease in the water contact angle of GO-coated nonwoven fabric was obtained when compared to neat nonwoven fabric. After the reduction with Vitamin C, the water contact angle increased to a value of 94°.

Nevertheless, the water contact angle of the reduced sample by using rosehip extract powder decreased dramatically, and the surface of the sample became hydrophilic.

CONCLUSIONS

In this study, the GO-dip-coated polyester spunbond nonwoven fabric is used as a substrate to fabricate electrospun GO-filled PVDF nanofibers. The GO coating concentration remained constant, and the amount added to the PVDF polymer solution was changed. Moreover, the GO-filled PVDF nanofibers were post-processed by chemical reduction with Vitamin C and rosehip extract powder. The electrospun PVDF nanofibers with different amounts of GO were characterized by FTIR, XRD, and SEM. The mechanical properties, electrical surface resistivity, and water contact angle of the samples were analyzed. FTIR and XRD results revealed an increase in the b phase by the addition of GO. After the reduction of GO-filled PVDF nanofibers, the crystalline b phase was obtained higher level than the neat PVDF nanofibers. The morphological study obtained by SEM images confirmed both the dip-coating of GO nanosheets between the polyester fibers and the formation of PVDF nanofibers with uniform structures. The mechanical performance of the electrospun nanofibers in terms of tensile strength was obtained highest at the 1 wt% GO-filled sample in both directions. The tensile strength and elongation results revealed the increase of mechanical properties by the addition of different amounts of GO and the application of the chemical reduction process compared to that of the neat PVDF nanofibers. The surface electrical resistivity of the reduced GO-coated nonwoven fabric was found as $7.06 \cdot 10^3$ kΩ and $5.57 \cdot 10^2$ kΩ for the samples NW-RGO-R and NW-RGO-C, respectively. A slight decrease in hydrophobicity was observed after the GO coating of the polyester nonwoven fabric coated. The hydrophobic structure of the neat PVDF nanofiber decreases after reduction both with Vitamin C and rosehip extract powder. However, after reduction with rosehip extract powder, both the nanofibers and the nonwoven fabric turned into a hydrophilic state.

REFERENCES

[1] Ferri, A., Plutino, M.R., Rosace, G., *Recent Trends in Smart Textiles: Wearable Sensors and Drug Release Systems*, In: AIP Conference Proceedings, 2019, 2145

[2] Kan, C.-W., Lam, Y.-L., *Future Trend in Wearable Electronics in Textile Industry*, In: Applied Science, 2021, 11, 3914

[3] Dang, T., Zhao, M., *The Application of Smart Fibers and Smart Textiles*, In: Journal of Physics: Conference Series, 2021, https://doi.org/10.1088/1742-6596/1790/1/012084

[4] Ruckdashel, R.R., Khadse, N., Park, J.H., *Smart E-Textiles: Overview of Components and Outlook*, In: Sensors, 2022, 22, 16, 6055, https://doi.org/10.3390/s22166055

[5] Yu, X., Chen, H., Zhang, M., Zhao, Y., Qu, L., Shi, G., *Graphene-Based Smart Materials*, In: Nature Reviews Materials, 2017, 2, 17046, https://doi.org/10.1038/natrevmats.2017.46

[6] Chen, Y., *Graphene Synthesis and Assembly for Graphene Actuators*, Master Thesis, University of Florida, 2012

[7] Pumera, M., *Electrochemistry of Graphene, Graphene Oxide and Other Graphenoids*, In: Electrochemistry Communications, 2013, 36, 14–18

[8] Heo, J.S., Hossain, M.F., Kim, I., *Challenges in Design and Fabrication of Flexible/Stretchable Carbon- and Textile-based Wearable Sensors for Health Monitoring: A critical review*, In: Sensors (Basel), 2020, 20, 14

[9] Measurement Specialties, Inc., *Piezo Film Sensors Technical Manual, Measurement Specialties*, 1999

[10] Yapici, M.K., Alkhidir, T.E., *Intelligent Medical Garments with Graphene-Functionalized Smart-Cloth Ecg Sensors*, In: Sensors (Basel), 2017, 17, 4

[11] Wang, D., Li, D., Zhao, M., Xu, Y., Wei, Q., *Multifunctional Wearable Smart Device Based on Conductive Reduced Graphene Oxide/Polyester Fabric,* In: Applied Surface Science, 2018, 454, 218–226

[12] Cao, J., Wang, C., *Multifunctional Surface Modification of Silk Fabric Via Graphene Oxide Repeatedly Coating and Chemical Reduction Method*, In: Applied Surface Science, 2017, 405, 380–388

[13] Şimşek, R., *Obtaining Nano Fibrous Surfaces from Polyvinylidene Fluoride (pvdf) Polymer and Examining the Energy Production Properties of These Surfaces*, Master's Thesis, Marmara University Institute of Science and Technology, Istanbul, Türkiye, 2015

[14] Abbasipour, M., Khajavi, R., Yousefi, A.A., Yazdanshenas, M.E., Razaghian, F., *The piezoelectric response of electrospun PVDF nanofibers with graphene oxide, graphene, and halloysite nanofillers: a comparative study,* In: Journal of Materials Science: Materials in Electronics, 2017, 28, 15942–15952

[15] Abolhasani, M.M., Shirvanimoghaddam, K., Naebe, M., *PVDF/Graphene Composite Nanofibers with Enhanced Piezoelectric Performance for Development of Robust Nanogenerators*, In: Composites Science and Technology, 2017, 138, 49–56

[16] Kawai, H., *The Piezoelectricity of Poly (vinylidene Fluoride)*, In: Jpn. J. Appl. Phys., 1969, 8, 7, 975

[17] Hari, S.N., *Ferroelectric Polymers Chemistry, Physics, and Applications*, Florida: CRC Press, 1995

[18] Gültekin, N., Usta, İ., Yalçin, B., *Green Reduction of Graphene Oxide Coated Polyamide Fabric Using Carob Extract*, In: AATCC Journal of Research, 2020, 7, 6, 33–40

[19] Shao, F., Bian, S.W., Zhu, Q., Guo, M.X., Liu, S., Peng, Y.H., *Fabrication of Polyaniline/Graphene/Polyester Textile Electrode Materials for Flexible Supercapacitors with High Capacitance and Cycling Stability*, In: Chemistry-An Asian Journal, 2016, 11, 1906–1912

[20] Rathinamoorthy, R., Raja Balasaraswathi, S., *Effect of Surface Modification of Polyester Fabric on Microfiber Shedding from Household Laundry*, In: International Journal of Clothing Science and Technology, 2022

[21] Ouadil, B., Cherkaoui, O., Safi, M., Zahouily, M., *Surface Modification of Knit Polyester Fabric for Mechanical, Electrical and UV Protection Properties by Coating with Graphene Oxide, Graphene and Graphene/Silver Nanocomposites*, In: Applied Surface Science, 2017, 414, 292–302

[22] Emiru, T.F., Ayele, D.W., *Controlled Synthesis, Characterization and Reduction of Graphene Oxide: A Convenient Method for Large Scale Production*, In: Egyptian Journal of Basic and Applied Sciences, 2019, 4, 74–79

[23] Roy, K., Ghosh, S.K., Sultana, A., Garain, S., Xie, M., Henkel, K., et al., *A Self-Powered Wearable Pressure Sensor and Pyroelectric Breathing Sensor Based on GO Interfaced PVDF Nanofibers*, In: ACS Applied Nano Materials, 2019, 2, 4, https://doi.org/10.1021/acsanm.9b00033

[24] Fu, R., Chen, S., Lin, Y., He, Y., Gu, Y., *Preparation and Piezoelectric Investigation of Electrospun Polyvinylidene Fluoride Fibrous Membrane,* In: Journal of Nanoscience and Nanotechnology, 2016, 16, 12, 12337–12343

[25] Saygh, A.A., Ponnamma, D., El Ma'adeed, M.A., Vijayan, P., Karim, A., Hasan, M.K., *Flexible Pressure Sensor Based on PVDF Nanocomposites Containing Reduced Graphene Oxide-Titania Hybrid Nanolayers*, In: Polymers, 2017, 9, 2, 33

[26] Ahmed, A.I., Mariam, Al A.S., Miroslav, M., Adrian, S.L., *Electrospun PVDF Graphene Oxide Composite Fibre Mats with Tunable Physical Properties*, In: Journal of Polymer Research, 2016, 23, 11

[27] Na, M., Rebecca, C.E.P., Yanqiu, Z., Huanting, W., Xiwang, Z., *The Effect of Reduction Degree of GO Nanosheets on Microstructure and Performance of PVDF/GO Hybrid Membranes,* In: Journal of Membrane Science, 2016, 501, 169–178

[28] Rahman, M.A., Lee, B.C., Phan, D.T., Chung, G.S., *Fabrication and Characterization of Highly Efficient Flexible Energy Harvesters Using PVDF–Graphene Nanocomposites*, In: Smart Materials and Structures, 2013, 22, 8

Authors:

GUL OZKAN[1], MUSTAFA SABRI OZEN[2], GULTEKIN NERGIS DEMIREL[2]

[1]Marmara University, Institute of Pure and Applied Science, Department of Textile Engineering, Istanbul, Türkiye

[2]Marmara University, Faculty of Technology, Department of Textile Engineering, Istanbul, Türkiye
e-mail: ndemirel@marmara.edu.tr, mustafaozen@marmara.edu.tr

Corresponding author:

GUL OZKAN
e-mail: gulseyhanozkan@gmail.com

Determinants of foreign direct investment in the textile sector: a research with IT2 Fuzzy TOPSIS methodology

DOI: 10.35530/IT.076.02.2024116

RECEP UĞURCAN ŞAHİN
NALBANT KEMAL GÖKHAN
ABDULKADİR KESKİN
YAVUZ ÖZDEMİR
ABDURRAHMAN KESKİN

ABSTRACT – REZUMAT

Determinants of foreign direct investment in the textile sector: a research with IT2 Fuzzy TOPSIS methodology

This study aims to identify the determinants of foreign direct investment (FDI) in the textile sectors in Poland, Romania, Hungary, Slovakia, Czechia and Türkiye. The study assesses these criteria through paired comparisons conducted by experts who have a minimum of 10 years of professional experience in the field and analyses them using the IT2 Fuzzy Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) technique. According to the findings, the criteria with the highest degree of importance are national security, inflation rate, patent and trademark protection, transportation networks and market size. On a country-by-country basis, Poland has a higher investment attraction potential compared to other countries according to the criteria of openness, corruption, legal regulations and privatization policies, import and export quotas, education and professional status, renewable energy resources, sustainability, intellectual property protection, patent and trademark protection and national security. Hungary scores highest on import and export quotas and tax rates, while Slovakia stands out on import and export quotas and waste management/environmental regulations. Romania scores highest on profitability and debt financing, labour costs and import and export quotas. Czechia scores highest on inflation rate, political stability, legal regulations and privatization policies, economic incentives, general trade policies, import and export quotas and cultural situation and lifestyle. Türkiye scores the highest in terms of market size, GDP growth rate, access to raw materials and markets, technological infrastructure and innovation, transport networks, production sites, energy production, import and export quotas and business-friendly approaches.

Keywords: *foreign direct investment, textile industry, textile investment, IT2 Fuzzy TOPSIS*

Determinanți ai investițiilor străine directe în sectorul textil: o cercetare cu metodologia IT2 Fuzzy TOPSIS

Acest studiu își propune să identifice factorii determinanți ai investițiilor străine directe (FDI) în sectoarele textile din Polonia, România, Ungaria, Slovacia, Cehia și Turcia. Studiul evaluează aceste criterii prin comparații în perechi efectuate de experți care au o experiență profesională de minimum 10 ani în domeniu și le analizează utilizând tehnica IT2 Fuzzy Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS). Conform rezultatelor, criteriile cu cel mai înalt grad de importanță sunt securitatea națională, rata inflației, protecția brevetelor și a mărcilor comerciale, rețelele de transport și dimensiunea pieței. Dintre toate țările analizate, Polonia are un potențial mai ridicat de atragere a investițiilor în comparație cu alte țări în funcție de criteriile privind deschiderea, corupția, reglementările juridice și politicile de privatizare, cotele de import și export, educația și statutul profesional, resursele de energie regenerabilă, durabilitatea, protecția proprietății intelectuale, protecția brevetelor și a mărcilor comerciale și securitatea națională. Ungaria obține cel mai mare punctaj în ceea ce privește cotele de import și export și ratele de impozitare, în timp ce Slovacia se evidențiază în ceea ce privește cotele de import și export și gestionarea deșeurilor/reglementările de mediu. România obține cel mai mare punctaj în ceea ce privește profitabilitatea și finanțarea datoriilor, costurile forței de muncă și cotele de import și export. Cehia este cel mai bine cotată în ceea ce privește rata inflației, stabilitatea politică, reglementările juridice și politicile de privatizare, stimulentele economice, politicile comerciale generale, cotele de import și export, situația culturală și stilul de viață. Turcia obține cel mai mare punctaj în ceea ce privește dimensiunea pieței, rata de creștere a PIB-ului, accesul la materii prime și piețe, infrastructura tehnologică și inovarea, rețelele de transport, locurile de producție, producția de energie, cotele de import și export și abordările favorabile întreprinderilor.

Cuvinte-cheie: *investiții străine directe, industria textilă, investiții textile, IT2 Fuzzy TOPSIS*

INTRODUCTION

With the acceleration of globalization, the mobility and volume of capital, seen as the key to commercial activities and economic growth, have gradually increased. Although the increase in capital mobility and volume causes some problems, it generally provides positive developments by creating opportunities for countries. In economically underdeveloped and developing countries, capital shortages due to insufficient national savings make it very difficult for these countries to achieve or sustain economic growth without FDI. In this context, governments often rely on FDI to meet their financing needs. Therefore, these countries develop and implement attractive measures and incentive policies to attract capital to their countries [1, 2].

Manufacturing, as one of the fundamental components of industrialization, is a driving force for economic growth. Particularly, the textile sector within the manufacturing industry is crucial for achieving economic growth and development in some countries (especially developing countries). However, to realize growth and development goals in these countries, there is a need for Foreign Direct Investment (FDI) in the textile sector, as in other sectors. The textile sector is attractive for FDI due to its labour-intensive nature (beneficial for countries with low wage levels) and the lower production costs and higher profitability associated with its use of low technology [3]. Nevertheless, the complex structure of factors influencing FDI in the textile sector spans a wide range, from labour costs to tax rates. Despite this complexity, the incentive policies developed by governments to attract FDI contribute to the sector's appeal. This study aims to identify the determinants of FDI in the textile sector by providing empirical evidence to explain the complexity of factors influencing FDI decisions. In this context, the study consists of three sections. The first section reviews the literature, the second section presents the methodology used in the study, and the third section discusses and presents the findings obtained from the analysis.

In the literature examining the determinants of FDI inflows in the textile sector, which forms the core of this study, there are both theoretical and empirical studies that are either consistent with or diverge from each other on certain points. Upon reviewing these studies, it is observed that there are both micro-scale research specific to the textile sector and macro-scale studies that include multiple sectors or all sectors. Haque et al. [4] examined the role of cash flow in determining corporate investments by using unbalanced panel data of 159 textile firms listed on the Karachi Stock Exchange (KSE) from 1998 to 2011. Their findings show that cash flow has a significant and positive impact on corporate investments. Maharani and Wiagustini [5], by analysing 14 companies from the textile and apparel sub-sectors listed on the Indonesia Stock Exchange, revealed that growth opportunities, capital structure, and profitability positively affect investment decisions. Soeng and Supinit [6] identified that quota-free access to the US and EU markets, low wage rates, and free taxation advantages with large markets attract international investments in Cambodia's textile and apparel sector.

Ullah et al. [7] investigated the role of firm size in the relationship between financial factors and investment decisions of textile firms listed on the Pakistan Stock Exchange (PSX). They applied fixed effects regression analysis on a sample of 20 textile firms for the period 2009–2018. They found that financial leverage, cash flow, and firm size have a significant and positive impact on investment decisions, while profitability does not have a significant effect. Winn and Dardis [8] analysed post-World War II investment behaviour in the US textile industry, considering liquidity constraints and the two components of investment, namely expansion and modernisation investments, using both cross-sectional and time series data. Time series data show that capital-labour substitution is a significant determinant of investment, and depreciation expenses have a meaningful impact on investment. Additionally, liquidity constraints play a crucial role in the textile sector in government policies.

Özkaya [9], in his study on the factors affecting intra-industry trade in the textile sector, associated the preference of foreign investors for Türkiye in textile investments with Türkiye's lower labour costs compared to the EU region. Additionally, findings from regression analysis indicate that foreign direct investments in the textile sector negatively impact the level of intra-industry trade. Polat and Payaslıoğlu [10] analysed the fundamental determinants of foreign investments in 13 sub-sectors of the manufacturing industry, including the textile sector in Türkiye, using data from the period 2007–2012. According to the findings, investment incentives and tax rates are determinants for FDI. Liu et al. [11] analysed FDI in the manufacturing industry, including the textile sector in China, across four main regions. They concluded that local market size, labour costs, and the agglomeration effect are determinants of attracting FDI in the low-technology textile sector. Wu et al. [12] found that China's outward FDI promotes growth in the middle segment of the textile industry. The World Bank's [13] 2015 study on Sub-Saharan African countries indicated that the main determinants of FDI in Ethiopia's textile sector are market size and political-social stability. Additionally, low labour and raw material costs and investment incentives were highlighted as other significant determinants. Bartels et al. [14] examined data on 758 foreign investors in 10 Sub-Saharan African countries using factor analysis. According to the findings, the provision of information and public services that reduce transaction costs regarding sectors and markets before and after investment influences investors' FDI decisions. Moreover, it was determined that the choice of location for FDI is strongly affected by political economy factors.

Saravanan [15] suggests that the Indian government's flexible rule, known as the automatic route, which allows international investors to invest without prior approval from the government or the Reserve Bank of India, has encouraged FDI inflows into the textile sector. Danciu and Strat [16] examined the main determinants of foreign direct investments across different regions in Romania using a sample of 235 companies. According to the findings from the analysis conducted through two main clusters, factors such as the availability and quality of the workforce, labour and operational costs, market seeking, low rent and land prices, production site, and the distance between the production site and potential customers influence foreign investors' investment decisions. Cieślik [17] used panel data methods to empirically investigate the reasons for FDI inflows from OECD countries to Poland between 1996–2015. The findings indicate that the primary reason for FDI inflows into Poland is the search for efficiency, with a preference for the pure vertical integration model of multinational companies. For the sub-sample period of 1996–2004, both market-seeking and efficiency-seeking factors were prominent.

Wang and Swain [18] linked the determinants of FDI inflows into Hungary and China during 1978–92 to market size, low-cost labour, and currency depreciation. Additionally, a positive correlation between OECD growth rates and FDI in Hungary was identified. Tsaurai [19], using data from 1991–2015 and an OLS multiple regression model, empirically tested the determinants of FDI in Hungary. Contrary to common belief, the findings indicate that inflation has a positive impact on FDI. Furthermore, exchange rates, education, and economic growth have a positive but not significant effect on FDI in Hungary.

Bobenič et al. [20] applied correlation and regression analyses to country-level data from the Visegrad countries (the Czech Republic, Hungary, Poland, and Slovakia) for the period 1989–2016. They found that gross wage levels and an educated labour force positively affect FDI inflows in the Visegrad countries. Additionally, corporate tax rates, trade openness, and research and development expenditures have a negative effect on FDI. Su et al. [21] examined several macroeconomic factors influencing FDI in the Visegrad group countries after the European Union's (EU) enlargement in 2004. They found that perceived corruption is a significant factor affecting FDI in all countries. Furthermore, a significant long-term relationship was identified between FDI, the corruption index, and the highly educated workforce. Darmo et al. [22] aimed to identify the determinants of FDI flows for the Visegrad countries for the period 2001–2014. They concluded that economic size, corporate tax rates, inflation, trade openness, the level of corruption, and labour cost-productivity and quality are significant determinants.

The studies reveal that the factors shaping corporate and international investment decisions in the textile sector are multidimensional and complex. The findings emphasize various factors that need to be considered in developing strategies to attract investment in the textile sector. For the sustainable growth and increased competitiveness of the sector, a holistic analysis of the factors influencing investment decisions at both micro and macro levels is required. In this context, our study aims to contribute to the development of more effective and strategic investment policies in the textile sector. Fuzzy logic research is scarce in the literature that specifically focuses on the textile area. Hence, this study will make a valuable contribution to the existing body of knowledge in the textile industry.

The remainder of this paper is structured as follows: A description of the problem is provided, and the IT2 Fuzzy TOPSIS method is examined in the following section. A textile investment factor evaluation using the IT2 fuzzy TOPSIS methodology. Furthermore, computational results and comparisons are provided. In the conclusion section, the results are discussed, evaluations are made, and prospective future research directions are highlighted.

IT2 FUZZY TOPSIS METHODOLOGY

The primary goal of this study is to examine the factors affecting textile investments and emphasize the importance of effectively overcoming the diverse challenges that emerge throughout the decision-making process. The study used the trapezoidal Interval Type-2 (IT2) Fuzzy Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) technique. This research is focused on the selection of a country to invest in. The decisions were taken by three individuals who hold positions of authority and responsibility within the organization and business. Each expert in the research was assigned equal weight. Five crucial factors and twenty-six sub-factors were chosen in this problem, and each of these criteria was assigned the necessary weight. Furthermore, six alternatives were selected, as seen in figure 1.

The arrows in figure 1 illustrate the problem's hierarchy. Economic factors criteria (MC1) include the following subcriteria: openness to the outside (SC11), profitability and debt financing (SC12), inflation rate (SC13), labour costs (SC14), market size (SC15), and GDP growth rate (SC16). Infrastructure and Logistics criteria (MC2) include the following subcriteria: access to raw materials and markets (SC21), technological infrastructure and innovation (SC22), transportation networks (SC23), production sites (SC24), and energy production (SC25). The following subcriteria are included in Political Factors (MC3): political stability (SC31), corruption (SC32), legal regulations and privatization policies (SC33), economic incentives and general trade policies (SC34), import and export quotas (SC35), and tax rates (SC36). Social and Environmental Factors (MC4) includes the following subcriteria: cultural situation and lifestyle (SC41), education and professional status (SC42), business-friendly/friendly approaches (SC43), renewable energy resources (SC44), waste management/environmental regulations (SC45), sustainability (SC46). Safety (Risk) Factors (MC5) includes the following subcriteria: intellectual property protection (SC51), patent and trademark protection (SC52), and national security (SC53). Alternatives from A1 to A6 were identified as Poland, Romania, Hungary, Slovakia, Czechia, and Türkiye, respectively.

Experts 1–3 are D1, D2, and D3. This study used trapezoidal interval type-2 fuzzy sets (IT2 FSs) and TOPSIS [23–26].

In 2008, Lee and Chen first presented the IT2 fuzzy TOPSIS technique. The current study used the IT2 fuzzy TOPSIS approach conducted by Lee and Chen [27] and Cengiz [28] to choose the most suitable textile. The problem was resolved by employing the IT2

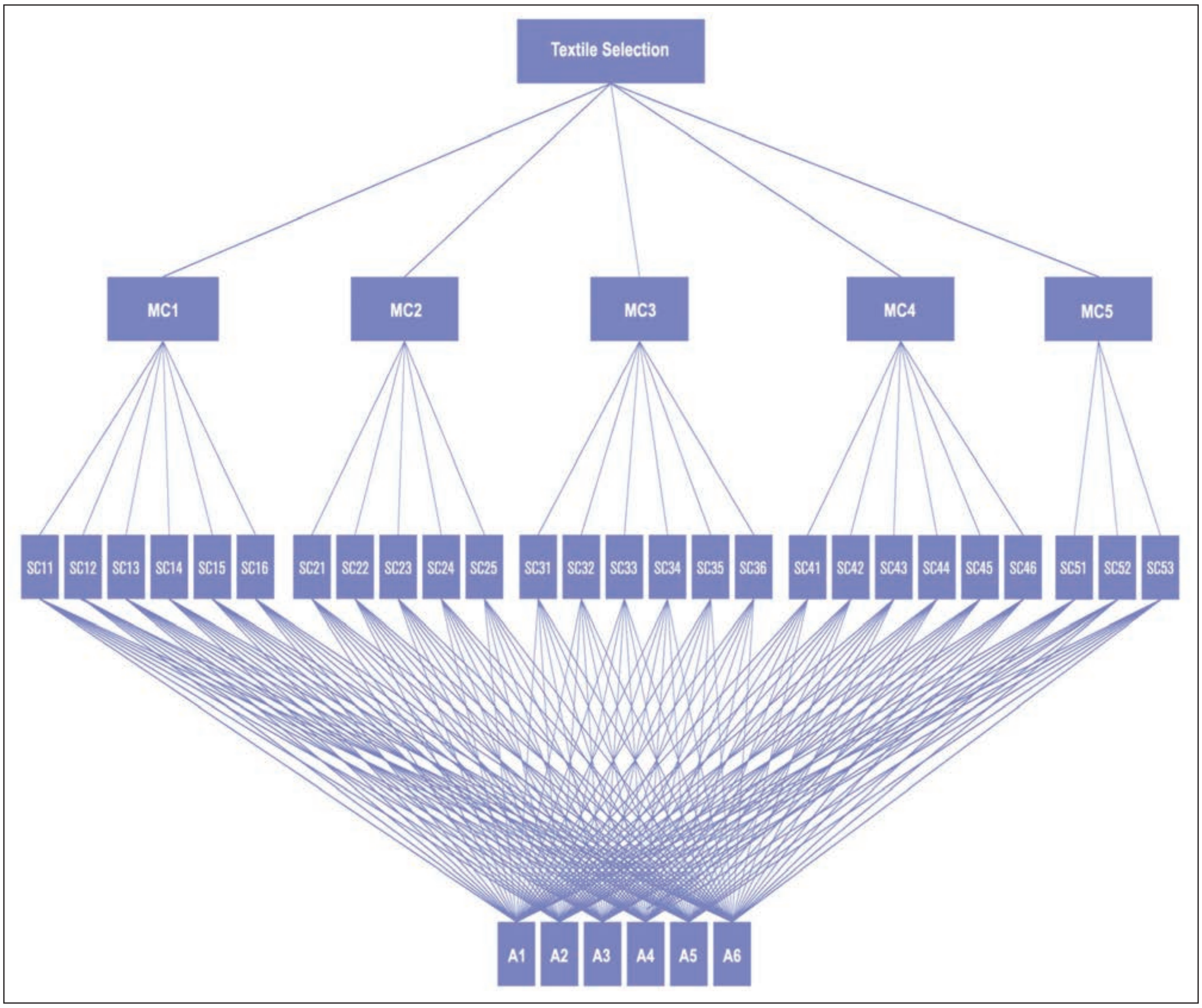


Fig. 1. A hierarchical framework of the textile investment factors problem

fuzzy TOPSIS approach, which used fuzzy numbers, as shown in table 1. Chen and Lee used table 1 to display the seven linguistic characteristics connected to IT2 FSs [29].

Table 1 displays the linguistic expressions and interval fuzzy numbers used in the process of identifying the main criterion, sub-criteria, and alternatives. The IT2 fuzzy TOPSIS algorithm was utilized for the entire process of alternative selection. This solution was implemented to resolve the problem of square matrices that occur while using alternative matrices for sub-criteria. A comprehensive matrix was executed using the average weighting method, which incorporated the significance weights of each criterion. Afterwards, the decision matrix was calculated using the supplied weights. The procedure of assigning values to rank IT2 FS was carried out. Furthermore, the calculation of the positive ideal solution (PIS) and

Table 1

THE LINGUISTIC EXPRESSIONS RELATED TO INTERVAL TYPE-2 FUZZY SYSTEMS [29, 30]

Linguistic expressions	Trapezoidal IT2 fuzzy numbers
Very Low (VL)	((0, 0, 0, 0.1; 1, 1) (0, 0, 0, 0.05;0.9, 0.9))
Low (L)	((0, 0.1, 0.1, 0.3; 1, 1) (0.05, 0.1, 0.1, 0.2; 0.9, 0.9))
Medium Low (ML)	((0.1, 0.3, 0.3, 0.5; 1, 1) (0.2, 0.3, 0.3, 0.4; 0.9, 0.9))
Medium (M)	((0.3, 0.5, 0.5, 0.7; 1, 1) (0.4, 0.5, 0.5, 0.6; 0.9, 0.9))
Medium High (MH)	((0.5, 0.7, 0.7, 0.9;1; 1) (0.6, 0.7, 0.7, 0.8; 0.9, 0.9))
High (H)	((0.7, 0.9, 0.9, 1; 1, 1) (0.8, 0.9, 0.9, 0.95; 0.9, 0.9))
Very High (VH)	((0.9, 1, 1,1; 1, 1) (0.95, 1, 1,1; 0.9, 0.9))

negative ideal solution (NIS) was executed. The next section provides a thorough examination of the prescribed procedures that must be adhered to effectively utilize this methodology. The distances between each choice were computed. After completing a thorough study, the proximity coefficient was calculated, leading to the identification and selection of the most beneficial option.

The conventional method is to use a number scale, often spanning from 1 to 9, to evaluate many alternatives based on a predetermined set of criteria. Table 1 displays the numerical values assigned to the language variables. The decision-makers, who were responsible for making the final choice, were assigned the task of evaluating each criterion for every alternative. The IT2 fuzzy TOPSIS approach is utilized to address the assessment of the foreign direct investment problem. The derived weighted decision matrix is the outcome of using IT2 fuzzy TOPSIS. The distances between each possible alternative are calculated. Afterwards, the proximity coefficient is computed and used to choose the most advantageous choice. According to the data presented in table 2, the observed order is x1 > x6 > x5 > > x2 > x3 > x4.

Table 2

RESULTS OF THE IT2 FUZZY TOPSIS

Country	Weights	Normalized values
x1 (Poland)	0.69	25.20%
x2 (Romania)	0.39	14.33%
x3 (Hungary)	0.34	12.49%
x4 (Slovakia)	0.29	10.52%
x5 (Czechia)	0.47	17.20%
x6 (Türkiye)	0.55	20.25%

The membership functions of type-1 fuzzy sets (FSs) are composed of two dimensions, whereas the membership functions of type-2 fuzzy sets (FSs) are composed of three dimensions. Because it gives extra degrees of freedom, the new third dimension makes it feasible to directly simulate uncertainty. This is because the dimension offers additional degrees of freedom [31]. The T2 fuzzy set approach, in contrast to T1 FSs, offers flexibility and represents uncertainty. Moreover, a T2 fuzzy set ensures an adequate representation of uncertainty. T2 FSs enable rule-based fuzzy logic systems to model and minimize delays [32–34]. There are some recent studies in the literature using IT2 fuzzy TOPSIS [35,36].

CONCLUSION

The main purpose of this study is to determine the investment potential of six different European countries by addressing the factors affecting textile investments. Using a trapezoidal IT2 fuzzy TOPSIS approach made completing this challenge easier. Based on the supplied weights for textile country alternatives, the analysis shows that alternative x1 (Poland) has achieved a score of 25.20%. Comparatively, alternative x6 (Türkiye) has obtained a score of 20.25%, while alternative x5 (Czechia) has acquired a score of 17.20%. Alternative x2 (Romania) has attained a score of 14.33%, followed by alternative x3 (Hungary) with a score of 12.49%, and alternative x4 (Slovakia) with a score of 10.52%. x1 (Poland) was selected as the best alternative. The fact that these countries are located in Europe and the ratios of their textile production levels to GDP are close to each other, these two criteria were taken into account in the sample selection. According to the findings, SC53 (national security) >SC13 (inflation rate) >SC52 (patent and trademark protection) >SC23 (transportation networks) >SC15 (market size) constitute the top 5 criteria in terms of importance. The results are consistent with the literature. In terms of countries, A1 (Poland) has a higher investment attraction potential compared to other countries based on SC11 (openness), SC32 (corruption), SC33 (legal regulations and privatization policies), SC35 (import and export quotas), SC42 (education and professional status), SC44 (renewable energy sources), SC46 (sustainability), SC51 (intellectual property protection), SC52 (patent and trademark protection) and SC53 (national security). A2 (Romania) is the highest scoring country according to criteria SC12 (profitability and debt financing), SC14 (labour costs) and SC35 (import and export quotas). A3 (Hungary) scored the highest according to SC35 (import and export quotas) and SC36 (tax rates), and A4 (Slovakia) scored the highest according to SC35 (import and export quotas) and SC45 (waste management/environmental regulations). A5 (Czechia) scored the highest on SC13 (inflation rate), SC31 (political stability), SC33 (legal regulations and privatization policies), SC34 (economic incentives and general trade policies), SC35 (import and export quotas) and SC41 (cultural situation and lifestyle). A6 (Türkiye) is the highest scoring country according to SC15 (market size), SC16 (GDP growth rate), SC21 (access to raw materials and markets), SC22 (technological infrastructure and innovation), SC23 (transportation networks), SC24 (production sites), SC25 (energy production), SC35 (import and export quotas) and SC43 (business friendly/friendly approaches). The level of importance of the criteria, which are weighted by using the expert opinions and ratings of three senior executives operating in the textile sector, differs within each country. Each country is differentiated from other countries according to some criteria. Looking at the overall weighted scoring, the ranking of the countries is as shown in Table 2. The findings may give important ideas to potential investors for foreign direct investment inflows to the textile sectors of these countries.

Different IT2 fuzzy methodologies (DEMATEL-ANP, FANP, FAHP) may be implemented in future investigations that pertain to foreign direct investment in the textile sector. Additionally, fuzzy methods that are incorporated with IT2 can be employed to evaluate the effectiveness of different methods. This issue is addressed using the IT2 fuzzy TOPSIS method, which is the preferred approach. The effectiveness of the IT2 trapezoidal fuzzy TOPSIS approach has been shown by its successful application in optimizing the assessment process. Potential areas for future research to expand upon our findings are focused on IT2 fuzzy methods. Some programs can be written to simplify the calculation process for IT2 fuzzy logic methods. Solution processes can achieve quicker results with these programs.

REFERENCES

[1] Iamsiraroj, S., *The foreign direct investment–economic growth nexus*, In: International Review of Economics & Finance, 2016, 42, 116–133, https://doi.org/10.1016/j.iref.2015.10.044

[2] Reiter, S.L., Steensma, H.K., *Human development and foreign direct investment in developing countries: the influence of FDI policy and corruption*, In: World Development, 2010, 38, 12, 1678–1691, https://doi.org/10.1016/j.worlddev.2010.04.005

[3] Keane, J., Te Velde, D.W., *The role of textile and clothing industries in growth and development strategies*, In: Overseas Development Institute, 2008, 7, 1, 141–147

[4] Haque, A., Naeem, K., Qureshi, W., *Impact of internal finances on corporate investment in Pakistan textile firms*, In: Science International, 2014, 26, 5, 2591–2593

[5] Maharani, P.E., Wiagustini, N.L.P., *Determınant of Investment Decısıon Wıth Growth Opportunıty As Moderatıon Varıable: Study On Sub-Sector Textıle And Garment Companıes Lısted On The Indonesıan Stock Exchange*, In: Journal of Economic, Business and Accounting, 2024, 7, 2, 2827–2844, https://doi.org/10.31539/costing.v7i2.7406

[6] Soeng, S., Supinit. V., *The Analysis of Foreign Direct Investment in Textile and Garment Industries in Cambodia*, In: International Journal of Thesis Projects and Dissertations, 2016, 4, 1, 64–70

[7] Ullah, K., Arif, M., Urooge, S., *The impact of financial factors on investment decision with moderating role of firm size: Evidence from textile-based firms in Pakistan*, In: The Journal of Humanities and Social Sciences, 2021, 29, 1, 77–88

[8] Winn, M., Dardis, R., *Investment behavior in the United States textile industry*, In: Textile Research Journal, 1970, 40, 9, 826–832

[9] Özkaya, M.H., *Tekstil sektöründe endüstri-içi ticareti etkileyen faktörler üzerine ampirik çalışma*, In: Uşak Üniversitesi Sosyal Bilimler Dergisi, 2010, 32, 136–157, https://doi.org/10.12780/UUSBD78

[10] Polat, B., Payaslıoğlu, C., *Determinants of foreign direct investment to Turkey: A sectoral approach*, In: Topics in Middle Eastern and African Economies, 2014, 17, 2, 1–28

[11] Liu, K., Daly, K., ve Varua, E.M., *Regional determinants of foreign direct investment in manufacturing industry,* In: International Journal of Economics and Finance, 2012, 12, 4, 178–192, http://dx.doi.org/10.5539/ijef.v4n12p178

[12] Wu, H.L., Chen, C.H., Chen, L.T., *Determinants of foreign trade in China's textile ındustry*, In: The International Trade Journal, 2012, 26, 2, 112–138, https://doi.org/10.1080/08853908.2012.657586

[13] Chen, G., Geiger. M., Fu, M., *Manufacturing FDI in Sub-Saharan Africa: trends, determinants, and impacts*, World Bank Group, 2015

[14] Bartels, F.L., Alladina, S.N., Lederer, S., *Foreign direct ınvestment in Sub-Saharan Africa: motivating factors and policy ıssues*, In: Journal of African Business, 2009, 10, 2, 141–162, https://doi.org/10.1080/15228910903187791

[15] Saravanan, S., *Foregın direct ınvestment in the manufacturing ındustry: wıth specıal refence to textile ındustry in India*, In: Parıpex-Indian Journal of Research, 2017, 6, 1, 793–795

[16] Danciu, A.R., Strat, V.A., *Main Determinants of Foreign Direct Investments in Romania- A Quantitative View of the Regional Characteristics Involved in the Investment Strategies of Foreign Companies*, In: Procedia- Social and Behavioral Sciences, 2012, 58, 1193–1203, https://doi.org/10.1016/j.sbspro.2012.09.1101

[17] Cieślik, A., *Determinants of foreign direct investment from OECD countries in Poland*, In: Eurasian Economic Review, 2019, 10, 1, 9–25, https://doi.org/10.1007/s40822-019-00136-y

[18] Wang, Z.Q., Swain, N.J., *The determinants of foreign direct investment in transforming economies: Empirical evidence from Hungary and China*, In: Weltwirtschaftliches Archiv, 1995, 131, 359–382, https://doi.org/10.1007/BF02707440

[19] Tsaurai, K., *Foreign direct ınvestment dynamics in Hungary*, In: Journal of Economics and Behavioral Studies, 2017, 9, 6(J), 122–131, https://doi.org/10.22610/jebs.v9i6(J).2010

[20] Bobenič Hintošová, A., Bruothová, M., Kubíková, Z., Ručinský R., *Determinants of foreign direct investment inflows: A case of the Visegrad countries*, In: Journal of International Studies, 2018, 11, 2, 222–235, https://doi.org/10.14254/2071-8330.2018/11-2/15

[21] Su, W., Zhang, D., Zhang, C., Abrhám, J., Simionescu, M., Yaroshevich, N., Guseva, V., *Determinants of foreign direct investment in the Visegrad group countries after the EU enlargement*, In: Technological and Economic Development of Economy, 2018, 24, 5, 1955–1978, https://doi.org/10.3846/tede.2018.5487

[22] Darmo, Ľ., Novák, M., Kálovec, M., Rybošová, P., *Determinants of the fdı ınflow into the Visegrad Countries*, In: Ekonomický časopis/Journal of Economics, 2020, 68, 10, 1057–1080, https://doi.org/10.31577/ekoncas.2020.10.05

[23] Kahraman, C., Öztayşi, B., Sarı, İ.U., Turanoğlu, E., *Fuzzy analytic hierarchy process with interval type-2 fuzzy sets,* In: Knowledge-Based Systems, 2014, 59, 48-57, https://doi.org/10.1016/j.knosys.2014.02.001

[24] Şentürk, S., Erginel, N., Binici, Y., *Interval Type-2 Fuzzy Analytic Network Process for Modelling a Third-party Logistics (3PL) Company*, In: Journal of Multiple-Valued Logic & Soft Computing, 2017, 28, 311–333

[25] Chen, S.M., Lee, L.W., *Fuzzy multiple attributes group decision-making based on the interval type-2 TOPSIS method*, In: Expert Systems with Applications, 2010, 37, 4, 2790–2798, https://doi.org/10.1016/j.eswa.2009.09.012

[26] Özdemir, Y., Özdemir, S., Nalbant, K.G., *A Hybrid Methodology for Prioritizing of Store Plan Alternatives Produced with Rule-Based Design*, In: International Journal of Information Technology & Decision Making, 2021, 20, 6, 1685–1709, https://doi.org/10.1142/S0219622021500486

[27] Lee, L.W., Chen, S.M., *Fuzzy multiple attributes group decision-making based on the extension of TOPSIS method and interval type-2 fuzzy sets*. In: 2008 International Conference On Machine Learning and Cybernetics, 2008, 6, 3260–3265, https://doi.org/10.1109/ICMLC.2008.4620968

[28] Cengiz Toklu, M., *Interval type-2 fuzzy TOPSIS method for calibration supplier selection problem: A case study in an automotive company*, In: Arabian Journal of Geosciences, 2018, 11:341, 1–7, https://doi.org/10.1007/s12517-018-3707-z

[29] Chen, S.M., Lee, L.W., *Fuzzy multiple attributes group decision-making based on the ranking values and the arithmetic operations of interval type-2 fuzzy sets*, In: Expert Systems with Applications, 2010, 37, 1, 824–833, https://doi.org/10.1016/j.eswa.2009.06.094

[30] Abdullah, L., Najib, L., *A new type-2 fuzzy set of linguistic variables for the fuzzy analytic hierarchy process*, In: Expert Systems with Applications, 2014, 41, 7, 3297–3305, https://doi.org/10.1016/j.eswa.2013.11.028

[31] Nalbant, K.G., *A methodology for personnel selection in business development: An interval type 2-based fuzzy DEMATEL-ANP approach*, In: Heliyon, 2024, 10, 1, https://doi.org/10.1016/j.heliyon.2023.e23698

[32] Nalbant, K.G., Ozdemir, S., Ozdemir, Y., *Evaluating the campus climate factors using an interval type-2 fuzzy ANP*, In: Sigma Journal of Engineering and Natural Sciences, 2024, 42, 1, 89–98, https://doi.org/10.14744/sigma.2024.00011

[33] Senturk, S., Binici, Y., Erginel, N., *The theoretical structure of fuzzy analytic network process (FANP) with interval type-2 fuzzy sets,* In: IFAC-PapersOnLine, 2016, 49, 12, 1318–1322, https://doi.org/10.1016/j.ifacol.2016.07.706

[34] Nalbant, K.G., Özdemir, Ş., Özdemir, Y., *Selecting an alternative concrete batching plant location using IT2 fuzzy anp methodology*, In: İstatistik ve Uygulamalı Bilimler Dergisi, 2022, 5, 10–16, https://doi.org/10.52693/jsas.1091307

[35] Madi, E.N., Zakaria, Z.A., Sambas, A., Sukono, *Toward Effective Uncertainty Management in Decision-Making Models Based on Type-2 Fuzzy TOPSIS*, In: Mathematics, 2023, 11, 16, 3512, https://doi.org/10.3390/math11163512

[36] Najafi, S.M.R.P.A., Mohammadi, N., *Supply Chain Risk Assessment of Steel Industry Using Hybrid Type Fuzzy TOPSIS Approach and Fuzzy Hierarchical Analysis*, In: Journal of Industrial Engineering International, 2023, 19, 1, 94

Authors:

RECEP UĞURCAN ŞAHİN[1], NALBANT KEMAL GÖKHAN[2], ABDULKADİR KESKİN[3], YAVUZ ÖZDEMİR[4], ABDURRAHMAN KESKİN[5]

[1]Yalova University, Faculty of Economic and Management Sciences, Labor Economics and Industrial Relations, Yalova University Central Campus, On Çınarcık Road 77200, Yalova, Türkiye
e-mail: recepugurcansahin@hotmail.com, ORCID: 0000-0001-8286-3325

[2]Istanbul Beykent University, Faculty of Engineering – Architecture, Department of Software Engineering, Ayazaga District, Hadim Koruyolu St. No:19 Sariyer, 34398, Istanbul, Türkiye
e-mail: kemalnalbant@beykent.edu.tr, ORCID: 0000-0002-5065-2504

[3]Istanbul Medeniyet University, Faculty of Political Sciences, Management, Ünalan District D-100 Highway, North Campus, C Block, Floor: 7, Üsküdar, 34700, Istanbul, Türkiye
ORCID: 0000-0002-4795-1028

[4]Istanbul Health and Technology University, Faculty of Engineering and Natural Sciences, Department of Industrial Engineering, Sütlüce Campus, Sütlüce District, İmrahor Street, No: 82, Beyoğlu, 34275, Istanbul, Türkiye
e-mail: yavuz.ozdemir@istun.edu.tr, ORCID: 0000-0001-6821-9867

[5]Bayburt University, Faculty of Humanities and Social Sciences, Department of Sociology, Bâbertî Social Complex Tuzcuzade District, Demirözü Street on Erzincan Road 2.7 km, 69000, Bayburt, Türkiye
ORCID: 0000-0003-1547-0358

Corresponding author:

ABDURRAHMAN KESKİN
e-mail: abdurrahmankeskin@bayburt.edu.tr

Analysis of the dual network relationship and its evolutionary characteristics of global textile new material technology cooperation R&D in the 21st century

DOI: 10.35530/IT.076.02.202491

PENGFEI WANG HUA CHENG

ABSTRACT – REZUMAT

Analysis of the dual network relationship and its evolutionary characteristics of global textile new material technology cooperation R&D in the 21st century

Vigorously developing new materials technology is of great significance to improving the high-tech level of the textile industry, enhancing the transformation and upgrading of the textile industry, promoting the sustainable development of the industry and enhancing the comprehensive national strength. In this paper, the data of 6982 invention patents created by global textile new material technology cooperation are chosen as the research object, and the patent technology network analysis method is used to examine the dual network relationship and its evolution features. The results suggest that the core subjects represented by multinational corporations, well-known universities and scientific research institutes integrate resources to conduct technology cooperation research, and the cooperation network's innovation activities in this field tend to be stable, but there is no relatively stable collaborative relationship between innovation organizations. Furthermore, technology nodes, technology subgroups, spillover effects between technologies, diffusion and fusion, and technology correlation strength have greatly improved. At the same time, reasonable division of labor and coordination of the collaborative activities among nodes in the core, middle, and edge layers of the network are crucial, and the division of labor and cooperation within the network are of great significance for improving collaborative innovation efficiency. This study is useful to determine the innovation subjects, network structure and technological evolution of global textile new material technology cooperation research and development, but there is no analysis of the relationship between organizational cooperation network and technological network and its evolution characteristics in this field. As a result, this article tries to supplement existing research in terms of both research object and research content, to fill the gaps in the existing research.

Keywords: *textile, new materials, technology R&D, network structure, patentometrics, evolution characteristics*

Analiza relației rețelei duale și a caracteristicilor sale evolutive privind cooperarea globală în domeniul cercetării și dezvoltării tehnologiei materialelor textile noi în secolul al XXI-lea

Dezvoltarea viguroasă a tehnologiei materialelor textile noi are o mare importanță pentru îmbunătățirea nivelului de înaltă tehnologie al industriei textile, susținerea transformării și modernizării industriei textile, promovarea dezvoltării durabile a industriei și sporirea puterii naționale. În această lucrare, datele din 6982 de brevete de invenție create prin cooperarea globală în domeniul tehnologiei materialelor textile noi sunt alese ca obiect de cercetare, iar metoda de analiză a rețelei tehnologice de brevete este utilizată pentru a examina relația de rețea duală și caracteristicile evoluției acesteia. Rezultatele sugerează că subiecții de bază reprezentați de corporațiile multinaționale, universitățile de renume și institutele de cercetare științifică integrează resursele pentru a efectua cercetări de cooperare tehnologică, iar activitățile de inovare ale rețelei de cooperare în acest domeniu tind să fie stabile, dar nu există o relație de colaborare relativ stabilă între organizațiile de inovare. În plus, nodurile tehnologice, subgrupurile tehnologice, efectele de propagare între tehnologii, difuzarea și fuziunea, precum și puterea corelației tehnologice s-au îmbunătățit considerabil. În același timp, diviziunea rezonabilă a muncii și coordonarea activităților de colaborare între nodurile din straturile central, mijlociu și periferic ale rețelei sunt esențiale, iar diviziunea muncii și cooperarea în cadrul rețelei sunt foarte importante pentru îmbunătățirea eficienței inovării colaborative. Acest studiu este util pentru a determina subiectele de inovare, structura rețelei și evoluția tehnologică a cooperării în domeniul cercetării și dezvoltării globale a tehnologiilor materialelor textile noi, dar nu există o analiză a relației dintre rețeaua de cooperare organizațională și rețeaua tehnologică și caracteristicile evoluției acesteia în acest domeniu. Drept urmare, acest articol încearcă să suplimenteze cercetările existente atât în ceea ce privește obiectul cercetării, cât și conținutul cercetării, pentru a umple lacunele din studiile de cercetare existente.

Cuvinte-cheie: *textile, materiale noi, cercetare și dezvoltare tehnologică, structura rețelei, patentometrie, caracteristici de evoluție*

INTRODUCTION

New materials are the cornerstone of the upgrading of traditional industries and the development of strategic emerging industries, and as a key resource input [1], they play a vital role in promoting the technological revolution and sustainable development of the industry. Compared with the traditional material industry, new materials refer to materials with excellent properties and special properties that are newly discovered or produced through artificial new synthesis or modified by traditional materials, so they have the characteristics of being technology-intensive, large investment in R&D (research and development), and high added value of products.

At present, the global textile industry has shifted from a high-speed growth stage to a high-quality development stage, and textile technology innovation is undoubtedly an important guarantee for high-quality and sustainable development. As a key area of international competition, textile new material technology is a key force in promoting the high-end and intelligent development of the textile industry, and it is also an important engine for realising the modernization of the textile industrial system. Therefore, the research and development of new textile material technology is of great significance for achieving the sustainable development goals of a green, low-carbon, and energy-saving human society.

Technological innovation and development cannot be separated from international R&D cooperation [2]. In the process of innovation and development of textile new materials technology, exploring the cooperative network relationship and evolution characteristics among R&D subjects and analyzing the diffusion, integration, and technological correlation intensity between technologies will help enterprises formulate reasonable R&D cooperation plans and innovation strategies [3], and thus gain the first-mover advantage in technology layout and competition and worthy of scholars' thinking and research.

Furthermore, more and more scholars have paid attention to the introduction of the "network view" to research on technological cooperation in R&D [4, 5]. By analysing the cooperative behavior of different organizations in technology R&D, according to the different nodes' attributes, it can be mainly divided into an organizational cooperation network composed of organizations as nodes and a patent citation network composed of patents as nodes [6, 7]. The former is used to analyze the composition, status and cooperation methods of network members, as well as their relationship with partners and projects, and points out that the research on organizational cooperation network can present the form of cooperation network and clarify the core subjects and relevant participants [8–10]. The latter is mainly used to identify technology and technology development path, show the focus of technology R&D at different stages, and present the development trend of technology diversification and core innovation activities of enterprises from the technological and geographical levels [11, 12].

However, existing studies lack the characteristics and evolution trend analysis of the textile new materials technology cooperative R&D network. So, the matching analysis of the technology network and the organizational cooperation network can provide a more accurate and comprehensive technical panorama, to provide a reference for the government's science and technology innovation policy formulation and technology research and development.

Given this, this paper discusses the network relationship and evolution characteristics of global textile new material technology cooperation R&D by constructing an organizational cooperation network and a technical network, aiming to provide theoretical enlightenment and decision-making support for the technical layout and management practice of the textile industry. The significance of this study is as follows: (1) laying a theoretical foundation for the future cooperative R&D and innovation of emerging technologies in the textile industry; (2) while providing academic reference, the global textile new material technology cooperation R&D analysis index can be used to establish the relationship between innovation subjects and technical fields and determine the rules of technology association; (3) by analyzing the organizational cooperation network and technology network, we can discover the evolution process of innovation in this field, predict the future technology research and development trend and development frontier, and help enterprises and governments to formulate relevant industrial policies.

DATA SOURCE

The data in this paper are from the PatSnap patent database platform (https://analytics.zhihuiya.com/). For textile new material technology, its international patent classification (IPC) includes two categories: D (textile) and A41 (clothing). Therefore, the new material industry in the national strategic emerging industry classification is selected in the database, and the patent legal status is selected as "valid" in combination with the IPC D01 Fiber, D02 Yarn, D03 Weaving, D04 Weaving, D05 Sewing and D06 Fabric Treatment. In addition, since the beginning of the 21st century, global scientific and technological innovation has entered a period of unprecedented intensity and activity, and a new round of scientific and technological revolution and industrial transformation is reshaping the global innovation map and the global economic structure. At the same time, the period from invention patent application to publication and authorization is about 18 months, so the search time range is limited to 2000–2021.

Together, the world's Five Intellectual Property Offices (IP5) process about 80% of the world's patent applications and about 95% of all work carried out under the Patent Cooperation Agreement (PCT). Therefore, China, the United States, South Korea, Japan, and Europe are selected as innovation regions for the study. Through the above strategies, the number of applicants was set at least 2 or more, and then the search results were combined to obtain 6982 patent data consistent with this study.

METHODOLOGY

Analysis framework

In this paper, the patent technology network analysis method is used to construct the organizational cooperation network and technical network of textile new material technology. Organizational cooperation networks use organizations as nodes to analyze relationships and structures between different organizations. The technology network takes technology as a node and uses technology keywords and IPC classification numbers instead of specific technologies, which is used to analyze the changes in the layout, development trend, and relationship between technologies of patented technologies. Combined with relevant research [10–12], the analysis framework of this paper is shown in figure 1. Firstly, the downloaded patent data was cleaned and screened, and relevant patent information was used to establish a data matrix. Secondly, the cooperative patents of two or more patentees are selected, and the organizational cooperation co-occurrence matrix and IPC technology co-occurrence matrix are constructed, and the organizational cooperation network and technical network for the research and development of textile new material technology are constructed with the help of Gephi software. Finally, the network structure is analyzed from the aspects of network structure, R&D subject, and technology spillover effect, and the characteristics of the organization and cooperation network of global textile new material technology and the characteristics of the IPC technology network are identified.

Network data metrics

Table 1 shows that the data indicators of the new material technology R&D cooperation network are analyzed from three dimensions: network structure, innovation organization characteristics, and technical characteristics. Among them, the network structure is a quantitative analysis of the overall structure of the network, including the network size, degree, network density, network diameter, and average clustering coefficient, which helps to intuitively understand the development dynamics, structural characteristics, and evolution process of network cooperation. The characteristics of innovative organizations include the identification of core organizations and the analysis of the number and proportion of organizations such as enterprises, universities, and research institutes. The technical characteristics involve the breadth and strength of technology, revealing the degree of correlation and integration among technologies.

In this study, Gephi is used to calculate the nodes, the connectivity between nodes and the relative distance of the R&D collaboration network, which helps to intuitively understand the development dynamics, structural characteristics and evolution process of organizational collaboration, etc. The network metrics in table 1 are calculated as follows:

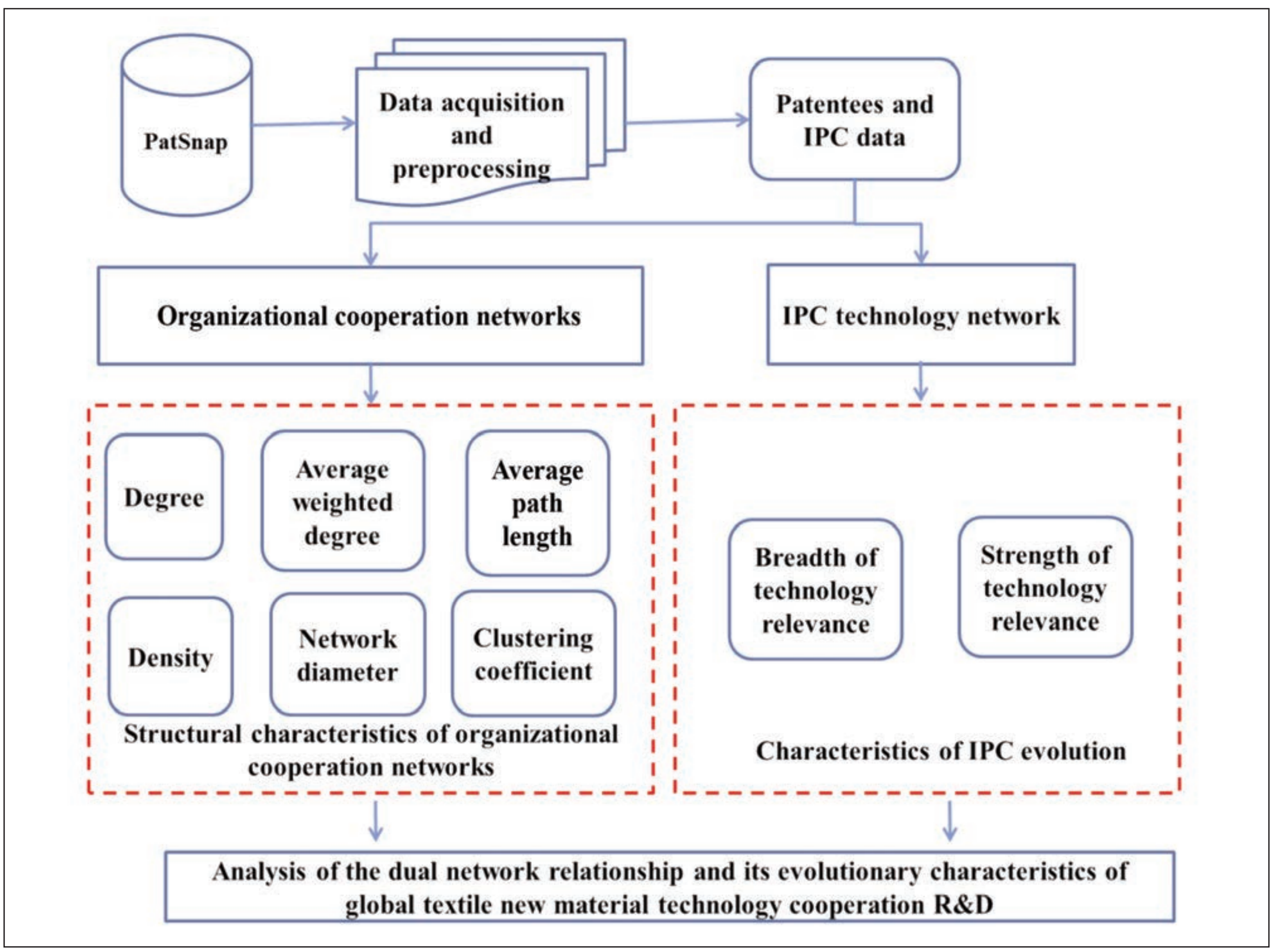


Fig. 1. A dual network analysis framework for collaborative R&D of new textile material technologies

Table 1

DATA INDICATORS OF NEW MATERIAL TECHNOLOGY R&D COOPERATION NETWORK		
Dimensions	**Measurement indicators**	**Explanation**
Network structure	Network scale	The number of network nodes and connections between nodes, the more nodes and edges, the larger the network size
	Average path length	The average of the distances between pairs of nodes where there are connected paths
	Degree	The larger the degree of a node, the higher the degree centrality of the node, and the more important the node is in the network.
	Density	The ratio of the number of connected edges (excluding self-connections) to the total number of nodes in the network is calculated. The results are used to determine the connectivity of the network, i.e., the density of a fully connected network is 1
	Network diameter	The maximum value of the distance between any two nodes in the network is taken to reflect the density of the cooperative innovation network.
	Clustering Coefficient	The average of the clustering coefficients of all nodes in the network
Innovative organizational characteristics	Core organization	The larger the node, the more innovative subjects it cooperates with, and the thicker the connection, the more frequent the number of cooperations between nodes, and the top 10 organizations at different stages are selected.
	Organizational cohesion	The higher the PageRank value, the stronger the cohesion of the innovation subject in the network and the richer the innovation resources it holds
	Proportion of organization types	The proportion of universities, enterprises and research institutes at different stages
Technical characteristics	Breadth of technology relevance	The number of co-occurrences associated with technology domains, a measure of the breadth of technology convergence
	Strength of technical relevance	The strength of the connection between a technology field and other technology fields measures the depth of technology integration

The average path length of the network is the average of the distance between pairs of nodes where there is a connected path, denoted as L, i.e.:

$$L = \frac{2}{n(n-1)} \sum_{i,j} d_{ij} \quad (1)$$

where n is the number of network nodes, and d_{ij} is the distance between nodes i and j.
Network diameter, the maximum value of the distance between any two nodes in the network, is denoted as D, reflecting the density of the cooperative innovation network.

$$D = \max_{i,j} d_{ij} \quad (2)$$

Network density is the ratio of the number of edges that have the highest number of connected edges (excluding self-connections) to the total number of relationships between nodes in a given network. The results are used to determine the connectivity of the network, i.e. a fully connected graph with a density of 1 is denoted as ND:

$$ND = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} d_{ij}}{n(n-1)}, \quad (i \neq j) \quad (3)$$

where N is the total number of nodes in the network. The Degree refers to the average of the degrees of all nodes in the network, which can reflect the average number of partners owned by all nodes in the network:

$$Degree = \sum_{i,j=1}^{N} a_{ij} / N \quad (4)$$

a_{ij} is the degree value between the node pairs i and j. Weighted Degree refers to the average value of the weighted w_{ij} of all nodes in the network.

$$WD = \sum_{i,j=1}^{N} w_{ij} / N \quad (5)$$

The clustering coefficient C refers to the average of the clustering coefficients of all nodes in the network, which can be expressed as:

$$C = \frac{1}{n} \sum_{1}^{N} \frac{2e_i}{k_i (k_i - 1)} \quad (6)$$

Where e_i is the actual number of edges between adjacent nodes of node i, and k_i is the degree of node i.

ANALYSIS AND DISCUSSION

Analysis of the development trend of R&D cooperation

According to the technology life cycle theory, the development of industrial technology will go through four stages: embryonic stage, growth stage, maturity period, and decline period [13–15]. In this paper, the cumulative number of patent applications per year is taken as the vertical axis, the year of the patent application is taken as the horizontal axis, and the development trend of global textile new material technology cooperation and R&D is fitted with the help of the Loglet Lab software S-curve (figure 2). The dots in the graph represent the actual number of patent accumulations, and the solid line represents the predicted number of patent applications. The cumulative number of patents with the Saturation (K) value of the saturation point is 509.252, which is the highest value of patent applications, after that, patent growth will enter a period of decline, with little room for technological development and a gradual decrease in the number of applications. The growth time was 7.186 years, and the Midpoint of the S-curve occurred in 2014. It shows that the growth time of global textile new material technology, as estimated by the system, is 7 years, that is, the patent applications continue to grow until 2007, which is the embryonic period. Since 2008, it has entered a period of growth, during which technology research and development cooperation has shown a trend of rapid development. After 2015, the growth rate showed a slowdown trend, especially due to the impact of COVID-19, and after 2020, the international cooperation and innovation activities of enterprises and scientific research institutions in various countries could not be carried out normally, so the number of patent applications showed a downward trend, but the total amount is still increasing, and the global technical cooperation research and development in this field has entered a mature stage.

According to the growth process of global textile new material technology, and considering that the publication of patent documents has a certain time lag, the patent data is divided into three stages: 2000–2007, 2008–2014, and 2015–2021.

Through the analysis of the development trends of the above stages, it is found that the relevant policy documents issued by various countries and market demand changes have a relatively close relationship with the development of this field. At the level of comprehensive strategic planning, since 2000, the United States began to implement the “National Nanotechnology Initiative” (NNI) [16], and the textile new material technology has experienced a slow growth from scratch, at this time the technology is in its infancy, and the market application of this technology is relatively small at this stage. The Materials Genome Initiative launched in 2011 [17], and the National Network for Manufacturing Innovation (now known as Manufacturing USA) [18], launched in 2012, coordinate the participation of all parties at the national level to promote the R&D activities and applications of materials science, nanoengineering, and high-performance computing to ensure that the United States is a world leader in the R&D of new materials technologies. As countries attach great importance to this field and the continuous increase of talent and capital investment, the global textile new material technology has entered a period of rapid growth.

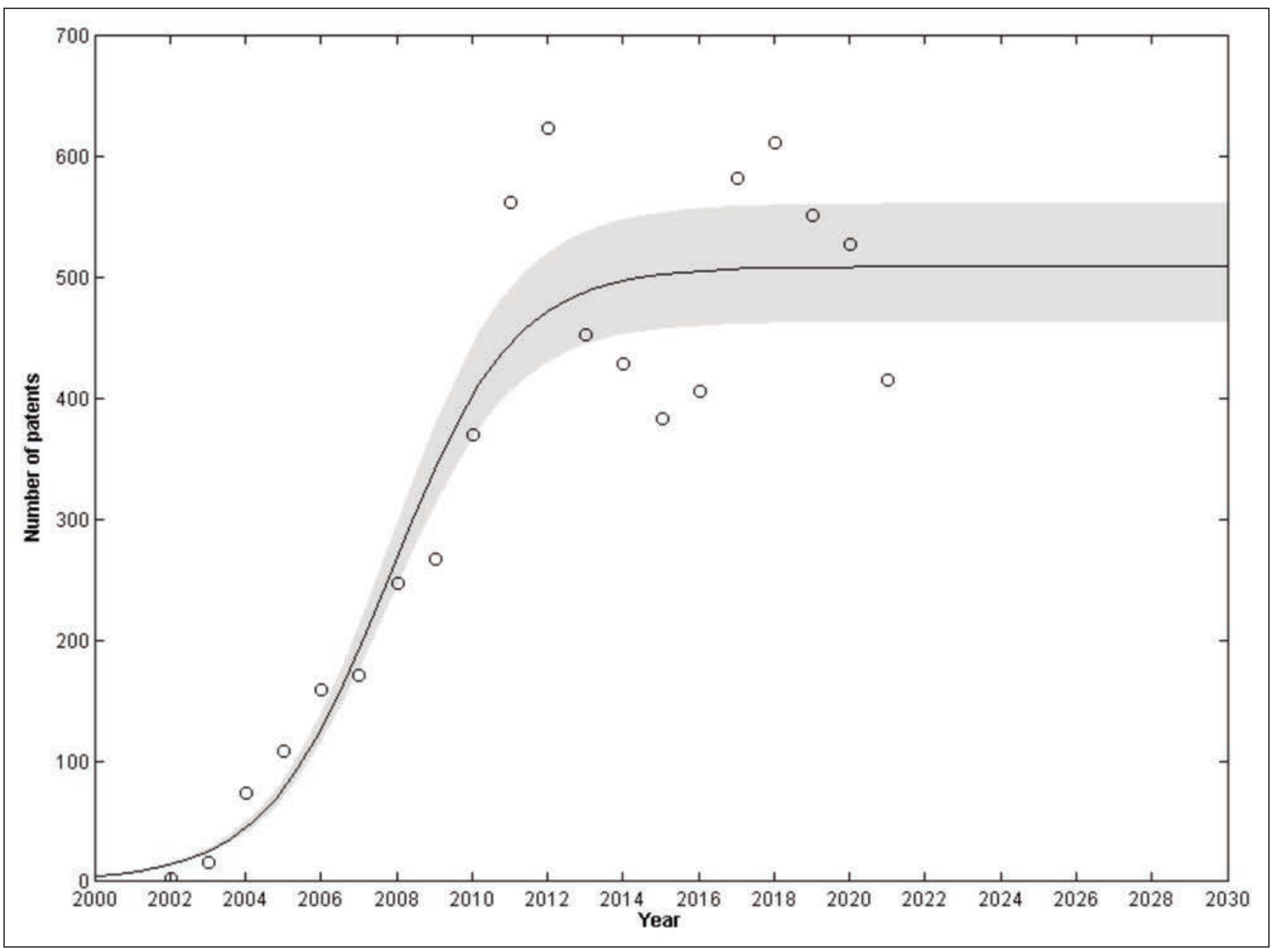


Fig. 2. Development trend of R&D cooperation in textile new material technology

Japan and the European Union closely follow the pace of development of the United States. The former's new materials industry is guided by the industrial policy to occupy the world market, so the focus is to make the new material field with huge market potential and high added value, specialized and industrialized as soon as possible. The latter vigorously promotes the development of ten major material fields, including nanobiotechnology, superconductors, composite materials, and smart textile materials. At the same time, with the development and growth of Chinese and South Korean textile enterprises, especially the huge market competitiveness after China acceded to the WTO, it has played a positive role in promoting the R&D of textile new material technology in the world. Therefore, from 2015 to 2021, the annual number of patent applications was in a state of fluctuating growth, but it remained at a high level, and the global textile new material technology has entered a mature period at this stage.

Analysis of organizational cooperation networks

Evolutionary characteristics of network structure

To study the structural characteristics of the global textile new material technology R&D cooperation network, this paper combines the perspective of cooperation among major patent holders and the three stages of R&D cooperation development, and uses Gephi to construct topological evolution maps of the network in different periods, and the results are shown in figure 3. Among them, the larger the node, the more nodes cooperate with it, and the thicker the connection, the more frequent the cooperation between nodes. From 2000 to 2007, there was R&D cooperation carried out by a few key subjects in the cooperative network map, which were closely interconnected, forming a relatively concentrated innovation group and playing a prominent role in the cooperation network. However, during this period, the network scale was relatively small, the network structure was relatively loose, and the market radiation to the international textile industry was limited. After 2008, R&D activities became more active, the network structure showed a multi-node multilateral radiation network state, and the network connection was relatively dense. During this stage, the number of cooperative R&D network nodes continued to increase, and the correlation between key nodes continued to strengthen, and a R&D group of innovative organizations had taken shape. However, with the concentrated role of the reform and reorganization of global multinational corporations and the influence of the international scientific and technological innovation pattern, enhancing the market competitiveness of enterprises through independent innovation has gradually become the main theme of development. In 2020, the United States released its National Strategy for Critical and Emerging Technologies, emphasizing that the United States will ensure its leading position in cutting-edge science and technology through strengthened technology control and global alliances. The EU has also proposed to increase its strategic autonomy to deal with industrial and technological dependence. Therefore, in the third stage, although the scale of the R&D cooperation network is unprecedentedly large, the group of innovative organizations with international influence has decreased significantly, and the radiation ability to the industry is relatively weakened.

The analysis of the indicators of organizational cooperation network helps to sort out the evolution characteristics of different stages of global textile new material technology R&D cooperation. In table 2, the diameter of the R&D cooperation network in the embryonic and growth stages is 9, and it has developed to 13 in the mature stage, which is in line with the proposal of Bettencourt et al. [19] that the cooperative innovation network in the field of science and technology has stabilized in the range of 12 to 14 after development, indicating that the innovation activities of the innovation group cooperation network have become stable.

According to the research results of Watts [20] and Uzzi [21], the average degree, average weighting degree and average clustering coefficient reflect the tightness of the network, and the first two values in table 2 show a significant upward trend, indicating that the scale of cooperative R&D is expanding and

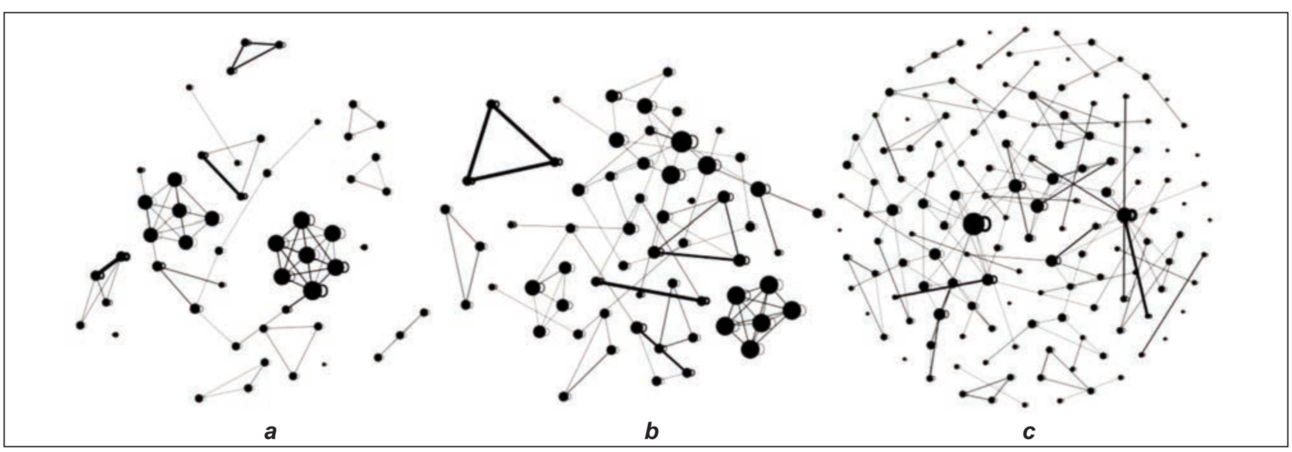


Fig. 3. Evolution mapping of R&D collaboration network topology: *a* – 2000–2007; *b* – 2008–2014; *c* – 2015–2021

Table 2

STRUCTURAL CHARACTERISTICS OF ORGANIZATIONAL COOPERATION NETWORKS			
Network characteristic parameters	**2000–2007**	**2008–2014**	**2015–2021**
Degree	2.657	2.729	2.957
Weighted degree	10.371	35.85	39.8
Network diameter	9	9	13
Network density	0.019	0.02	0.021
Average path length	3.416	3.516	3.687
Clustering coefficient	0.822	0.747	0.777

the number of partners in R&D institutions is gradually increasing. However, the clustering coefficient shows a downward trend, indicating that cooperation between innovative organizations is not close, a relatively stable cooperative relationship has not been formed, and an increasing number of enterprises choose to improve the competitiveness of their products and technologies in the market through independent innovation.

Characteristics of innovative organizations

According to the type of organizational cooperation, the innovation organizations are divided into companies, scientific institutions, and others, and the results are shown in table 3. The results found that, in terms of organization types, the proportion of companies is the highest in all countries around the world, exceeding 60%. In Japan, from 2000 to 2007, the proportion of enterprises as innovative organizations was as high as 90.00%. It shows that companies have always been the core force of technology R&D, and also the key subject of promoting technological innovation and development. From 2015 to 2021, the number of research projects in universities and institutions has expanded rapidly, especially in China, Japan, and South Korea, and there was a clear differentiation of innovation organizations, and the proportion of universities and institutions has increased by at least 10% compared with the embryonic stage of technology. As an important part of the country's industry-university-research (IUR) collaborative innovation ecosystem, colleges and universities play an increasingly important role in the R&D and sustainable development of textile new material technology [22, 23].

In terms of the number of organizations, the growth rate of innovation bodies in China, Japan, and South Korea is more obvious, especially in the former. The number of companies and scientific institutions has developed rapidly from 74 and 21 in the embryonic stage of technology R&D to 1918 and 946 in the mature stage of technology, becoming an important innovation body in the field of global textile new material technology R&D.

The analysis of the distribution and evolution of innovation bodies in different stages is helpful to analyse the characteristics of subjects in the R&D cooperation network in different periods (the results as shown in table 4). Next, Gephi's PageRank algorithm is used

Table 3

TYPES AND PROPORTIONS OF ORGANIZATIONAL COOPERATION			
Year	**Country: number of companies (rate%)**	**Country: scientific institutions (rate%)**	**Country: others (rate%)**
2000-2007	US: 162 (77.14)	US: 42 (20.00)	US: 6 (2.86)
	CN: 74 (76.29)	CN: 21 (21.65)	CN: 2 (2.06)
	JP: 180 (90.00)	JP: 16 (8.00)	JP: 4 (2.00)
	KR: 43 (74.14)	KR: 15 (25.86)	KR: 0 (0.00)
	EP: 44 (89.80)	EP: 5 (11.20)	EP: 0 (0.00)
2008-2014	US: 875 (81.02)	US: 177 (16.39)	US: 28 (2.59)
	CN: 915 (80.19)	CN: 222 (19.46)	CN: 4 (0.35)
	JP: 566 (80.06)	JP: 123 (17.40)	JP: 18 (2.54)
	KR: 266 (70.93)	KR: 103 (27.47)	KR: 6 (1.60)
	EP: 178 (83.96)	EP: 29 (13.68)	EP: 5 (2.36)
2015-2021	US: 322 (68.80)	US: 130 (27.78)	US: 16 (3.42)
	CN: 1918 (66.46)	CN: 946 (32.78)	CN: 22 (0.76)
	JP: 507 (78.48)	JP: 125 (19.35)	JP: 14 (2.17)
	KR: 294 (60.12)	KR: 187 (38.24)	KR: 8 (1.64)
	EP: 156 (78.79)	EP: 36 (18.18)	EP: 6 (3.03)

Table 4

TOP 10 PAGERANK OF ORGANIZATIONAL COLLABORATION NETWORKS			
No.	2000–2007	2008–2014	2015–2021
	Institutions (Country)	Institutions (Country)	Institutions (Country)
1	DuPont (US)	Sinopec (CN)	Donghua University (CN)
2	Tsinghua University (CN)	FiberVisions LP(US)	Sinopec (CN)
3	Foxconn (Taiwan, CN)	ES Fibervisions (US)	Wuhan Textile University (CN)
4	Toray (JP)	Daiwabo (JP)	Zhejiang Longsheng (CN)
5	Daiwabo (JP)	Tsinghua University (CN)	Daiwabo (JP)
6	Kuraray (JP)	JNC (JP)	Shinshu University (JP)
7	Mitsubishi Chemical (JP)	KOREA TEXTILE DEV INST (KR)	TB Kawashima (JP)
8	Kao (JP)	Shinshu University (JP)	Soochow University (CN)
9	ES Fibervisions (US)	Yibin Hester Fiber (CN)	Cathay Biotech (CN)
10	FiberVisions LP (US)	Yibin Siliya (CN)	Asahi Kasei (JP)

to count the number of other organizations directly connected to the innovation subject. The higher the PageRank value, the stronger the cohesion of the innovation subject in the network and the richer the innovation resources it holds [24–26]. From 2000 to 2007, Japanese multinational companies played a pivotal role in the technical cooperation and R&D network of textile new materials, and internationally renowned enterprises represented by Toray, Daiwabo, and Kuraray were at the core of the network in the R&D of carbon fiber, functional materials, and rayon, etc. [27]. Together with DuPont in the United States and Tsinghua University in China, the above-mentioned corporations played an important role in the innovation and development of textile new material technology.

With the continuous progress and development of textile technology, China began to emerge as several innovative forces in 2008–2014, with Sinopec, Yibin Hester Fiber, and Yibin Siliya as the representatives of well-known chemical and fiber enterprises emerging in the international textile market. However, the United States and Japan still have strong technological R&D advantages, especially in the field of high-performance fibers, composite fiber materials, and intelligent equipment etc., and the above innovative bodies constitute an important research force in the global textile new material technology R&D network.

However, from 2008 to 2014, the main body of innovation in the R&D of new textile material technology in the world underwent major changes, and China and Japan became the core forces of cooperative research in this field. The former, colleges and universities represented by Donghua University, Wuhan Textile University, and Suzhou University, have gradually become an important part of the organizational cooperation network, which also verifies that the above-mentioned universities are an important part of the national IUR collaborative innovation ecosystem. The latter's innovative organizations remain globally competitive in the fields of green materials, high-performance fibers, and advanced textile products.

Analysis of the IPC technical network

Combined with the time dimension and IPC technology sub-categories, the network evolution analysis helps obtain the development trend and evolution characteristics of global textile new material technology at different stages. Figure 4 shows that in different periods of technical cooperation R&D, there are key technology nodes with more obvious nodes and labels in the IPC network evolution map, and this type of node is interrelated with other technology nodes, forming several technology subgroups.

Among them, from 2000 to 2007, D01F (chemical characteristics of making rayon filaments and fibers, and equipment dedicated to the production of carbon fiber), D06M (processing fiber products of fibers and fabrics), D04H (manufacturing textiles) and B32B (layered products) and other technologies were more prominent, which has a strong radiation effect on other related technologies during this period, so it is more competitive in the market. With the rapid development of textile technology, compared with the embryonic period, the key technical nodes such as D01D (mechanical method or equipment for making chemical filament and fiber), D03D (woven fabric, weaving method, and loom), C08L (composition of polymer compounds) and D02G (fiber, filament) appeared from 2008 to 2014. After 2015, the global technical cooperation research and development in the field of new textile materials has entered a mature and period, and the overall technical association network has stabilized, and technologies such as C08K (using inorganic or non-polymer organic substances as ingredients) and A41D (outerwear, protective clothing, and clothing accessories) have become an important direction of innovation and development in the textile industry.

The textile new material technology has a prominent spillover effect, and different technical fields in technology R&D have the characteristics of diffusion and fusion [28, 29]. This paper evaluates the evolution of

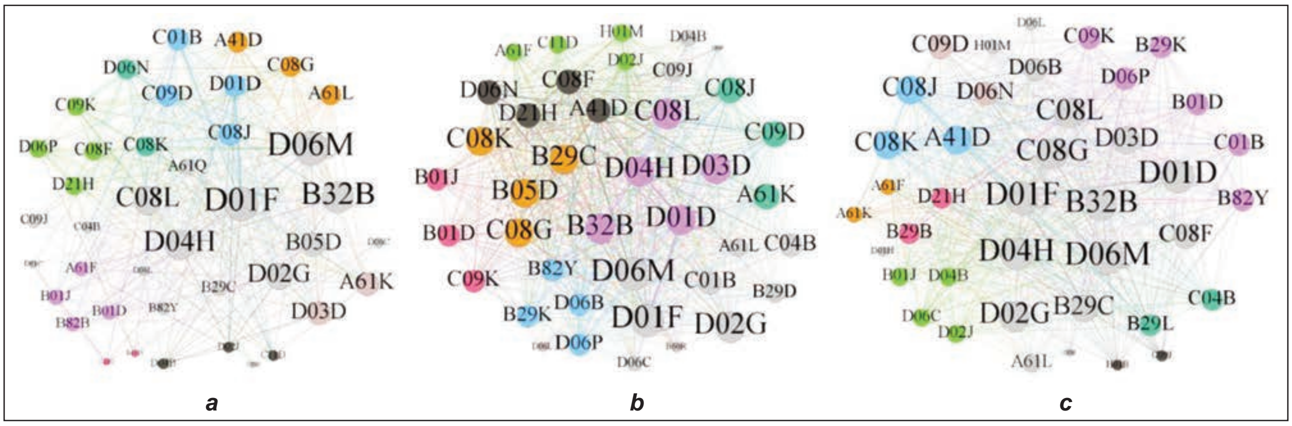


Fig. 4. Evolution mapping of IPC network for global textile new material technology cooperation R&D:
a – 2000–2007; *b* – 2008–2014; *c* – 2015–2021

technology networks in the development process by establishing the matrix of technology convergence and co-occurrence, as shown in table 5 below. The connection strength in the technology field is the ratio of the number of co-occurrences and the number of technology linkages among technologies [30–32].

Since the 21st century, D01F, D06M, D04H, and D01D have been the textile new material technology fields with the largest number of technical associations and the highest technical correlation strength. In the embryonic stage, the number of co-occurrences in the technology field is relatively small, the intensity of technology correlation is not high, the overall technology spillover effect is weak, and the technology diffusion and fusion are mainly carried out within the technology subgroups. From 2008 to 2014, the correlation intensity of IPC network technology increased significantly, and the number of co-occurrences between technologies increased significantly. By the mature stage, C08J (the general process of processing and batching), C08G (polymer compounds obtained by reactions other than carbon-carbon unsaturated bonds), and D06P (dyeing or printing of textiles) and other related technical fields with rapidly increasing correlation strength have appeared, which has played a positive role in promoting the technological innovation and development of textile new materials in the world.

DISCUSSIONS

The findings of this paper help sort out the characteristics of the innovation subjects, organizational cooperation network relationships, and IPC technology networks in the global textile new material technology cooperation and research and development. Although the existing research objects in the academic community involve several emerging industries and technology fields, there is no study on the network relationship and the analysis of the evolution characteristics of technology cooperation and R&D of textile new materials. Therefore, this paper attempts to supplement the existing research from two aspects of the research object and the research content, to potentially fill the gap in existing research.

New materials are one of the key areas of international competition and a key factor in determining a

Table 5

COMPARISON OF ENTROPY, CONTRAST AND EME VALUES WITH EXISTING METHODSEVOLUTION CHARACTERISTICS OF THE GLOBAL TEXTILE NEW MATERIAL TECHNOLOGY FIELD AT DIFFERENT STAGES

No.	2000–2007			2008–2014			2015–2021		
	IPC4	Number of co-occurrences	Strength of association	IPC4	Number of co-occurrences	Strength of association	IPC4	Number of co-occurrences	Strength of association
1	D01F	322	9.47	D01F	1821	46.69	D01F	2186	55.54
2	D06M	249	7.32	D01D	1202	33.39	D06M	1359	34.85
3	D04H	204	6.80	D04H	1102	30.61	D01D	1190	31.32
4	D01D	129	6.14	D06M	1165	29.87	D04H	975	26.35
5	D03D	130	5.65	C08L	829	23.03	C08L	887	25.34
6	C08J	180	5.63	B32B	778	21.61	C08J	684	20.73
7	D02G	133	5.12	C08G	592	16.91	C08G	711	19.75
8	C01B	99	4.71	C08K	549	15.69	C08K	640	19.39
9	D02J	47	4.70	C08J	496	15.50	D06P	432	16.00
10	B29C	65	4.33	B29C	533	15.23	C09B	143	14.30

country's high-end manufacturing and national defense security. The United States and Japan and other developed countries through economic strength, core technology, research and development capabilities and market share and other advantages, the use of large multinational companies to occupy a monopoly position in the global market, and in the textile new materials industry to take the lead in completing the technical layout. In terms of organizational cooperation networks, Japan mainly adopts the "government-industry-academia" R&D and application integration model to promote the innovation and breakthrough of textile new materials. Studies have shown that the more successful the inter-organization R&D collaboration, the higher the quality and quantity of external resources available through the collaboration [33]. In the technology R&D network, put forward the goal of "focusing on the practicality of new materials and considering the harmonious development of the environment and resources", so in the global carbon fiber technology, functional chemical products, chemical new materials and artificial fibers and other cutting-edge materials fields occupy a pivotal international position. Although China's textile new materials technology R&D started relatively late, the development is relatively rapid. Under the guidance of the national IUR collaborative innovation to the innovation consortium policy, by leading enterprises to integrate scientific research institutes, institutions of higher learning and the innovation of the main body of cooperation organizations, to solve the key core technology of industrial development and enhance the level of industrial technological innovation.

With the acceleration of a new round of scientific and technological revolution and industrial transformation, especially for the impact of COVID-19 and global geopolitical factors, the allocation of global technology factors and market factors is undergoing profound changes. In the field of textile new material technology R&D, the United States and Japan have the most competitive technology R&D networks in a relatively mature market around the world. In China and South Korea, the technology R&D network is in a stage of rapid development [34]. From the macro perspective, the focus of the global textile new material technology cooperation R&D network is gradually shifting towards the Asian region, and the technology gap in the global major innovation regions is narrowing as the competition in this field has entered a white-hot stage.

CONCLUSIONS

Theoretical implications

Based on the patent data of global textile new material technology cooperation R&D, this paper uses the patent technology network analysis method to quantitatively analyze the structural characteristics, evolution, and trend of organizational cooperation networks and technology networks. The results of the study are summarized as follows:

- At present, the trend of global textile new material technologies cooperation R&D corresponds to three stages, namely the germination period (2000–2007), the growth period (2008–2014), and the maturity period (2015–2021), respectively. However, under the influence of COVID-19 and global geopolitics, the cooperative innovation activities of enterprises and scientific research institutions around the world cannot be carried out normally, and the global technology cooperation R&D network was seriously disrupted.
- There are a few key innovative bodies in the embryonic stage of the organizational cooperation network. Since 2008, the network structure has shown a multi-node multilateral radiation network state, with a rapid increase in the number of network nodes and a continuous strengthening of the correlation between key nodes, and a R&D group of innovative organizations has begun to take shape. The innovation activities of the organizational cooperation network tend to be stable in the mature stage, but there is no relatively stable cooperative relationship between innovation organizations. Japan's innovation community has always played a key and important role in the collaborative R&D network, occupying a central position in technological fields such as green materials, high-performance fibers and advanced textile products.
- It was discovered that enterprises are the backbone of promoting the innovations and development of global textile new material technologies, however, universities and scientific research institutions play an increasingly important role in China's R&D network, becoming an important part of the national IUR collaborative innovation ecosystem.
- At different times of the IPC technology R&D network, there are key technology nodes and technology subgroups, forming a development process from D01F, D06M, D04H, and other technologies to D01D, D03D, D02G, and A41D. The technology spillover effect, the diffusion and integration within the technology subgroups, and the significant enhancement of technology correlation have played a positive role in promoting technological innovation and the development of new textile materials in the world.

Practical implications

Based on the main conclusions of this article, the following policy implications are proposed for decision-making reference by governments, decision-makers, enterprises, and university research institutions.

Firstly, it is necessary to improve the service platform and service organization of the cooperative R&D network to realize the complementary advantages of the network subjects, to boost the cooperative innovation efficiency, collaborative innovation ability, and technological innovation level among the network subjects, and thus achieving the purpose of reducing R&D risks and saving R&D costs. Secondly, to optimize the innovation environment of the cooperative

R&D network, a good innovation policy environment is an important way to optimize the cooperative R&D network, and the government can help realize the benign evolution and sustainable development of the cooperative R&D network through the construction of policies, legal systems, funds and digital infrastructure. Thirdly, to maintain the stability of a cooperative R&D network structure, it is crucial to strengthen the influence and control of the core subjects within the network. The core nodes within the network play the key role in transmitting information and knowledge interaction among network subjects. Therefore, by enhancing the network power of the core subjects in the network and effectively playing their functions and roles in the network, their cooperative innovation behaviors can be adjusted to achieve the goal of optimizing the network structure. Last but not least, it is essential to divide and coordinate the collaborative activities of the nodes in the core, intermediate, and edge layers of the network rationally. The division of labor and coordination within the network are significant for increasing the efficiency of cooperative innovation. Moreover, it is necessary to strengthen the division of labor and coordination of cooperative innovation activities among cross-level subjects in the network, promote the integration and matching of existing resources by network subjects, maximize the complementarity of resources and knowledge flow between networks, and prevent unhealthy competition in cooperative R&D networks.

Limitations and future research directions

Although this paper has reference significance and value for filling the global textile new material technology cooperation R&D network and its evolutionary characteristics, there are still certain limitations. Due to the shortcomings of patent databases, the function of the technology roadmap cannot be used to more thoroughly study the infrastructures and paths of evolution of the technology R&D network. However, by limiting the scope of the study to the IP5, the research horizon will be subject to some limitations. In the future, more extensive global data will be available to compare different countries for further and more comprehensive analysis.

ACKNOWLEDGEMENTS

This research was funded by the Silk & Fashion Culture Research Center of Zhejiang Province, Zhejiang Provincial Key Research Institute of Philosophy and Social Science (grant number 2022JDKTYB27).

DATA AVAILABILITY STATEMENT

The data presented in this study are openly available at: https://analytics.zhihuiya.com (Accessed on 25 January 2024).

REFERENCES

[1] Provin, A.P., Regina De Aguiar Dutra, A., Machado, M.M., Vieira Cubas, A.L., *New materials for clothing: Rethinking possibilities through a sustainability approach – A review*, In: J Clean Prod 2021, 282, 124444

[2] Arranz, N., de Arroyabe, J., *The choice of partners in R&D cooperation: An empirical analysis of Spanish firms*, In: Technovation 2008, 28, 88–100

[3] Simonen, J., McCann, P., *Innovation, R&D cooperation and labor recruitment: evidence from Finland*, In: Small Bus Econ Group, 2008, 31, 181–194

[4] Wu, A.H., *Collaborative eco-innovation and green knowledge acquisition: The role of specific investments in the Chinese new energy vehicle industry*, In: Bus Strategy Environ, 2023, 32, 2245–2260

[5] Yu, X.K., Cui, Y., Chen, Y.L., Chang, I.S., Wu, J., *The drivers of collaborative innovation of the comprehensive utilization technologies of coal fly ash in China: a network analysis*, In: Environ Sci Pollut Res Int, 2022, 29, 56291–56308

[6] Wang, D.P., Wei, X.Y., Fang, F., *The resource evolution of standard alliance by technology standardization*, In: Chin Manag Stud, 2016, 10, 787–801

[7] Raiteri, E., *A time to nourish? Evaluating the impact of public procurement on technological generality through patent data*, In: Res Policy, 2018, 47, 936–952

[8] Stolze, H.J., Murfield, M.L.U., Esper, T.L., *The Role of Social Mechanisms in Demand and Supply Integration: An Individual Network Perspective,* In: J Bus Logist, 2015, 36, 49–68

[9] Capponi, G., Corrocher, N., *Patterns of collaboration in mHealth: A network analysis*, In: Technol Forecast Soc Change, 2022, 175, 121366

[10] Fiori, G., Basso, F.G., Porto, G.S., *Cooperation in R&D in the pharmaceutical industry: Technological and clinical trial networks in oncology*, In: Technol Forecast Soc Change, 2022, 176

[11] Maleki, A., Rosiello, A., *Does knowledge base complexity affect spatial patterns of innovation? An empirical analysis in the upstream petroleum industry*, In: Technol Forecast Soc Change, 2019, 143, 273–288

[12] Li, Y.Y., Zhu, Z., Guan, Y.F., Kang, Y.F., *Research on the structural features and influence mechanism of the green ICT transnational cooperation network*, In: Econ Anal Policy, 2022, 75, 734–749

[13] Ernst, H., *The Use of Patent Data for Technological Forecasting: The Diffusion of CNC-Technology in the Machine Tool Industry*, In: Small Bus Econ Group, 1997, 9, 361–381

[14] Cho, H.P., Lim, H., Lee, D., Cho, H., Kang, K.I., *Patent analysis for forecasting promising technology in high-rise building construction*, In: Technol Forecast Soc Change, 2018, 128, 144–153

[15] Qiu, Z.P., Wang, Z., *Technology Forecasting Based on Semantic and Citation Analysis of Patents: A Case of Robotics Domain*, In: IEEE Trans Eng Manag, 2022, 69, 1216–1236

[16] Chan, W.C.W., et al., *The 15th Anniversary of the US National Nanotechnology Initiative*, In: ACS Nano, 2018, 12, 10567–10569

[17] Lu, X., *Remarks on the recent progress of Materials Genome Initiative*, In: Sci Bull (Beijing), 2015, 60, 1966–1968

[18] Clark, J., Doussard, M., *Devolution, disinvestment and uneven development: US industrial policy and evolution of the national network for manufacturing innovation*, In: Camb J Regions Econ Soc, 2019, 12, 251–270

[19] Bettencourt, L., Kaiser, D.I., Kaur, J., *Scientific discovery and topological transitions in collaboration networks*, In: J Informetr, 2009, 3, 210–221

[20] Watts, D.J., *Networks，dynamics，and the small – world phenomenon*, In: American Journal of Sociology, 1999, 105, 493–527

[21] Uzzi, B., Spiro, J., *Collaboration and creativity: the small world problem*, In: AJS, 2005, 111, 447–504

[22] Wang, W.J., Liu, Y.W., *Does University-industry innovation community affect firms' inventions? The mediating role of technology transfer*, In: J Technol Transf, 2022, 47, 906–935

[23] Daniel, A.D., Alves, L., *University-industry technology transfer: the commercialization of university's patents*, In: Knowl Manag Res Pract, 2020, 18, 276–296

[24] Lin, C. et al., *Social Network Analysis in Enterprise*, In: Proc IEEE Inst Electr Electron Eng, 2012, 100, 2759–2776

[25] Luo, Q., Zhong, D., *Using social network analysis to explain communication characteristics of travel-related electronic word-of-mouth on social networking sites*, In: Tour Manag, 2015, 46, 274–282

[26] Zhang, H., Gong, X., *Consumer susceptibility to social influence in new product diffusion networks: how does network location matter?,* In: Eur J Mark, 2021, 55, 1469–1488

[27] Okamuro, H., Kato, M., Honjo, Y., *Determinants of R&D cooperation in Japanese start-ups*, In: Res Policy, 2011, 40, 728–738

[28] Leibowicz, B.D., Krey, V., Grubler, A., *Representing spatial technology diffusion in an energy system optimization model*, In: Technol Forecast Soc Change, 2016, 103, 350–363

[29] Arque-Castells, P., Spulber, D.F., *Measuring the Private and Social Returns to R&D: Unintended Spillovers versus Technology Markets*, In: J Polit Econ, 2022, 130, 1860–1918

[30] Peng, J.P., Quan, J., Zhang, G.Y., Dubinsky, A.J., *Knowledge Sharing, Social Relationships, and Contextual Performance: The Moderating Influence of Information Technology Competence*, In: J Organ End User Comput, 2015, 27, 58–73

[31] Bayo-Moriones, A., Billon, M., Lera-López, F., *Are new work practices applied together with ICT and AMT?*, In: Int J Hum Resour Manag, 2017, 28, 553–580

[32] Wang, J.T., Hsu, T.Y., *Early discovery of emerging multi-technology convergence for analyzing technology opportunities from patent data: the case of smart health*, In: Scientometrics, 2023, 128, 4167–4196

[33] Okamuro, H., *Determinants of successful R&D cooperation in Japanese small businesses: The impact of organizational and contractual characteristics*, In: Res Policy, 2007, 36, 1529–1544

[34] Park, J., Kim, J., Woo, H., Yang, J.S., *Opposite effects of R&D cooperation on financial and technological performance in SMEs,* In: J Small Bus Manag, 2022, 60, 892–925

Authors:

PENGFEI WANG[1,2], HUA CHENG[1,2]

[1]School of Economics and Management, Zhejiang Sci-Tech University, Hangzhou, 310018, 2 Second Avenue, Qiantang Zone, Hangzhou Province, China

[2]Key Laboratory of Intelligent Textile and Flexible Interconnection of Zhejiang Province, Hangzhou, 310018,2 Second Avenue, Qiantang Zone, Hangzhou Province, China
e-mail: wangpf@zstu.edu.cn

Corresponding author:

HUA CHENG
e-mail: chenghua@zstu.edu.cn