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ADAPTIVE CLOTHING DESIGN: FROM FOCUS GROUP EVALUATION TO FUNCTIONAL PROTOTYPES

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ABSTRACT

The importance of adaptive clothing has grown considerably in response to the needs of individuals with physical disabilities, whether congenital or acquired. This study explores the principles of user-centred design in developing adaptive clothing, using a framework informed by focus group discussions. The aim was to gather detailed insights to guide the design process, ensuring that users' needs and preferences are effectively addressed. To achieve this, three separate focus groups were created, comprising 7 medical staff, 5 patients from the surgical department, and 12 patients undergoing rehabilitation. This diverse representation sought to address the different needs associated with varying mobility levels, treatment durations, and care requirements. The approach aims to understand the experiences and needs of adaptive clothing users thoroughly. As a result, an effective adaptive design was developed, focusing on clothing that is not only functional and visually appealing but also genuinely meets the users' needs.

KEYWORDS

Adaptive Clothing Design; Digital Fashion; Human Factors; Human-Centred Design; Disability; Focus Group.

INTRODUCTION

Recently, the adaptive clothing market experienced substantial growth, focusing on inclusive design for apparel and footwear tailored to individuals with various congenital or acquired functional impairments, whether resulting from injuries or chronic diseases [1]. At the same time, scientific interest in developing such clothing has also increased [2-3].

The variability in terminology has continued to be a challenge within the field. There are several possible terms to describe this type of apparel. While "functional" and "inclusive" clothing are commonly used [4], the term "adaptive clothing" more accurately defines garments that are designed to be both practical and visually appealing, as well as ergonomic, to meet an individual's specific needs [3, 4]. For this reason, we employ the term "adaptive" in our recent research.

Research on adaptive clothing and design is diverse and interdisciplinary. Therefore, researchers often focus on specific clothing types [5, 6], disabilities [3, 7-11], regions [3, 12], age groups [13-15], and other factors such as purpose - for example, hospital patients undergoing treatment [10, 16-17], etc.

Effective adaptive clothing design requires an interdisciplinary approach that integrates psychology, physiotherapy, design, and engineering. This combination aims to create attire that is comfortable, functional, and fashionable. The literature review revealed that adaptive clothing design is centered on meeting the needs of individuals with disabilities, specifically ensuring their physiological and psychological comfort when wearing clothing [2, 3]. This encompasses several aspects, including:

- the use of innovative technologies [2, 3, 18-19],
- biomechanical and functional principles for ensuring the comfort of apparel [11, 12, 17, 20],
- socio-cultural and psychological aspects [3, 8, 12, 21],
- aesthetic and emotional reactions [3, 15, 16]
- barriers or the impact of adaptive clothing on the quality of life of individuals with functional impairments [3, 7, 12, 22].

Innovations in adaptive clothing aim to design garments made from materials that are easy to put on and take off. For instance, magnetic zippers are being

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used to simplify the dressing process [2, 3]. These advancements also involve creating fabrics with specific features, such as antibacterial and hypoallergenic properties [3]. Additionally, there are materials designed to heat immobile body parts of individuals with disabilities, utilising electrically conductive threads [18]. Moreover, shape-memory fabrics are being developed to adjust to the unique needs of each user [19].

Advances in computer technology enable us to evaluate the areas of greatest stress and pressure on the body during the design phase of adaptive clothing, allowing informed decisions to be made and assessed through 3D visualisation and to leverage digital tools for inclusive design [11, 20].

Several studies in the field of adaptive clothing focus on biomechanics and ergonomics aimed at achieving comfort for individuals lying down [10], those in wheelchairs [9, 16], clothing usability during movement [17], and ease of putting on and taking off garments [13, 14]. They also explore how materials can provide comfort and support, considering physiological limitations [3, 17]. In the study [17], this aspect included characteristics of hospital patients' motor regimes, such as general, ward, semi-bed, bed, and strict bed, alongside the topography of medical procedures and regions affected by physical, psychophysical, chemical, and biological factors on clothing. Based on this, recommendations were made for designing adaptive clothing tailored to different patients depending on their motor regime [17]. The ergonomic design for adaptive clothing focused on how the shape and structure of garments can maintain physical comfort [11], reduce joint and muscle load, and how appropriately chosen materials can facilitate movement and lessen discomfort during wear [8].

Except for the studies aimed at enhancing physical comfort in the development of adaptive clothing, several referenced studies [2, 3, 7-9, 15] also examine the psychological and socio-cultural aspects of clothing design for individuals with functional impairments. The key points of the research were how adaptive clothing helps individuals with disabilities maintain their independence, boost their self-esteem, and how it influences social integration and reduces social barriers.

Challenges related to clothing can significantly hinder individuals with disabilities and their families from fully participating in society [21]. The lack of suitable clothing creates barriers related to functional, sociopsychological, cultural, sensory sensitivity, and fashion consumption issues, which affect their ability to engage in social activities, maintain relationships, work, and participate in daily events. These combined barriers highlight the importance of sociopsychological factors in shaping experiences associated with adaptive clothing consumption [3, 5, 12, 22].

The social inclusion of individuals with disabilities is a crucial issue. Experts from various fields, including clothing design [9], are working to develop products that address their specific needs. In response to this challenge, researchers have proposed innovative and technological solutions for adaptive clothing. These solutions focus on personalisation and adaptation to new lifestyles, promoting social inclusion and integration, especially for individuals with multiple sclerosis. Another study [19] examines the impact of ergonomic design on adaptive clothing, highlighting its role in boosting a person's self-confidence and ability to dress independently, ultimately improving their quality of life. This research also stresses the importance of the aesthetic appeal of adaptive clothing in maintaining social standing and contributing to an individual's overall well-being.

One way to improve the social inclusion of people with disabilities is to involve them at each stage of the clothing development process, thereby building trust and collaboration with them. This approach will help create comfortable, stylish, and fashionable adaptive clothing that meets their needs [14].

Integrating digital tools and innovations into the design process can support aesthetic requirements. CLO 3D digital modelling to create ergonomic designs and assess the psychophysiological effects of colour allows for the optimisation of colour combinations for individuals with limb injuries and the generation of design sketches in a sport-casual style aimed at daily use, comfort, and social settings inclusion [23].

In [16], interviews were conducted to explore patients' emotional reactions to adaptive clothing in university hospitals. The findings revealed that patterns and motifs designed with healing proportional ratios can positively influence a patient's condition, effectively creating clothing intended for healing. Patients reported that specific clothing designs provided them with a sense of trust, stability, and comfort. Additionally, the design of apparel for patients not only shapes the brand image of medical institutions but also enhances the quality of medical care by focusing on patient recovery.

A survey [2] found that clothing has a significant impact on mobility, self-care, and various personal factors. Approximately 49% of individuals with functional impairments identified essential clothing design features that should be considered [2]. Additionally, research on the online consumption of adaptive clothing has identified that functionality is the primary requirement for consumers, whether shopping in-store or online [1].

To address inclusion challenges, it is crucial to promote disability-inclusive fashion by adopting advanced mass customisation technologies. These studies [12, 23] proposed strategies for developing inclusive fashion products that enhance the well-being of individuals with disabilities. As a result, there is a pressing need for a universal fashion market that caters to both disabled and non-disabled consumers, regardless of their physical differences [12, 24].

To gain a thorough and contextual understanding of the purpose of adaptive clothing and the adaptive design process, as well as to promote innovations in this field, a user-centred design (UCD) approach is employed [3, 12, 14]. UCD is a design method that prioritises the user throughout the design process [3]. It focuses on understanding the user's needs and limitations to guide design choices. A key aspect of this methodology is iterative prototyping, which enables users to interact with physical products in real-world conditions. This process allows designers to refine garments based on direct user feedback and experience. Emphasising user experiences and processes is essential for creating products that not only function effectively but also meet users' aesthetic preferences [3].

In [12], using UCD established the fundamental requirements for designing adaptive outerwear, which, through parametric digital modelling, allows customised options based on different sizes and physical conditions, blending both functionality and aesthetics. Similarly, other research has demonstrated that adaptive clothing design should go beyond utility to incorporate sensory, cultural, and aesthetic aspects, ensuring comprehensive inclusion of people with disabilities [6]. Building on this, a wide range of clothing-related barriers, from mechanical and ergonomic issues to sensory discomfort and social stigma, were identified. Overcoming these barriers requires continuous communication with consumers throughout the entire design process. This type of collaboration not only enhances garment quality, functionality, and inclusiveness but also promotes social integration, contributing to users' physiological and psychological comfort through fashionable, accessible design.

Despite a growing interest in adaptive fashion, there remains a significant gap in studies focusing on clothing design for individuals with limb injuries, amputations, or partial loss of limb function. This group comprises stroke survivors and individuals affected by illness or trauma. In Ukraine, the ongoing military conflict has intensified this need by increasing the number of traumatic injuries caused by mines and explosives. Developing adaptive clothing for these individuals is both urgent and socially vital.

A review of current literature highlights several key requirements for high-quality adaptive clothing for individuals with limb injuries. Firstly, the adaptive design must overcome functional barriers [3, 7, 12]. Garments should be customized to suit specific physical conditions, especially limb amputation, asymmetry, or support devices such as prostheses or other aids. Functional comfort must be considered for the physiological and physical attributes of consumers with disabilities [12]. For physiological comfort and hygiene, materials should be soft, breathable, and skin-friendly, meeting high ergonomic and hygienic standards [2, 3]. Adaptive clothing must possess suitable aesthetic qualities [3, 7, 12, 23] that match current fashion trends, allowing individuals to showcase their style while ensuring practicality and dignity. The design of adaptive clothing should aim to enhance the wearer's psychological comfort [3, 7]. These requirements will be aimed at creating adaptive clothing that not only fulfils practical needs but also supports the dignity and personal expression of individuals with limb injuries.

To validate this suggestion, three categories were outlined [25]:

- Functional Comfort: This includes the ease of adapting to different activities, quick access to fasteners, and the simplicity of putting on and taking off items.
- Physiological Comfort: This encompasses sensory comfort, thermal regulation, fit, and the weight of the fabric.
- Psychological Comfort: This refers to aesthetic and expressive satisfaction, the appropriateness of items for daily life in a hospital setting, as well as considerations of privacy and dignity.

To avoid limiting the depth of user input and to reduce opportunities for a more thorough exploration of user challenges. Therefore, it is advisable to organize structured, face-to-face focus groups involving not only individuals with limb injuries but also specialists such as designers, doctors, psychologists, and sewing professionals [3, 25]. This will enable a more holistic and expert-driven discussion, providing comprehensive insights into user needs and enhancing the adaptive design process. Importantly, user engagement should be integrated at every stage of the design—from preliminary research and conceptual sketching to the expert evaluation of prototypes.

EXPERIMENTS

Materials

The research aimed to explore users' needs and evaluations of experimental adaptive clothing. To gather insights, the study was conducted with a diverse group of participants, including medical specialists (such as surgeons and rehabilitation experts with experience in treating injuries), patients with various injuries and functional movement limitations, and professionals specializing in sewing, product design, and technology. This composition was selected to provide comprehensive insights into the requirements and challenges faced by users of current adaptive clothing.

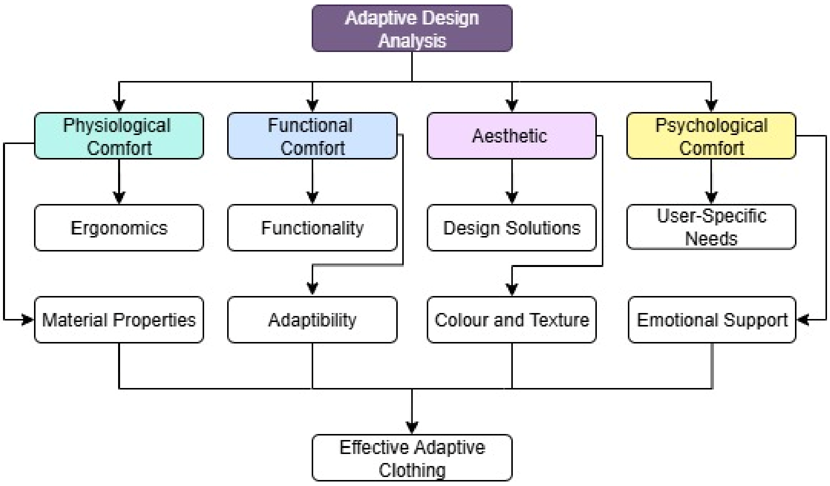

Figure 1. Comfort categories for effective adaptive clothing.

The structure for analysing user needs for adequate adaptive design is illustrated in Figure 1. This model identifies four core domains of comfort: physiological, functional, aesthetic, and psychological. To consider aesthetics, we established it as a distinct comfort category. Each domain includes subcategories derived from resource analysis.

Experimental Design

To establish these requirements (Fig. 1), specific restrictions were introduced. This was necessary because many aspects of the requirements could hinder conducting high-quality personal interviews with respondents because of the lengthy survey process. This is particularly important for patients in the surgical department, who are essential for meeting the survey's time constraints. As a result, the scheme outlined identifies four key groups of requirements for adaptive clothing.

Physiological comfort addresses ergonomics and the properties of materials. Functional comfort focuses on the necessary functions of garments and their adaptability. Aesthetic aspects cover user-friendly design solutions and psychosocial considerations in colour selection for apparel. The psychological comfort involves factors related to dignity, emotional well-being, and societal inclusion.

The research was conducted in two stages. The first stage involved a questionnaire survey, as described in the previous article [26], along with the development of prototypes – Experimental Adaptive Clothing. After the production of this clothing, samples were included in a focus group survey conducted during the second stage.

To build trust and gather honest responses from focus group participants, a team of four experts visited the hospital's surgical department and rehabilitation centre from March 9 to May 25, 2024. The four conducted focus group discussions using the questions listed in Table 1, with one person responsible for audio recording and another for photos and videos.

Two to three meetings were held with each focus group to build an emotional connection. The respondents were positive about the survey and became increasingly open, especially during the second and third meetings. Respondents openly discussed personal experiences. Some points of these discussions involved sensitive topics and the barriers they encountered in their clothing-related lives. They shared thoughts about current barriers and offered suggestions for potential adaptive design solutions.

A detailed methodology for conducting focus group surveys in hospital settings, surgical departments, and rehabilitation centres has been developed to address the requirements for adaptive clothing effectively. This methodology highlights principles of inclusivity, user experience, an interdisciplinary approach, and the integration of digital technologies for data collection and analysis.

During the preparatory phase, three distinct Focus Groups were created based on the objectives of the study: 1) medical staff, 2) patients from the surgical department, and 3) patients from rehabilitation centres. The number of groups reflects the varying needs associated with different mobility levels, treatment durations, and care specifics for individuals with injuries. Participant selection was based on established guidelines [12] that considered factors such as gender, age, and functional disabilities.

The development of the focus group scenario involved creating a survey through semi-structured interviews conducted across three Focus Groups. This process followed a pre-prepared set of key questions based on a UCD approach (Fig. 1), emphasising the active involvement of users in the adaptive apparel design process (Table 1). The questions were divided into five sections. The first

Table 1. Sample interview questions.

Section	Requirements	Key Question Number (KQ)	Sample Questions
1 Main information	General	KQ1	What is your injury?
		KQ2	What clothing did you wear during treatment?
		KQ3	Have you previously used adaptive clothing? If so, which one?
		KQ4	What difficulties do you encounter when putting on or removing clothing?
2/ 3/ 4/ 5 Prototype Assessment of the ES/EP/ET/ESh	Physiological Comfort	KQ5	What should the quality of textile materials be for adaptive clothing, such as that used in ES/EP/ET/ESh?
		KQ6	How do you assess the comfort and practicality of the neckline in the ES/ET?
		KQ7	How do you evaluate the sleeve width and length of the ES/ET for comfort?
		KQ8	What are your thoughts on the convenience of the leg width in the EP/ESh?
		KQ9	How would you evaluate the convenience of short length?
	Functional comfort	KQ10	How easy is it to put on and take off the proposed ES/EP/ET/ESh?
		KQ11	How easily can you access medical procedures or use medical devices while wearing ES/EP/ET/ESh?
		KQ12	What specific requirements or preferences do you have regarding the functionality of ES/EP/ET/ESh, such as ease of application, types of fasteners, fabric choices, and any special features?
		KQ13	How would you evaluate the convenience of the fasteners in the ES/EP/ET/ESh?
		KQ14	What are your thoughts on the convenience of the pockets in the ES/ET?
		KQ15	What is your opinion on the convenience of the hood in the ES?
		KQ16	What is your opinion on the convenience of the waistbands in the EP/ESh?
	Aesthetic	KQ17	Does this clothing look like everyday regular wear to you, or does it seem like a specialised medical product?
		KQ18	How suitable is the colour scheme of the ES/EP/ET/ESh?
		KQ19	What colours make you feel confident, calm, energised, etc.?
		KQ20	What emotional reactions are caused by the appearance of ES/EP/ET/ESh?
		KQ21	What fashion elements would you like to see in adaptive clothing? For example, asymmetrical designs, textured materials, contrasting inserts, logos, etc.
	Psychological comfort	KQ22	Does this clothing help you maintain your sense of self-worth during treatment or rehabilitation?
		KQ23	Does this clothing help you feel more independent?
		KQ24	Is it vital for you to be able to dress/undress yourself without help?
		KQ25	What emotional reactions are caused by the comfort of ES/EP/ET/ESh?
		KQ26	Does this clothing suit your style and age?

section was the same for all respondents, while sections two to five were customised based on the type of injury and the patients' needs for adaptive clothing (a sweatshirt, pants, a T-shirt, or shorts).

The described approach aims to gather data on users' experiences and preferences regarding adaptive clothing and evaluate the experimental adaptive items.

Focus Group meetings were held in hospitals and rehabilitation centres, using online digital platforms to understand specific needs and garment design elements better. The Focus Group interviews were conducted by a moderator experienced in working with individuals with disabilities or patients, along with a specialist knowledgeable in design thinking methods. Both experts also possessed knowledge in garment design and technology.

Data collection methods include free audio and video recordings of discussions, along with materials used to stimulate conversation, such as photos, 3D models, and clothing samples.A digital survey platform featuring an active QR code enabled participants to comment on and evaluate the experimental design solutions. This corresponds with the ideas of user involvement in the creation and development of adaptive clothing, as outlined in the research.

RESULTS AND DISCUSSION

The Survey of Focus Groups: Demonstration/Testing of Prototypes and Data Collection

(a) (b) (c)

Figure 2..The initial design solutions for the Experimental Sweatshirt (ES) and Pants (EP) (a), the Experimental T-Shirt (ET) (b) and the Experimental Shorts (ESh) (c).

In the survey conducted, three Focus Groups were allowed to evaluate the experimental adaptive clothing (prototypes), which included a sweatshirt (ES), pants (EP), a T-shirt (ET) and shorts (ESh) (Fig. 2).

Staff and patients had the opportunity to familiarise themselves in detail, examine and wear the experimental adaptive clothing.

The ES and EP are designed for everyday wear during the transitional season and are aimed at younger and middle-aged individuals. They feature a straight silhouette. The sweatshirt has a hip-length cut with long, sewn-in sleeves and a hood. Its design includes adjustable textile fasteners along the side sections of the front and back, as well as the lower parts of the sleeves. These fasteners allow for customisation in fit, connecting the front and back, as well as the sleeve sections.

The pants are long and feature strips along the side seams, fitted with textile fasteners that secure the front and back sections together. Additionally, they have side pockets integrated into the seams. The waistband includes an elastic ribbon with adjustable laces. These laces allow for a customised fit on both the left and right sides of the pants and act as join points on the waist when the pants are separated into front and back sections.

The ET and ESh were designed for everyday summer wear aimed at younger and middle-aged users. These items feature a straight silhouette. The T-shirt extends to the hips, with a round neckline and short, sewn-in sleeves. Its front and back necklines are adorned with bias tape. The side seams of both the front and back, as well as the lower sleeve allowances, are equipped with textile fasteners, Velcro. These fasteners secure both the front and back sections of the T-shirt, as well as the sleeves.

The shorts have a straight silhouette and sit above the knee. They are made of separate front and back sections, which also include textile fasteners, such as Velcro, to join both parts. Side pockets are conveniently built into the seams of the shorts' front section. The waistband features a wide elastic band and decorative laces that can be tied on either side to provide an adjustable fit, serving the same function as the pants.

During the survey, interviewers asked key questions and recorded the emotional responses of both patients and doctors to the Experimental Adaptive Clothing samples. The main aim was to ensure that the garments not only offered convenience and comfort during treatment but also encouraged positive emotions in patients through their high-quality design.

In Focus Group 1, which included six specialists in physical and rehabilitation medicine, participants evaluated experimental samples of adaptive clothing and expressed approval of their relevance and usefulness. They provided positive feedback on the design solutions, particularly noting the textile fasteners that allow for easy separation of the clothing into sections. This specific property allows easier access to the torso and limbs for medical procedures without requiring complete undressing. It also simplifies the process of putting on and taking off clothing for users with functional disabilities, enhancing their comfort during rehabilitation.

However, the experts provided some valuable feedback. They suggested enhancements to the hood's design and recommended increasing the colour options for the adaptive garments.

During the interview, one doctor demonstrated the practicality of a sweatshirt by mimicking the limited function of his right hand. He found the product helpful but recommended adding loops or grips to make it easier to handle.

Focus Group 2 consisted of five patients from the hospital's surgical department, all of whom had sustained severe injuries from bullet and shrapnel wounds. Table 2 presents the specific locations of their injuries. This information highlights the various challenges these people face daily and emphasises

Table 2. Injuries and physical activity restrictions among patients in Focus Group 2.

Patient number	Location of injury	Availability of medical devices, prostheses, bandages, etc	Nature of the limitation of physical activity
Patient 2A (Fig. 3a)	Left hand	Apparatus for external fixation on the shoulder, forearm and hand of the left hand	The hand is fixed, and the movement of the hand is limited. It is difficult to dress oneself, bend down, and lie down to sleep, making it uncomfortable.
Patient 2B	Torso from the left side	Plaster bandages	Restriction of movements of the trunk and left arm.
Patient 2C (Fig. 3b)	Right buttock, right leg	Bandages	Unstable walking, unable to bend the leg at the knee, challenging to bend over, and difficult to dress oneself.
Patient 2D (Fig. 4a)	Left hand	Apparatus for external fixation on the shoulder, forearm and hand of the left hand	The hand is fixed, limiting the movement, making it challenging to dress oneself, bend over, and sleep comfortably.
Patient 2E (Fig. 4e)	Right leg	External fixation device on the thigh and lower leg of the right leg	The leg is fixed, the movement of the leg is limited, it is difficult to dress yourself, it is uncomfortable to sit, lie down, or sleep

how such traumatic injuries affect their overall well-being and recovery.

Patient 2A, aged 35-40 years, was seen wearing a red knitted sweatshirt with a Velcro fastener along the left shoulder and sleeve seams, a gift from a hospital roommate, Patient 2B. Volunteers adapted this sweatshirt into clothing suitable for his needs. The garment features a deep armhole measuring between 23 and 25 cm and has wide sleeves throughout, which Patient 2A finds comfortable and convenient.

“Adaptive clothing should be tailored for individual injuries and needs, ensuring it does not cause allergies or sores. It is essential to use natural materials, and ready-made items can be modified as needed. Additionally, clothes choice may vary depending on the weather season.”

Patient 2A provided feedback on the ES he trialled. While he liked the design, he noted that the sleeves were too narrow to fit his Illizarov apparatus, and the opening was smaller than he required. He suggested that a hood was unnecessary, as he predominantly remains in a supine position, and it could cause discomfort.

Patient 2B, aged between 30 and 35 years, sustained shrapnel wounds to the torso. During the assessment, three plaster bandages were applied to the torso wounds: two on the back, one on the left side near the shoulder blade and armpit, and another on the front of the left chest area. After the injury, Patient 2B was admitted to the hospital, where he was offered the choice of suitable adaptive clothing tailored to his needs. He selected a jersey sweatshirt with Velcro closures on the shoulder, at the top of the sleeve, and underneath the sleeve, with the closures positioned on the left side due to his injury.

"I used the sweatshirt for some time, and it was convenient. The choice of clothing largely depends on the nature of the injury. For most situations, oversized T-shirts and hoodies, preferably in size XL, are suitable for nearly everyone. If the individual requires larger sizes, custom-made clothing may be necessary. Using Velcro for fastening can be a beneficial option, although it may lose effectiveness after each wash. Zippers can also be advantageous as they allow for expansion in the width of the clothing. These solutions are similar for shoulders, sides and sleeves. Additionally, for individuals who have specific areas of the body exposed due to the Illizarov apparatus, separate capes can be provided for the arms and legs. These capes must have fasteners and are designed to shield healing areas from external elements while offering the necessary support during the recovery process.”

At the time of the interview, Patient 2B did not require adaptive clothing. He had a positive impression of the adaptive clothing (ES and ET), specifically the black colour, which he felt suited him well. He was open to alternative colours, including dark grey and blue, and also mentioned that a green option would be acceptable, as it did not tire him. He emphasised that dark colours are preferable due to the potential for blood seepage from his wounds, which could stain lighter fabrics and make them difficult to clean.

Regarding fasteners, he found the Velcro strap easy to use and preferred it over zippers, buttons, or magnets, as these alternatives could cause discomfort and pressure on the soft tissues when lying down.

Patient 2C, aged 40-45 years, sustained injuries to his right buttock and right leg, resulting in limited knee mobility. During the interview, he was wearing regular knitted sweatpants and mentioned having difficulty putting them on and taking them off. He responded

(a) (b)

Figure 3. Patient 2A (a) and Patient 2C (b).

(a) (b)

Figure 4. Patient 2D (a) and Patient 2E (b).

positively to an experimental pair of pants, although he found it challenging to bend down and fasten the lower Velcro fasteners when they were fully unfastened. Additionally, Patient 2C appreciated the ESh, noting its comfort and the necessity of such clothing during the warm summer months.

Patient 2D, aged between 30 and 35, has sustained an injury to his left arm, requiring the use of an external fixation device. He wears a grey knitted sweatshirt with a left-side fastener accompanied by ties along the upper and lower sleeve seams, which merge into the side seam. At his request, his mother modified the sweatshirt by resewing the shoulder seam to make it easier to wear. Patient 2D finds it convenient to pull the sweatshirt over his head. However, he needs help to tie the fastener because the ties are too short for him to do so comfortably, especially considering the bulkiness of the fixation device on his arm. Having worn the external fixation device for a month, Patient 2D reports it causes significant discomfort, particularly during sleep. Its weight forces him to support it with a neckband, which leads to pain in his cervical spine. So, he has expressed a positive perception of alternative fasteners in ES, specifically praising the convenience of "Velcro". He also provided favourable feedback regarding the ET design, indicating a preference for it over non-adaptive clothing.

Patient 2E, aged 45-50 years, sustained a wound to the right leg, requiring the use of an external fixation device that extended from the thigh to the shin. At the time of the interview, Patient 2E was dressed in sweatpants made from a knitted fleece fabric, featuring through-fasteners along the side seams secured with Velcro tape, located on both legs. These pants, which he received from volunteers at a hospital, are quite roomy, with a leg width of 25 cm at the bottom. The right pant leg was unbuttoned to accommodate the fixation device. Patient 2E consistently wore these pants at all times, both during the day and at night while sleeping.

Having worn the external fixation device for a month, Patient 2E faces the prospect of an additional surgery due to improper bone growth, necessitating continued use of the apparatus for an extended period. In terms of undergarments, he wore adaptive briefs that also feature Velcro fasteners on both sides.

“When using an external Illizarov fixation device, it is advisable to choose pants with adjustable legs with fasteners or Velcro. In most cases, the legs should be flared or styled like harem pants. Additionally, the waistband should feature an elastic band and the laces for the waist adjuster, for a better fit and comfort.”

During the interview, Patient 2E responded positively to the adaptive clothing options available (EP and ESh), especially valuing the convenience of the Velcro fasteners. When asked about his adaptive clothing needs, he mentioned that he would require three items: two pairs of pants (one insulated, one lightweight), and a pair of shorts.

Generally, all the recommendations from Focus Group 2 for enhancing adaptive products are summarised as follows:

- Create alternative sweatshirts without hoods, which may be more comfortable for patients who spend time lying down.
- For hooded sweatshirts, lower the front of the hood to improve comfort and usability.
- Widen the sleeves of the sweatshirt and the pant legs to provide a better fit for patients who wear medical devices.
- Incorporate adjustable waistbands in pants and shorts for a personalised fit.
- Add custom elongated loops for easier gripping and fastening clothing.
- Broaden the Velcro strips and use rounded edges to increase comfort.
- Avoid added thickness in adaptive clothing to prevent discomfort in the areas of injury.
- Use dark colours, such as black, blue, dark grey, and green.

Focus Group 3 consisted of twelve patients and two staff from the hospital's rehabilitation department (Fig. 5). This department specialises in treating patients with diseases and injuries related to the musculoskeletal system. The group was engaged in discussion, demonstrations and evaluations of experimental adaptive clothing sets. During the experiment, the following data were collected and analysed. The responses of the most engaged participants are detailed below.

Patient 3A, aged 45 to 50, has lower limb injuries and uses two crutches for mobility. When asked about the requirements for adaptive clothing, he expressed specific demands for the textile fasteners:

"The Velcro must be of superior quality; otherwise, after approximately ten uses, it will no longer remain secure properly."

Patient 3B, a man aged around 40 to 45 years who has undergone an above-the-knee amputation of his left leg, currently relies on crutches for mobility and is awaiting prosthetic fitting. He has shared valuable insights about clothing adaptations that can improve comfort and practicality for people with amputations:

"For those who have no legs, it is necessary to make a pants leg up to the knee."

This change would make using the bathroom easier, as he noted that excess fabric often drags on the floor. Additionally, he emphasised the importance of having a kangaroo pocket on sweatshirts for various personal devices. Patient 3B also mentioned the inconvenience of fastening adaptive products with ties; he also discussed the usefulness of hooks as fasteners on pants:

"For fasteners, it is better to use Velcro, because the ties can come loose. I used underpants with ties, but they loosen during sleep, and you wake up without them. When the Velcro on the pants at the waist stopped being fastened, my wife sewed hooks on the waist for fastening, making it more convenient. The hooks are imperceptible in the product, and they nicely fix the pants on the waist."

Overall, his suggestions demonstrate a clear understanding of the challenges faced by amputees and the practical solutions that can improve their daily lives.

Figure 5. The Focus Group 3.

Patient 3C, a man aged between 50 and 55, has a left leg amputated below the knee and relies on two crutches for mobility. He emphasised the importance of adapting clothing for individuals with lower limb amputations. Additionally, he noted the impracticality of using zippers in adaptive clothing:

"To make it comfortable, the leg of the pants below the leg amputation should be cut off. Zippers are inconvenient during the rehabilitation stage; they get in the way. In cases where prosthetic legs will be used, standard sports pants can be worn, designed to allow for leg length adjustments with fasteners or Velcro. However, the pants should roll up normally to the knee; this applies to those who have lost a limb below the knee. It is also possible that the pant leg comprises parts that can be connected with zippers, but most men tend to forget where they have placed each part."

Patient 3D, a man aged between 30 and 35, expressed appreciation for the design and recommended spreading the colours for adaptive clothing.

"The hood is needed, it's also good that the sweatshirt is fully unzipped on both sides and split into front and back. Prints can appear on adaptive clothing just like they do on everyday wear, but with a motivational subtext. The colour scheme can be varied yet subtle, featuring shades such as khaki, grey, black, and dark blue, which are versatile and suitable anywhere."

Patient 3E is a 25- to 30-year-old man who uses two crutches due to an orthosis on his right leg and a bandage on his left wrist. He voiced concerns about his mobility, mentioning that the orthosis often slides on the floor.

"The orthosis slips too much on the floor, and I would like to wear breathable socks over it to increase comfort."

The other respondents offered similar comments and answered the key questions in a comparable way. During a discussion, other members of Focus Group 3 shared their ideas for improving adaptive clothing. They proposed adding a kangaroo pocket to a sweatshirt and developing innovative disposable adaptive garments for the operative and postoperative periods. The attending staff provided further design suggestions to enhance clothing comfort and functionality. Key proposals included moving the product's hanger to the outside of the back, removing the hood to prevent discomfort while sleeping, adding pockets for phones and other devices, and designing a grommet in the middle seam of pants and shorts for catheter insertion. Additionally, suggestions were made to include internal fasteners for urine and catheter containers, as well as to enable adjustable widths in pants and sleeves to suit individual patient needs.

Data Analysis and Discussion

Seventeen patients from Focus Groups 2 and 3 sustained various injuries, including hands (17.6%), torso (5.9%), buttocks (5.9%), and legs (70.6%), with leg amputations accounting for 29.4% and musculoskeletal damage - 5.9% (KQ1).

During the treatment, participants wore one or two types of adaptive clothing items (KQ2). These included knitted sweatshirts and hoodies (17.6%), T-shirts (11.8%), and pants or shorts, depending on the season (64.7%). Some individuals used adaptive clothing with fasteners such as Velcro (74.6%), ties (5.9%), or hooks (5.9%). Others opted for standard clothing, which proved to be difficult to wear (11.8%).

In Focus Groups 2 and 3, 88.2% of respondents had previously used adaptive clothing (KQ3). They appreciated features that made dressing and medical procedures easier, although 41.2% highlighted limitations with specific fasteners or designs.

The challenges reported (KQ4) include narrow sleeves that do not fit over external fixation devices (17.6%), small openings that limit access (47.1%), excessive fabric that drags on the floor for amputees (23.5%), and difficulties in fastening regular clothing with ties (41.2%) or zippers (58.8%). Additionally, a significant majority of respondents (94.1%) found that complete undressing during rehabilitation is problematic.

In general, eight medical staff members and five patients with hand and torso injuries evaluated the experimental adaptive clothing, focusing on the ES and ET. The same staff and twelve patients with leg injuries assessed the EP and ESh.

The physiological comfort of adaptive clothing was evaluated by twenty-five participants from three Focus Groups (KQ5-KQ9).

Participants indicated that the textile materials should be soft (80%), breathable (88%), hypoallergenic (64%), and gentle on the skin to prevent sores or allergies (16%). They also emphasised the importance of high-quality, durable textile fasteners, such as Velcro (76%), that can withstand repeated washings.

Eighty per cent of respondents indicated that lower or split neckline design solutions (hood, neckband, etc.) are more comfortable and accessible, especially for patients who need to lie down, emphasising the importance of comfort and practicality in neckline choices.

The sleeve width and length must be sufficient to accommodate medical devices and external fixators

(32%), to ensure ease of movement and accessibility (36%).

The respondents noted that the leg width in pants was adequate as long as it could fit external fixation devices and facilitated movement (52%). Shorts were commonly preferred for spring, summer, and autumn, especially when they provided comfort, effortless dressing, and accessibility to medical sites or devices (100%).

The significance of functional comfort in adaptive clothing (KQ10-KQ17) is determined by how easily garments can be worn and removed, and how the garment elements relate to their functional purpose. This was recognised as the top priority during the treatment phase (100%). Participants from all Focus Groups expressed a preference for loose-fitting clothing equipped with high-quality Velcro fasteners and designs that are specifically tailored to assist individuals with limited mobility. They preferred customisable options that cater to individual injury details, including features such as openings, pockets, and adjustable fastener positions.

Clothing that facilitated access to medical procedures and devices was highly valued, with 100% of participants supporting garments with side fasteners and 44% favouring removable sections, which minimise the need for complete undressing.

Velcro fasteners were preferred for their ease of use, quick fastening, and adjustability (96%). Participants also valued rounded edges and wider strips, which improved comfort (60%).

Pockets were regarded as practical and helpful in carrying essentials such as phones or other medical and non-medical devices, with 92% of respondents highlighting their significance.

The inclusion of a hood was seen as optional. Some participants (36%) found it unnecessary or potentially uncomfortable for lying patients, while others (20%) appreciated it for warmth or style.

The waistbands in both the EP and ESh were adjustable, elastic, and had laces for a personalised fit, receiving positive feedback from 64% of respondents. This design ensures both comfort and practicality.

In terms of aesthetics (KQ18–KQ22), a majority of respondents (78%) found adaptive clothing to be similar to everyday clothing. The colour scheme received positive feedback, particularly for darker tones; black received 100% approval, dark blue 60%, dark grey 92%, khaki 100%, and dark green 52%. These darker colours are effective at concealing dirt and evoke positive emotions, fostering a sense of calm and confidence. Focus group participants indicated that they found certain fashionable elements desirable, including inserts (48%), textured materials (28%), and prints with motivational inscriptions (88%).

Psychological comfort was evaluated through KQ23–KQ27. All patients agreed that clothing should uphold dignity, encourage independence, and minimise the need for external assistance. For many, the ability to dress and undress independently was crucial (62%). Respondents reported that adaptive clothing significantly reduces anxiety by making dressing and undressing easier (64%), facilitating medical procedures (82%), and enhancing self-esteem (72%).

By mapping user responses (KQ1-KQ26) to requirements shown in Fig. 1, a correspondence graph of human-centred adaptive clothing solutions was developed (Figure 6). It summarises users' expressed needs alongside the relevant adaptive design solutions identified during the focus group survey analysis. This highlights the importance of physiological, functional, aesthetic, and psychological comfort as viewed through specific, actionable design elements. The latter aim to address the challenges faced by people with limited mobility, injuries, those using medical devices during treatment or rehabilitation, or individuals with limb amputations.

Based on this analysis, design improvement suggestions for the adaptive clothing prototypes were developed (Figure 7). These suggestions were recommended for four adaptive products.

The design solutions developed through this user-driven process have been turned into refined product prototypes, as shown in Figure 8. A private company manufactured these prototypes under grant agreement No. 44033-CBB-CCI, which was funded by the Goethe-Institut, the German cultural center at the Embassy of the Federal Republic of Germany in Ukraine. The improved versions of the sweatshirt, T-shirt, pants, and shorts incorporate collective feedback from all three focus groups. Both patients and medical professionals contributed significantly to the final design modifications of the garments, clearly expressing their preferences for specific construction and styling techniques.

These garments not only demonstrate enhanced technical functionality but also embody a UCD philosophy that promotes dignity, independence, and emotional resilience during treatment and rehabilitation. This approach helps reduce barriers related to clothing challenges.

The survey conducted with three focus groups revealed significant potential for improving adaptive clothing used in the rehabilitation of patients with injured or amputated limbs. Improvements to these garments should prioritise greater aesthetic, physiological, functional, and psychological comfort, as well as adaptability to meet the needs of injured individuals. Therefore, this study confirms that the design of adaptive clothing, from Focus Group evaluation to creating functional prototypes based on testing experimental products, will greatly enhance quality of life and user satisfaction.

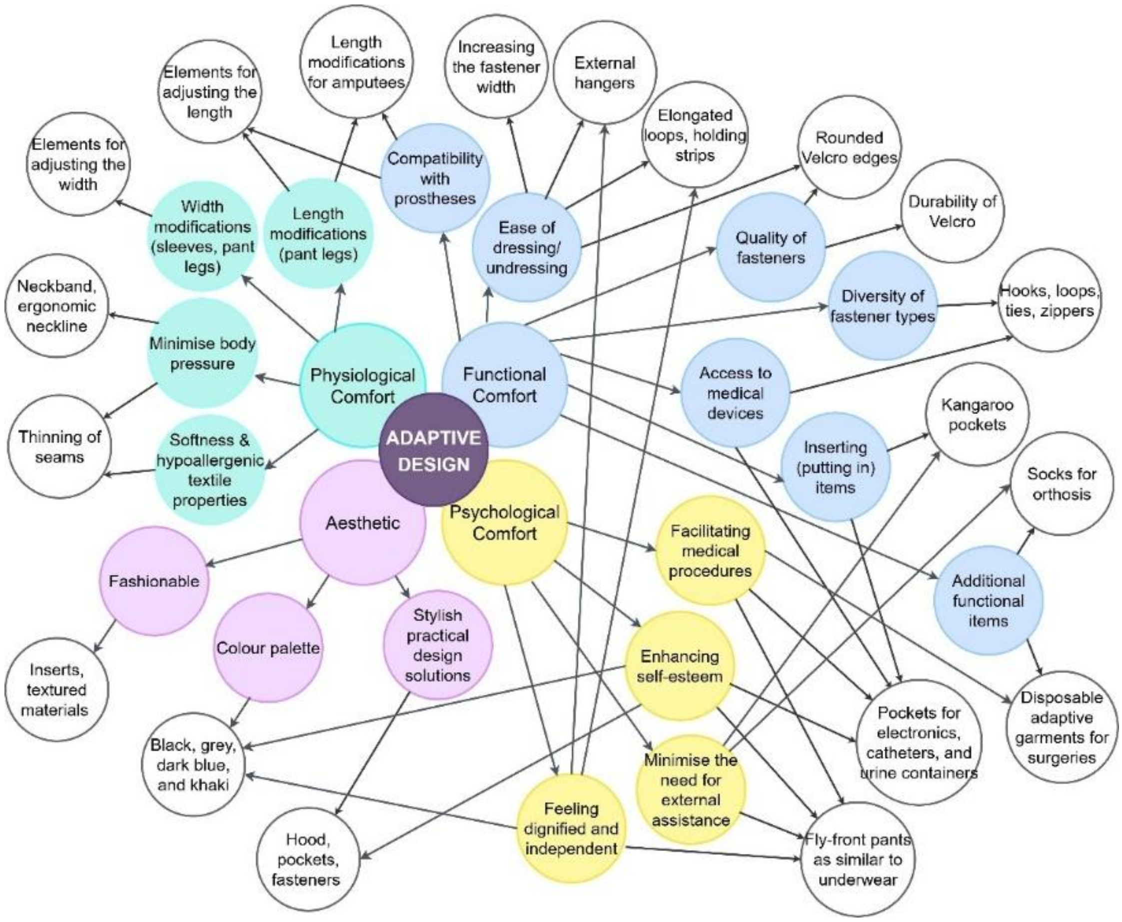

Figure 6. Correspondence graph of users' needs and adaptive design solutions.

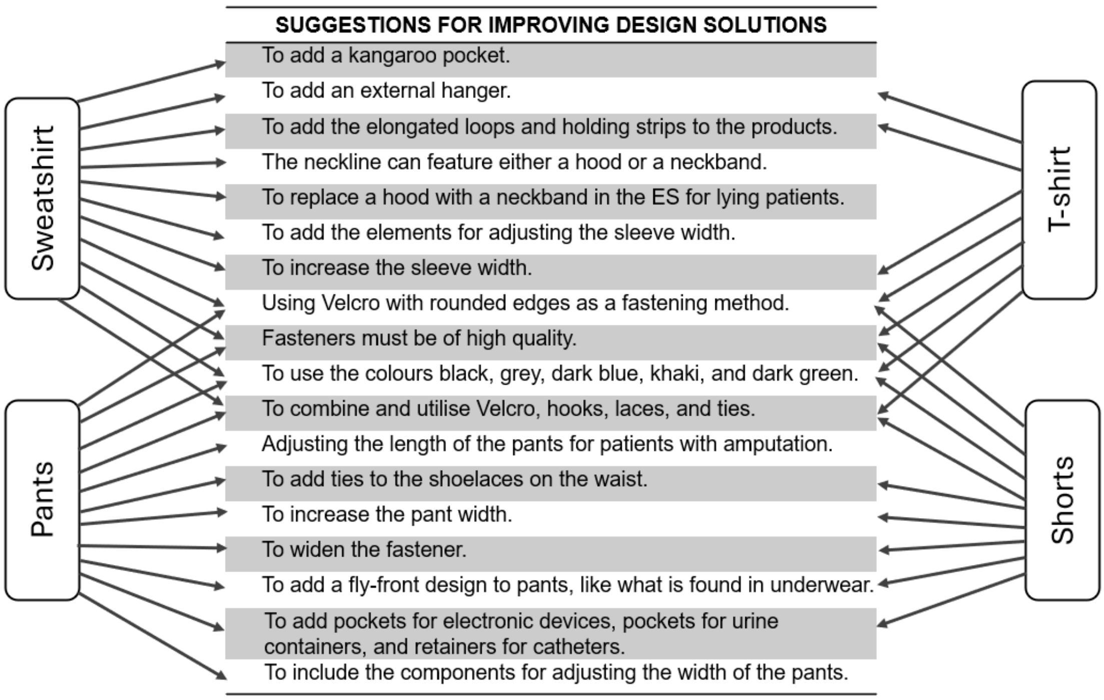

Figure 7. Enhancing the design solutions of the Experimental Adaptive Clothing.

(a) (b) (c)

Figure 8. The improved design solutions for the sweatshirt with hood and pants (a), the T-Shirt and shorts (b), and the sweatshirt without hood and shorts (c).

CONCLUSIONS

This study adopts a user-centred approach to designing and evaluating adaptive clothing for people with injuries or mobility challenges. By collecting feedback from medical professionals, surgical patients, and rehabilitation centre participants, the research identifies four key domains of comfort—physiological, functional, aesthetic, and psychological—that are essential for effective adaptive clothing design. The research assesses prototypes, including sweatshirts, pants, T-shirts, and shorts, using co-design methods. Insights from focus groups indicate that participants highly value comfort, accessibility, adaptability, and psychosocial factors such as dignity, independence, and style relevance. Adaptive design elements like adjustable Velcro fastenings, wider sleeves and pant legs, modular options, and colour choices are directly connected to user-reported challenges and needs. The obtained results contribute to both the theoretical and practical foundations of adaptive design and emphasise the importance of involving users throughout the product development process. This research combines interdisciplinary knowledge at the intersection of clothing design, rehabilitation medicine, and human-centred innovation. The study promotes inclusivity by highlighting the needs of individuals with temporary or permanent injuries, thereby improving their autonomy, emotional well-being, and participation in daily activities through adaptive clothing that supports recovery and social integration. Furthermore, the results provide insight for garment manufacturers to explore a growing niche market segment focused on adaptive clothing. Further research should focus on validating this methodology across diverse clinical populations and geographic regions to ensure its broader applicability.

In the future, there should be a greater focus on integrating digital technologies such as 3D body scanning and CLO 3D [9, 11]. These technologies offer promising opportunities for creating more efficient and personalised designs in adaptive clothing.

Additionally, future research could investigate the potential of innovative materials, including smart textiles [27, 28] and antibacterial fabrics [3, 29-31], as well as elements that provide therapeutic health benefits [32, 33]. These advancements could enhance both physiological comfort and the durability of products. Long-term studies are also recommended to evaluate the ongoing psychological and functional benefits of adaptive clothing in terms of users' recovery, independence, and overall quality of life.

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TRENDS AND GAPS IN SUSTAINABLE FASHION RESEARCH: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

This research consists of a bibliometric analysis on sustainable and fast fashion that were published between 2007 and March 2025. With 764 articles taken from the Web of Science the analysis contains co-citation, co-occurrence, and clustering techniques to map thematic trends. There is an intense growth in research after 2015 and even further intensification post-2020 in alignment with the rising consumer awareness and policy initiatives. The results demonstrate that sustainability is an interdisciplinary field spanning environmental sciences, business, consumer studies, and textile engineering. Fiber recycling, bio-based fabrics, and low-impact dyeing are emerging themes, while gaps remain in communication, ethics, and cultural dimensions.

KEYWORDS

Bibliometric Analysis, Circular Economy, Fast Fashion, Sustainable Fashion, Textile Innovation.

INTRODUCTION

The fashion industry ranks as the second most polluting industry after oil extraction and production industries [1]. Previous research mainly emphasized the negative environmental impacts of the textile industry; including excess water consumption and pollution [2], greenhouse gas emissions from fossil fuel processing [3], and the use of hazardous chemicals [4]. Ten percent of the global annual carbon emission comes from the fashion industry which is equivalent to the emissions caused by international flights and maritime shipping. Furthermore, the emission of the textile industry is expected to increase more than 50 percent by 2030 [5]. Fast fashion which mainly relies on supplying affordable versions of high fashion products without the extremely high price tag [6] has proven to be an effective strategy within the textile industry [7], and it relies on a linear business model characterized by a cycle of production, use, and disposal [8,9,7]. Fast fashion is characterised with its short lead time, mass production and low stock turnover ratio with new product deliveries around every two weeks. This extreme speed in the management of the supply chain is the main driver of success in the fashion industry [6]. The rise of fast fashion has significantly accelerated speed-to-market beginning from the 1990s [10] and garment production has almost increased by 200 percent in the last 15 years [11]. The industry's evolution towards fast fashion brings negative transition trends that are not sustainable [12,13].

In his book "Cannibals with Forks" Elkington introduced the triple bottom (TBL) philosophy of three pillars [14] economic prosperity, environmental quality and social justice mainly stated as. people, planet and profit. "People" refers to individuals and their interactions with society. "Planet" is related to the environment that companies operate in and "Profit" represents the economical value that is generated within society [15]. Increasing awareness about environmental and social sustainability challenges has brought many developments to the industry to make fashion sustainable as well as ethical [16,17]. Despite the fact that the economic contributions of the textile industry are major, it also has unique challenges to both environmental and social aspects of sustainability. The industry's numerous negative societal effects are mentioned by scholars such as inadequate working conditions [18], problems regarding health and safety [19], abuse of human rights such as child labour and modern slavery [20,21]. A dramatic example that reveals poor working conditions is the Rana Plaza Bangladesh incident in 2013 in which 1136 people that worked for the industry lost their lives. This incident raised awareness of poor working conditions and consumer's attention to the sustainable social practices in the fast fashion industry [23]. The

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negative environmental impacts of this industry are listed by scholars as inordinate water use, wastewater and water pollution [2,19,23,5] and plastic pollution [24,25,26]. As an example of the industry's excess usage of water; one t-shirt production necessitates 2700 L of water to produce. Additionally, in 2015 the industry of fashion utilised 79 billion cubic water. A fifth of the global water pollution comes from textile dyeing and finishing while 0.5 million tonnes of microplastics are added to oceans each year due to washing of clothes made of synthetic fibres.

Ten percent of the global greenhouse gas emissions is caused by the industry, and it requires attention to be brought on air pollution [5,27]. Garments are perceived as short-lived in accordance with the nature of the fast fashion industry and increasing overconsumption [28]. Fast fashion causes excessive amounts of waste, waste-related emissions and toxicity [29,30]. The sustainability of fashion has been gaining further recognition in research and eco-fashion, ethical fashion, slow fashion, and sustainable fashion are some of the main concepts that challenge the fast fashion paradigm. These concepts place sustainability as their strategy and aim to create a middle ground for economic and social development as well as the preservation of the environment [31].

Sustainable fashion has the goal to slow production, reduce environmental destruction, ameliorate working conditions, move to a new business model that is circular and/or collaborative and foster the utilisation of organic resources with minimal environmental effects [32,33,34]. An increasing number of studies show that, despite the higher costs, consumers are getting more interested in sustainable fashion products [35,36,37]. The main reason that consumers' tend to lean towards sustainable fashion products is due to environmental concerns [35]. The increased awareness forced fast fashion brands to develop strategies focusing on sustainability all through the supply chain. H&M is a pioneer company in the industry and it claimed that all its products will be renewable or sustainable by 2030 in its conscious collection and in the company statement in 2022 the company declared that "…improving sustainability performance in our own value chain and demonstrating the resilience of sustainable business.." [38].

This research looks into the main research trends between 2007 and 2025 and maps their thematic evolution with analysis with the aim of providing a holistic picture of fast fashion and sustainability. A bibliometric analysis is employed based on a systematic literature review to create maps of existing knowledge. This paper pursues three main objectives. First, it seeks to integrate existing research on fast fashion and sustainability in the fashion industry from 2007 to 2025. Second, it aims to provide a detailed analysis of the broader research landscape surrounding these topics. Finally, it offers a comprehensive knowledge map that captures the complex realities of fast fashion and its connection to sustainability. The next section presents the methodology, outlining the intricacies of data collection and processing. Section three highlights the research findings, delivering an in-depth analysis of active journals, collaborations between countries and institutions, document co-citation patterns, keyword co-occurrence, and the emerging clusters within the dataset. Section four introduces the knowledge map developed through this study, alongside a critical discussion grounded in bibliometric analysis. The final section concludes the paper and points toward potential directions for future research.

METHODOLOGY

Data Source and Search Strategy

Bibliometric analysis is a qualitative method in which the information visualization analysis tool is used to review research development trends with the utilization of physical units such as publications and bibliographic citations. By using this method the collection of literature is more efficient and the interrelationships between chosen publications within the options can be established. The key source of data used in this bibliometric research analysis is the Web of Science (WoS) database that was published by Thomson Reuters [39]. Compared to other databases like PubMed, Scopus, and Google Scholar, it is considered the most reliable database for studying literature in multidisciplinary fields [40]. This is the reason why WoS was chosen as the data source in the bibliometric analysis. Furthermore, sub-field databases Science Citation Index Expanded (SCI-EXPANDED) and Social Sciences Citation Index (SSCI), Conference Proceedings Citation Index—Science (CPCI-S), and Conference Proceedings Citation Index— Social Science Humanities (CPCI-SSH) were utilised as data providers. For the first stage, the researcher identified the key terms of the research, searching the highly cited publications focusing on the relation between sustainability and fast fashion. The search terms included the title, abstract, and keywords: TS= (("sustainability*" AND "fast*fashion")). The analysis of the publication years span between 2007 and 2025. The first relevant article on the intersection of fast fashion and sustainability is from the year 2007. On the search conducted on the 16th of March 2025, 764 research articles were found from the WoS database. The one time search was made in order to eliminate possible bias that can arise from updates made in the database. In this period (2007–2025), researchers are starting to focus more on various aspects of research regarding textile waste and the impact of textile waste on the environment. The WoS database the task of searching for required publicati-

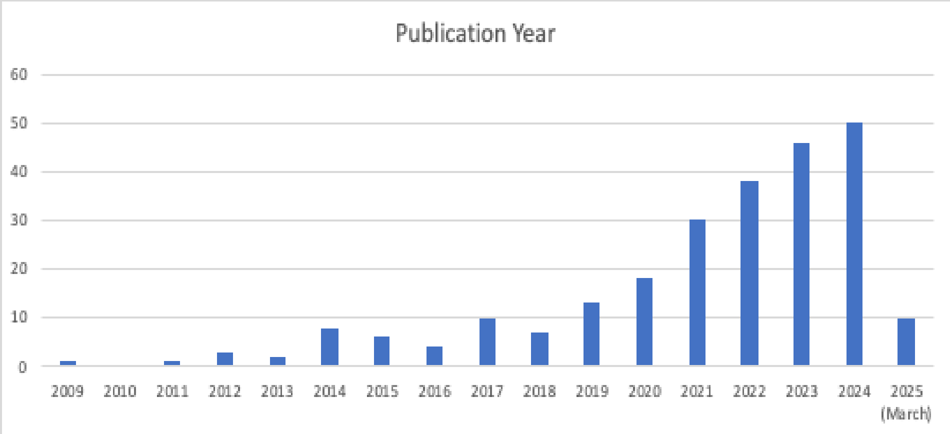

Figure 1. Distribution of academic publications between the years 2009 and 2025 (March).

-ons was done once on 16 March 2025 Furthermore the publications were solely in English.Only research articles were considered in this study therefore other document types like review papers, conference proceedings, meeting abstracts, early access articles editorial materials, data papers, and letters were not included in the analysis The trend analysis shows gradual expansion in academic interest over time with more significant progress from 2015 onwards. This depicts increasing academic interest in the environmental and social challenges that the fashion industry has. Especially recently there is a diversification in topics of research. Topics such as circular economy practices, ethical production and the utilisation of organic materials have gained. The year-wise analysis reveals both the evolving landscape of academic inquiry in the field as well as the emerging themes and potential areas for future research.

In the Figure 1 the distribution of academic publications between the years 2009 and 2025 (March) on the theme of fast fashion and sustainability are given. The data provides important insights on how the research area has evolved over time and where academic interest has been concentrated. There is very limited research between the years 2009 and 2014 indicating that there was low interest in fast fashion's relation with sustainability. However there was an important shift in 2015. As it can be seen on the graph there was a notable increase in the quantity of publications starting from 2015, with this growth accelerating particularly after 2020. 2021, 2022 and 2023 are the years with the highest research intensity. This indicates a significant increase in scientific interest in the environmental impacts of the fashion industry, circular economy approaches, ethical production processes, and the use of organic materials. It can be argued that external factors such as increased awareness of sustainability in the post-pandemic period, changes in consumer behavior, and the increased popularity of corporate sustainability reporting have also supported this trend. The data for 2025 appears relatively low as it only covers publications up to March; however, an increase can be expected in the remaining months of the year.

Table 1 below lists the journals with the highest concentration of academic publications in the field of sustainability and fast fashion. Sustainability is the journal with the highest number of published articles (58 articles) and it is accepted as a knowledge source in this field due to its interdisciplinary structure. Journal of Cleaner Production with 17 articles is in second place with its technical studies focusing on environmental sustainability and production processes. The *Journal of Fashion Marketing and Management* (8 articles) and the *Journal of Global Fashion Marketing* (7 articles), both of which focus on fashion marketing and consumer behavior, highlight the influence of consumer trends on sustainability strategies. The list is followed by *Fashion Practice* and *Business Strategy and the Environment* journals that have focused on the intersection of design processes and environmental strategies, and have studies that incorporate both cultural and managerial perspectives. This distribution reveals that research on sustainable fashion has taken on a multidimensional structure, spreading across various disciplines such as engineering, business strategy, design, and consumer behavior. Furthermore, various research showcases the role of textiles and materials, especially in areas like fiber recycling, low-impact dyeing, and the development of bio-based fabrics. The fashion industry's sustainable innovation is driven by important drivers that are material science and textile engineering. The below Table 2 displays the top ten most cited academic publications on fast fashion and sustainability. The article *'Fast Fashion, Sustainability, and the Ethical Appeal of Luxury Brands'*, leads the list which has received 465 citations. This shows that there is a high level of interest in ethical consumerism and the sustainability strategies of luxury brands. The first five articles on the table focus on different subthemes such as consumer behaviour, circular economy and supply chain management, highlighting their central role in sustainable fashion literature Notably, studies like the 'Slow Fashion Movement' and 'Sustainable Fashion

Table 1. Journals with the highest concentration of academic publications.

Journal	No of Articles
Sustainability	58
Journal of Cleaner Production	17
Journal of Fashion Marketing and Management	8
Journal of Global Fashion Marketing	7
Fashion Practice-The Journal of Design Creative Process & The Fashion Industry	6
Business Strategy and the Environment	5

Supply Chain' examine consumer perceptions alongside corporate practices. The high citations indicate that the articles have become reference points not only in academia but also in industrial policymaking. This trend reveals that sustainability is being addressed as a multidimensional phenomenon and is not limited to solely environmentally, but also technically, ethically, economically, and from a consumer-oriented perspective. The article "Fast Fashion, Sustainability, and the Ethical Appeal of Luxury Brands" written by Joy et al. [41] stresses on the contradiction that exists between the environmental values and fast fashion habits of young consumers. Despite the fact that participants have aroused interest in sustainability activities, they still engage with fast fashion due to its affordability and trends. The study revealed that eco-fashion lacks appeal and luxury fashion could link sustainability with consumer demand. The second most cited article "Sustainable Fashion Consumption and the Fast Fashion Conundrum [42]" focuses on the contradiction between consumers' awareness of sustainability and their continued preference for fast fashion. The study shows that despite the fact that environmental concerns are acknowledged, purchasing decisions are mainly affected by affordability and trendiness. Sustainable fashion is viewed as less accessible and stylish. The gap that exists between the values and behavior of consumers shows the need for cultural and behavioural change alongside technological solutions. The third article "Death by Waste: Fashion and Textile Circular Economy Case" [43] stresses on the extreme amount and urgency of the textile waste crisis. The research shows that in the past 20 years worldwide textile production and consumption has doubled. Over 66 percent of the discarded textiles go to landfill and less than 15 percent are being recycled. The research reveals that the environmental impact of both

Table 2. Top ten most cited academic publications.

Article Title	Source Title	Times Cited
Fast Fashion, Sustainability, and the Ethical Appeal of Luxury Brands	Fashion Theory-The Journal of Dress Body & Culture	465
Sustainable fashion consumption and the fast fashion conundrum: fashionable consumers and attitudes to sustainability in clothing choice	International Journal of Consumer Studies	356
Death by waste: Fashion and textile circular economy case	Science of the Total Environment	306
Sustainable supply chain management in the fast fashion industry: An analysis of corporate reports	European Management Journal	300
Slow fashion movement: Understanding consumer perceptions An exploratory study	Journal of Retailing & Consumer Services	217
Sustainable Markets: Motivating Factors, Barriers, and Remedies for Mobilization of Slow Fashion	Journal of Macromarketing	202
Sustainable Fashion Supply Chain: Lessons from H&M	Sustainability	197
Exploring young adult consumers' sustainable clothing consumption intention-behavior gap: A Behavioral Reasoning Theory perspective	Sustainable Production & Consumption	154
Closing the loop on take, make, waste: Investigating circular economy practices in the Swedish fashion industry	Journal of Cleaner Production	139
Governance of sustainable supply chains in the fast fashion industry	European Management Journal	132

Figure 2. Top 10 research areas of publication**.**

natural and synthetic fibers that include intensive water usage, chemical contamination, greenhouse gas emissions, and microplastic release require the integration of circular economy frameworks within the fashion sector.

Figure 2 below shows that the highest publication density is under the category of "Science & Technology – Other Topics; Environmental Sciences & Ecology" which mainly examines the technical, environmental, and scientific dimensions of the textile indıustry and fast fashion. The main focus is on textile innovation and material transitions in this category and fiber-to-fiber recycling, biodegradable fibers, and low-impact dyeing technologies are some examples of this category. These demonstrate the important effects of textile engineering and material science in the formation of sustainable solutions in the fashion industry. The second place is given to "Business & Economics" with its focus on economic impacts of fast fashion and sustainability, consumer behavior, and business models. This shows that the subject is not constrained to solely an environmental perspective but it also has economic and managerial standpoints. "Communications" and "Arts & Humanities" have less representation indicating that sustainability's sociocultural and communication parts have received less attention.

The Figure 3 illustrates the VOSviewer co-occurrence network map, showing the relationships among keywords in sustainable fashion research. Central terms such as "sustainability," "fashion," "consumption," and "circular economy" dominate the graph which reflects their importance in shaping the field. The clustering of keywords highlights distinct thematic connections: "fast fashion," "consumer behavior," and "overconsumption" form a critical discourse cluster on unsustainable practices, whereas

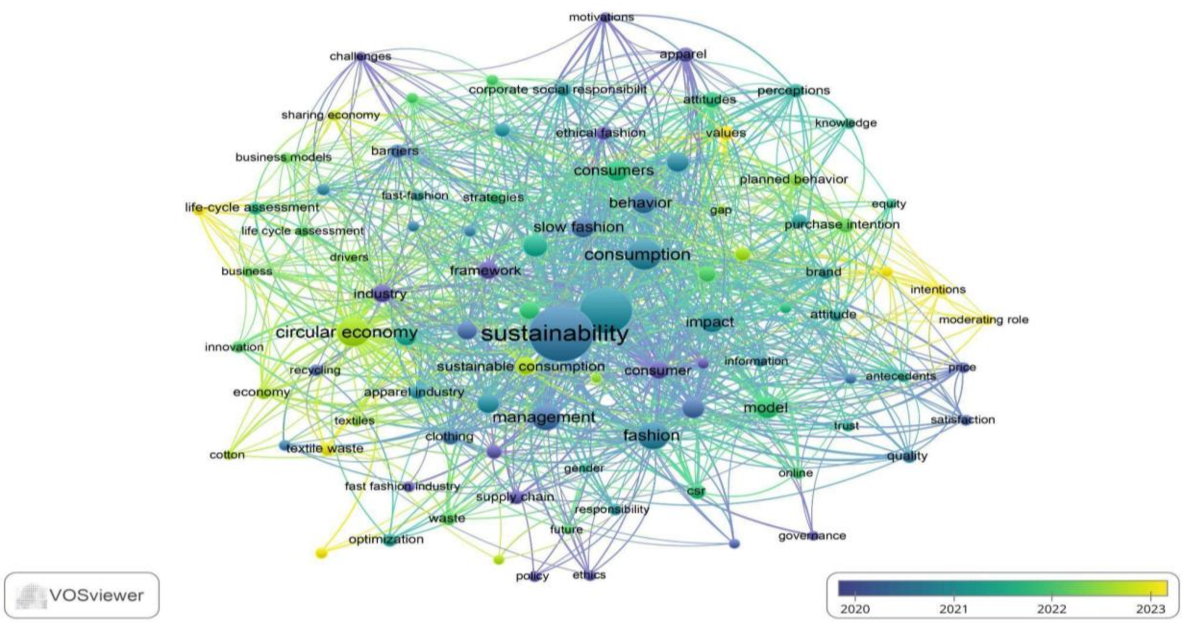

Figure 3. Co-occurrence network map.

"recycling," "innovation," and "circular design" point to technological and systemic solutions. Within these clusters, studies on technical textiles, material science, and eco-innovations are increasingly visible, emphasizing fiber-to-fiber recycling, bio-based fabrics, and low-impact dyeing methods as core areas of inquiry. The color gradient also demonstrates the temporal evolution of research. Darker nodes such as "environmental impact" and "sustainability" highlight long-standing concerns, while lighter ones like "circular economy" and "digitalization" represent recent research fronts (2022–2023).

The density of interconnections underscores the interdisciplinary character of the field, merging environmental science, consumer studies, business strategy, and textile engineering. Overall, the map shows that sustainable fashion is evolving toward a multidimensional research area where materials and textile technologies are becoming critical drivers of innovation, while also providing a tool to identify emerging trends and underexplored gaps. The second visualization is a heat map shown below in Figure 4. In the heatmap, the color gradient ranging from dark blue to bright yellow indicates the relative density of keyword occurrences, with yellow areas denoting high frequency and central importance. At the center of the map there is the term "sustainability" which is the densest and most interconnected keyword, highlighting its centrality in scholarly discussions. In close proximity to the term there are high-density terms such as "fashion," "consumption," "circular economy," "management," and "behavior," emphasizing their prominent association with sustainability research in the fashion area. Keywords like "slow fashion," "consumer behavior," "sustainable consumption," "supply chain," and "textile waste" reflect the evolving thematic focus of academic inquiry, indicating that environmental concerns, ethical consumption patterns, and systems thinking (like circularity) are gaining traction. On the contrary, terms that are towards the periphery with cooler tones (green to blue), such as "innovation," "attitudes," "corporate social responsibility" and "perceptions," can represent less popular yet still relevant sub-themes or nascent areas that require further investigation. The map captures the breadth of existing academic engagement while it also underscores the necessity of the need to focus on underexplored, policy-driven, and interdisciplinary research domains.

DISCUSSION

It links into the materials perspective by showing how advances in production technology and shifts in consumer demand can reduce textile footprints—without sacrificing flexibility or the ability to respond quickly to market needs. Moreover, technical research provides a scientific foundation for policymakers, enhances the feasibility of industrial strategies, and supports processes of social acceptance. In this sense, the production of technical knowledge not only drives progress within environmental engineering but also strengthens the effectiveness of regulatory and economic mechanisms. Furthermore, according to the literature a technological optimism exists around eco-innovations such as smart textiles and regenerative fibers. However systemic change cannot happen solely with technology due to adaptation barriers that can be cost, infrastructure, and lack of policy incentives. A more critical lens should question if these innovations bring the risk of becoming "green niches" instead of mainstream solutions. Lack of engagement with governance and policy frameworks illustrate that sustainability is usually

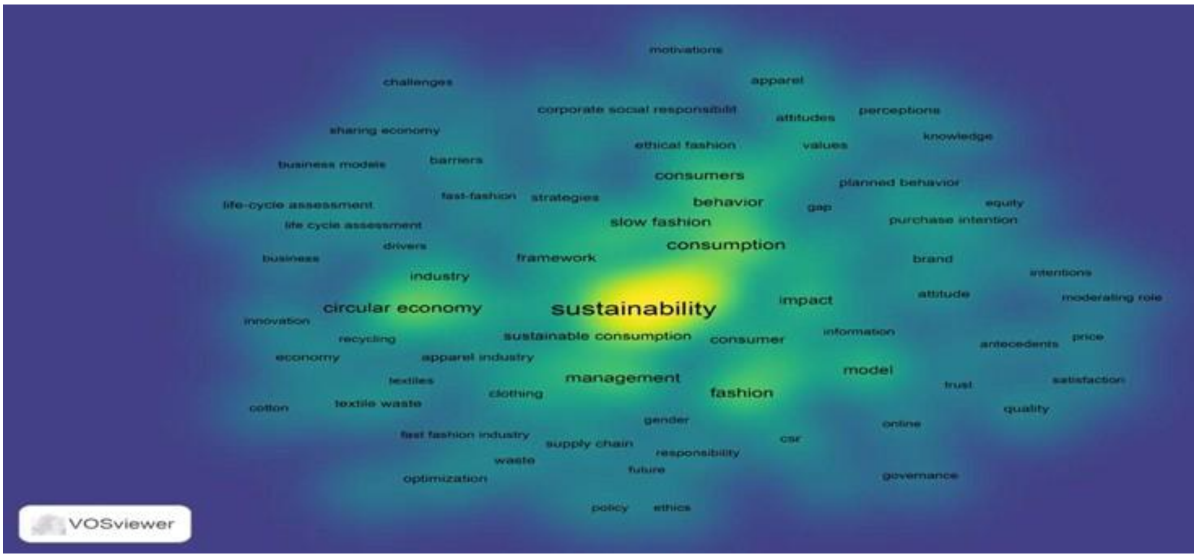

Figure 4. Heat map.

considered without taking into account regulatory mechanisms. The transformative potential of the innovations remain limited if they are not embedded into broader socio-political contexts such as the EU Green Deal or the carbon border adjustment measures. A balanced interdisciplinary approach is needed to strengthen the analytical depth of the field.

CONCLUSION

The research shows that there is a connection between sustainable fashion and advances in textile materials and engineering. The innovative environmentally friendly materials offer transformative opportunities for closing material loops such as regenerative fibers, recyclable composites, and smart textiles with embedded traceability functions. However, despite their transformative potential, the implementation of these innovations are mainly constrained by technical feasibility, cost, and limited industry adoption. Multi-disciplinary collaborations between material scientists, textile engineers, and sustainability scholars are targeted to close those gaps. Collaborations would result in improved environmental performance of fashion systems and the creation of scalable material innovations that are in alignment with circular economy principles. By bringing textile and material considerations more into sustainability research, it becomes possible to move beyond critique and develop practical solutions that can spark real, systemic change in both production and consumption.

Practicle Implications

From a practical perspective the findings of the research states that companies need to integrate sustainability practices into their daily business strategies in the fashion and textile industry. These strategies could involve adapting fiber recycling, low-impact dyeing technologies, and bio-based fabrics at scale. Managers need to guide organisations in balancing short-term profitability with long-term sustainability goals which is comğplicated as it calls for investment in cleaner production systems, transparent supply chains, and eco-material innovation. When brands embed sustainability into procurement, design, and logistics brands can decrease costs, mitigate reputational risks and build consumer trust.

Technological Imlications

This bibliometric analysis emphasizes the role of textile engineering and material science in determining the future of sustainable fashion. Reduced waste production, minimized environmental footprints, and increased product durability can be achieved through improvements in digital production, smart textiles, enzymatic processing and Industry 4.0 tools. The measurement and scaling of eco-innovations in material flows are enabled by circular economy indicators, data analytics, and automated traceability systems. To accelerate adaptation technological capabilities need to align with supportive infrastructure and regulations. In order to turn scientific progress into transformative sustainability outcomes R&D advancements could be connected with operational practices.

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RESEARCH ON INFLUENCE OF SEALING PARAMETERS ON STRENGTH AND WATER RESISTANCE OF STITCH-SEALING AND WELD-SEALING SEAM

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ABSTRACT

This study presents a comparative investigation of the performance of two-seam sealing techniques stitch-sealing and ultrasonic weld-sealing applied to three-layer waterproof fabric composites used in high-performance apparel. A Box-Wilson Central Composite Design was adopted to systematically evaluate the effects of three critical sealing parameters temperature, sealing speed, and air pressure on seam thickness, tensile strength, and hydrostatic water resistance. Experimental trials were conducted both before and after 10 standardized domestic laundering cycles, following ISO 811 (hydrostatic head test) and ISO 13935-2 (grab tensile strength) protocols. Results revealed that weld-sealed joints consistently exhibited lower seam thickness and superior water resistance under all tested conditions, contributing to enhanced wearer comfort. Conversely, stitch-sealed seams demonstrated significantly higher tensile strength, particularly under high-temperature and high-pressure settings. Quadratic regression modeling indicated that temperature was the most influential parameter, with notable two-factor interaction effects observed especially between temperature and air pressure. These findings underscore the importance of optimizing sealing conditions based on end-use requirements, offering a scientific basis for the rational selection of seam sealing technologies in the manufacturing of functional waterproof garments.

KEYWORDS

Sealing Parameters, Seam Strength, Stitch-sealing, Water Resistance, Weld-sealing, 3-layer Waterproof fabric.

INTRODUCTION

In the manufacturing of performance apparel from water-repellent textiles, such as sportswear and outdoor protective garments, the integrity of the seams is of paramount importance. These joints must not only ensure waterproof integrity but also possess sufficient flexibility to maintain the fabric's inherent hand and drape. Furthermore, they must exhibit robust mechanical strength and durability to withstand the demands of their intended application and maintain functional performance over time. While stitching is currently the most dominant joining technique, manufacturers are exploring other options to meet modern demands. Among these alternatives, adhesive bonding and welding are emerging as the most prominent new methods [1,2].

Welding technologies have become integral to the fabrication of technical textiles requiring advanced functional properties. These properties include high water penetration resistance, seam durability under mechanical stress, controlled air permeability, and superior aesthetic qualities [3,4]. Among these technologies, ultrasonic welding has emerged as a particularly significant method for creating high-performance seams. Ultrasonic welding is a solid-state joining technique that utilizes high-frequency acoustic vibrations to create continuous, durable, and impermeable seams. In contrast to conventional sewing. This technique offers significant process advantages, including lower energy consumption and the elimination of consumables such as needles and thread, thereby removing associated costs and potential points of mechanical failure [5]. The technique also affords greater design flexibility, enabling the creation of variable seam widths and the lamination of multiple layers in a single pass. Crucially, by obviating the need for stitching, ultrasonic welding eliminates the needle perforations that are inherent sources of water ingress in conventional seams [6, 7]. However, for many high-performance products, the primary joint must be augmented with a sealing process to meet stringent requirements for quality and mechanical strength.

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In the conventional assembly of breathable waterproof fabrics, the use of thread necessitates a subsequent seam sealing process [8]. A waterproof sealing tape is applied to prevent water ingress through the perforations created by the sewing needle, a critical step for ensuring garment integrity [9, 10].

Despite the widespread use of both stitch-sealing and the alternative weld-sealing method, there remains a notable gap in the literature regarding a systematic, direct comparison of their performance. Specifically, research that quantitatively analyzes the influence of individual process parameters on the resultant bond strength and water resistance of these two joint types is scarce. Such an analysis is essential for identifying the optimal processing conditions for each method, which would in turn enhance manufacturing efficiency, improve product durability, and reduce costs associated with defects. Therefore, the present study was undertaken to comparatively investigate the effects of key sealing parameters on the tensile strength and water penetration resistance of stitch-sealed versus weld-sealed seams. The objective is to provide a robust scientific basis to guide the selection and optimization of the appropriate joining technology for practical manufacturing applications.

EXPERIMENTAL

Materials

Three-layer fabric: The substrate for all seam evaluations was a 3-layer fabric. The construction consists of: (i) an external face fabric, which provides primary abrasion resistance and water repellency; (ii) a central microporous functional membrane, which serves as a barrier to liquid water penetration while allowing for the transmission of water vapor (breathability); and (iii) an internal liner fabric, which protects the membrane from abrasion and provides a comfortable tactile interface for the wearer. In this study, the face fabric (layer 1) with a compound of 60% recycles polyester, 40% polyester was laminated with PU coating for water repellency ability. The more detailed properties of the fabric are presented in Table 1.

Three-layer sealing tape: For all sealing processes, a 3-layer tape with an area weight of 230 g/m² and a thickness of 0.3 mm was employed. The tape is a composite structure consisting of a 100% polyurethane (PU) adhesive layer with a melting point of 300°C, a waterproof barrier layer composed of Thermoplastic polyurethane (TPU), and a final layer composed of a jersey knit polyester made from 100% polyester backing fabric. All sealing operations were performed on a NaWon HTM 5533S seam sealing machine. The schematic illustration of the tape was demonstrated in Fig. 1(a)

Table 1. Properties of 3-layer fabric for testing stitch-sealed and weld-sealed joints.

Layer	Layer 1	Layer 2	Layer 3
Material	Woven fabric, 60% Recycled polyester, 40% Polyester; 75D x 75D (laminated with PU)	Thermoplastic polyurethane (TPU)	Woven fabric, 100% polyester
Weight [gm^{-2}]	86.2	60.0	24.8
Thickness [mm]	0.15	0.05	0.1

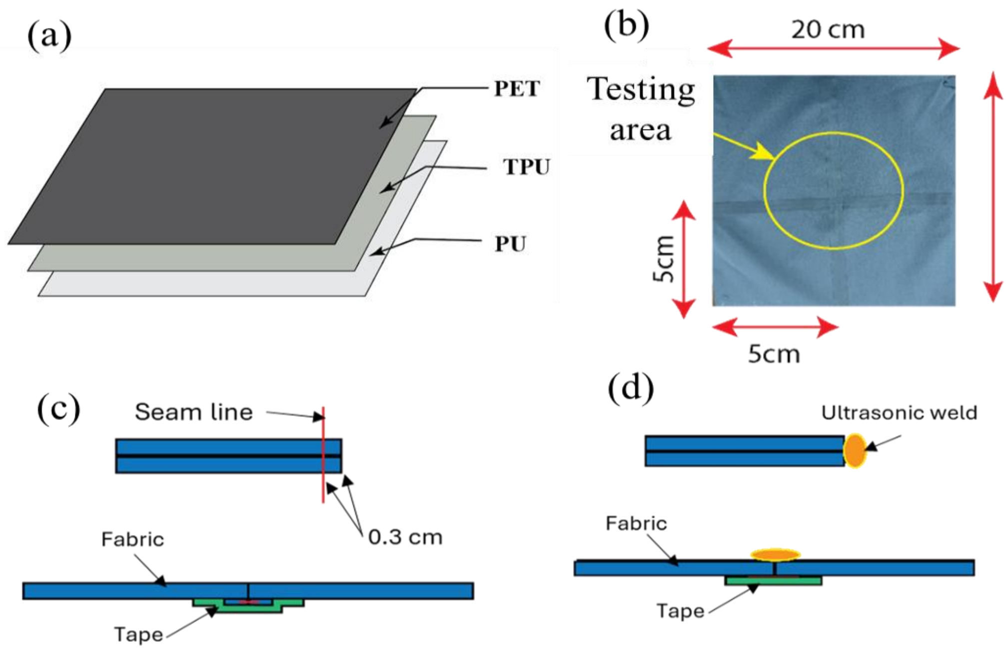

Figure 1. (a) Schematic illustration of three-layer sealing tape, (b) Position of water penetration resistance tests, (c) Schematic diagrams of stitch-sealing, (d) Schematic diagrams of weld-sealing.

In this research, both stitch-sealed and weld-sealed joints were fabricated and analyzed to facilitate a direct comparison of their efficacy in the context of waterproof jacket construction. Schematic diagrams of the stitch-sealing and weld-sealing processes are presented in Fig. 1(c) and 1 (d).

For the stitch-sealed joint, the parameters for the seam were as follows:

- Apparatus: A single-needle, edge-trimming lockstitch machine (Model: DLM-5420N-7) was utilized.
- Stitch type: The seams were constructed using a 301-lockstitch type.
- Stitch density: The stitch density was set to a range of 4–5 stitches/cm.
- Edge trim: 0.3 cm allowance from the seam line to the edge.

For the weld-sealed joint, the ultrasonic weld was utilized, the parameter for the weld were as follows:

- Apparatus: Nawon Ultrasonic Sealing Machine
- Pneumatic pressure: 0.3 MPa
- Welding Speed: 2.2 m/min
- Ultrasonic frequency: 40–42 kHz

To evaluate the performance retention of the seams after domestic laundering, specimens were subjected to 10 wash-and-dry cycles prior to tensile strength and water resistance testing. The standardized laundering parameters were as follows:

- The washing cycle is performed using an LG domestic washing machine. The wash temperature is set to 40°C, with a spin speed of 800 rpm. The duration of each cycle is 45 minutes. There is no detergent used in this process.
- The drying cycle is performed using a Whirlpool domestic tumble dryer. The drying temperature is set to 40°C with the tumble setting on low. The duration of the cycle is 40 minutes.

Experimental Design

In this study, a Design of Experiments approach was employed to investigate the influence of three critical sealing process parameters: Temperature, Sealing speed, and Air pressure - on the integrity of both stitch-sealed and weld-sealed joints. As these factors are known to have significant, interdependent relationships and exert a simultaneous influence on final joint quality, a second-order orthogonal experimental design was selected.

Specifically, a Box-Wilson Central Composite Design was utilized to structure the experimental plan. This methodology facilitates the development of empirical regression equations that model the simultaneous effects and interactions of the investigated factors. The design of the experiment and the subsequent statistical analysis of the data were carried out using Design-Expert® software (version 13.0). Alpha (α) is the axial point distance, which is a critical parameter in constructing this design. This parameter is determined by following equation [11]:

$$\alpha = 2^{k^{1/4}} \quad (1)$$

With the number of factors was k = 3, the design was configured with an axial point distance (α) of 1.68. The experimental ranges and corresponding coded levels for each parameter are detailed in Table 2.

The experimental design consisted of a total of 15 unique experimental conditions. These conditions comprised 4 factorial points, 6 axial points, and 5 central points. To ensure the reliability of the results, each of these experimental runs was replicated five times. The final response value for each condition was recorded as the arithmetic mean of the five replicates. The complete experimental matrix is detailed in Table 3.

Determination of Seam Thickness

The assessment of seam thickness serves as a quantitative indicator of the product's external appearance. The findings suggest that the application of seam tape produces flatter seams, contributing to a smoother overall seam finish. Consequently, this is expected to improve the wearer's tactile comfort by minimizing frictional forces between the body and the seam lines [12].

The thickness of the sewn-and-taped and the bonded seams was determined using a Fabric Thickness Tester, following the procedures outlined in TCVN 5071: 2007 (ISO 5084: 1996) [13].

Evaluation of Joint Water Penetration Resistance

To determine the waterproof integrity of stitch-sealed and weld-sealed joints on a three-layer fabric composite, the water penetration resistance was evaluated. Test specimens were fabricated as 20 cm × 20 cm squares, each featuring a single seam or weld line positioned centrally along the sample, as per technical standards. The water penetration resistance of all specimens was evaluated at the specific position illustrated in Fig. 1b.

The water resistance of the seams was evaluated via the Hydrostatic Head Test, in accordance with the ISO 811 standard [14]. The test was conducted by applying a constant hydrostatic pressure of 1.5 psi (equivalent to 1,055 mmH2O) to the face of the fabric for a duration of one minute. The specimen was deemed to have passed if no water penetration was observed on the seam line during the test period. The presence of any water on the reverse side indicated failure (Not pass). All tests were performed using an HTM 2225 Hydrostatic Head Tester.

Table 2. Experimental range and coded levels of investigated factors.

No.	Factor	Variability levels				
		-1.68	**-1**	**0**	**1**	**1.68**
1	X_1 - Temperature [°C]	455	480	540	600	625
2	X_2- Sealing speed [m/min]	2.2	2.5	3	3.5	3.8
3	X_3- Air pressure [Mpa]	0.03	0.04	0.045	0.05	0.06

Table 3. Experimental plan for investigating sealing factor effects.

No.	x_1	x_2	x_3	X_1 [°C]	X_2 [m/min]	X_3 [Mpa]
1	1	1	-1	600	3.5	0.04
2	1	-1	1	600	2.5	0.05
3	-1	1	1	480	3.5	0.05
4	-1	-1	-1	480	2.5	0.04
5	-1.68	0	0	455	3	0.045
6	1.68	0	0	625	3	0.045
7	0	-1.68	0	540	2.2	0.045
8	0	1.68	0	540	3.8	0.045
9	0	0	-1.68	540	3	0.03
10	0	0	1.68	540	3	0.06
11	0	0	0	540	3	0.045
12	0	0	0	540	3	0.045
13	0	0	0	540	3	0.045
14	0	0	0	540	3	0.045
15	0	0	0	540	3	0.045

Determination of Joint Tensile Strength

The tensile strength of the joints was determined using a monotonic tensile test. The procedure involved subjecting the seam specimen to a continuous, unidirectional tensile load until catastrophic failure occurred. The tensile strength was defined as the maximum force (in Newtons, N) that the specimen could withstand before rupture.

Tensile testing was conducted on a Mesdan Lab Strength Tester, following the grab test method outlined in the ISO 13935-2 standard [15]. Specimen preparation was carried out in accordance with the TCVN 1748-91 standard [16].

RESULTS AND DISCUSSION

Results of Seam Thickness For Stitch-Sealed and Weld-Sealed Joints

The appearance on the surface fabric and the cross - sectional images of the stitch-sealing and weld-sealing reveals distinct topographical differences between the two seam types (Fig. 2 from a to d). The weld-sealed joints exhibit a smooth, flat, and uniform surface profile. Conversely, the stitch-sealed seams, which involve applying tape over a line of stitching, present a noticeably uneven and raised profile. This surface irregularity is the primary factor contributing to the greater overall thickness measured in the stitch-sealed specimens.

Table 4 presents a comparison of seam thickness [mm] between two joining techniques: stitch-sealing and weld-sealing. The findings from experiments 5 and 6 reveal that joint thickness exhibits a decreasing trend with an increase in temperature. In contrast, experiments 7 and 8 demonstrated that a higher speed correlated with an increase in joint thickness. In experiments 9 and 10, while an increase in hot air pressure led to a reduction in joint thickness, this change was negligible.

The preliminary optimal parameters for achieving the minimum stitch-sealed joint thickness (1.21 mm) were determined from experiment 1 with the following Temperature of 600 °C, Sealing speed of 3.5 m/min, and Air pressure of 0.04 Mpa. While the preliminary optimal parameters for achieving the minimum weld-sealed joint thickness (0.56 mm) were determined from experiment 2 with the following Temperature of 600 °C, Sealing speed of 2.5 m/min, and air pressure of 0.05 Mpa.

Furthermore, the data consistently shows that in all experimental conditions, the weld-sealing joints were thinner than the stitch-sealing joints. This finding suggests that the reduced seam thickness achieved through the weld-sealing method is a key factor affecting wearer comfort.

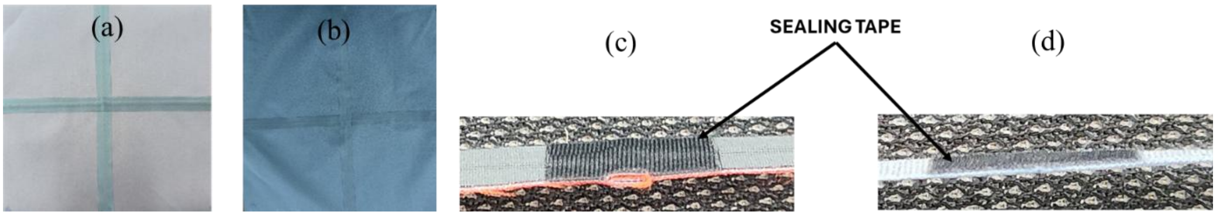

Figure 2. Appearance of (a) Stitch-sealing on fabric, (b) Weld-sealing on fabric, cross-sectional images of (c) Stitch-sealing (d) Weld-sealing

Table 4. Thickness of stitch-sealed and weld-sealed joints of testing specimens

No	X1	X2	X3	Thickness [mm]	
	[°C]	[m/ min]	[MPa]	*Stitch-sealing*	*Weld-sealing*
1	1	1	-1	1.21 ± 0.01	0.72 ± 0.01
2	1	-1	1	1.47 ± 0.01	0.56 ± 0.01
3	-1	1	1	1.45 ± 0.01	0.64 ± 0.01
4	-1	-1	-1	1.28 ± 0.01	0.66 ± 0.01
5	-1.68	0	0	1.35 ± 0.01	0.71 ± 0.01
6	1.68	0	0	1.27 ± 0.01	0.61 ± 0.01
7	0	-1.68	0	1.28 ± 0.01	0.60 ± 0.01
8	0	1.68	0	1.37 ± 0.01	0.79 ± 0.01
9	0	0	-1.68	1.39 ± 0.01	0.78 ± 0.01
10	0	0	1.68	1.37 ± 0.01	0.60 ± 0.01
11	0	0	0	1.26 ± 0.01	0.69 ± 0.01
12	0	0	0	1.27 ± 0.01	0.69 ± 0.01
13	0	0	0	1.27 ± 0.01	0.70 ± 0.01
14	0	0	0	1.28 ± 0.01	0.71 ± 0.01
15	0	0	0	1.27 ± 0.01	0.70 ± 0.01

Table 5. ANOVA for quadratic model of stitch-sealed seams' thickness

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0796	9	0.0088	41.53	0.0004	significant
X_1	0.0032	1	0.0032	15.02	0.0117	
X_2	0.0041	1	0.0041	19.01	0.0073	
X_3	0.0002	1	0.0002	0.9388	0.3771	
X_1X_2	0.0337	1	0.0337	158.42	< 0.0001	
X_1X_3	0.0058	1	0.0058	27.02	0.0035	
X_2X_3	0.0003	1	0.0003	1.44	0.2833	
X_1^2	0.0037	1	0.0037	17.47	0.0087	
X_2^2	0.0067	1	0.0067	31.39	0.0025	
X_3^2	0.0202	1	0.0202	94.73	0.0002	
Residual	0.0011	5	0.0002			
Lack of Fit	0.0009	1	0.0009	17.30	0.0141	significant
Pure Error	0.0002	4	0.0000			
Cor Total	0.0807	14				

Due to the experimental results, to optimize the thickness of the stitch-sealed seam, the effect of the sealing process parameters was analyzed. The ANOVA results are shown in Table 5. The results of ANOVA indicate that the interaction between temperature [°C] and speed [m/min] is the dominant influence on the thickness of the stitch-sealed seam throughout the entire process. The main factors X_1 – temperature [°C] and speed [m/min] - X_2 are important; these factors should be considered during the sealing process to ensure the thickness of the stitch-sealed seam is desirable. The interaction plot of the temperature and speed to the thickness of the stitch-sealed seam was demonstrated in Fig 3.

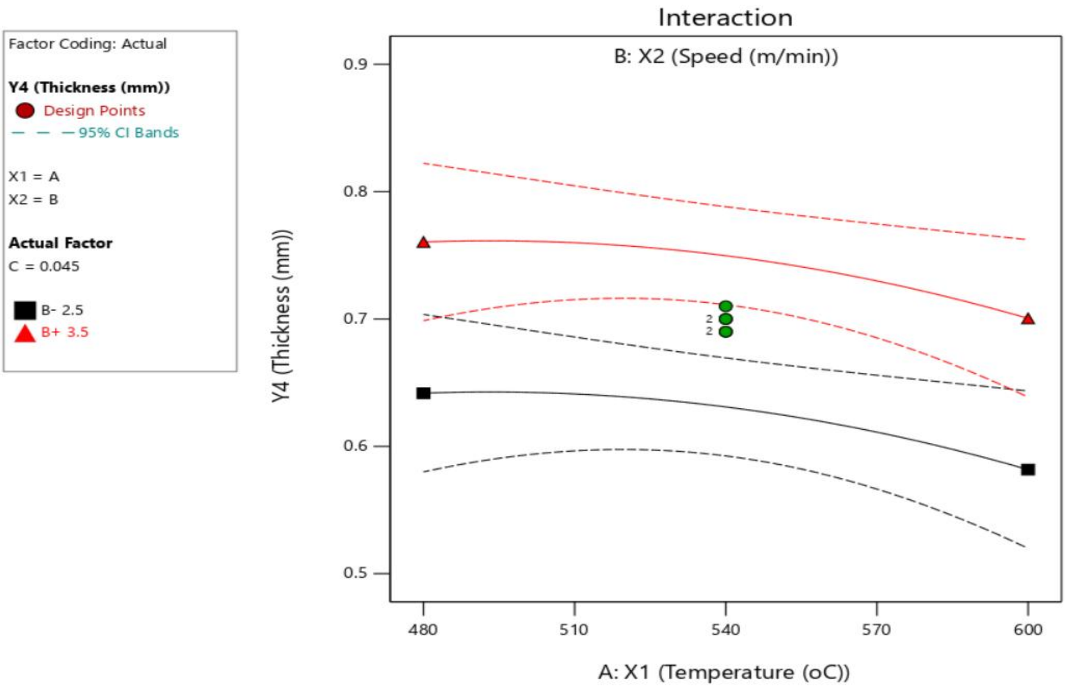

Figure 3. Interaction plot of stitch-sealing thickness - Y1 [N] at different levels of Temperature - X1[°C] and Sealing speed – X2 [m/min].

Table 6. Water penetration resistance results before and after 10 washing 10 cycles at stitch-sealing and weld-sealing areas

No.	X1	X2	X3	Before washing		After washing [10 cycles]	
	[°C]	[m/min]	[MPa]	*Stitch-sealing*	*Weld-sealing*	*Stitch-sealing*	*Weld-sealing*
1	1	1	-1	P	P	P	P
2	1	-1	1	P	P	P	P
3	-1	1	1	P	P	NP	P
4	-1	-1	-1	P	P	P	P
5	-1.68	0	0	P	P	P	P
6	1.68	0	0	P	P	P	P
7	0	-1.68	0	P	P	P	P
8	0	1.68	0	NP	NP	NP	NP
9	0	0	-1.68	NP	NP	NP	NP
10	0	0	1.68	NP	NP	NP	NP
11	0	0	0	P	P	P	P
12	0	0	0	P	P	P	NP
13	0	0	0	P	P	P	P
14	0	0	0	P	P	NP	P
15	0	0	0	P	P	P	P

P-Pass & NP – Not pass

Results of Joint Water Penetration Resistance for Stitch-Sealing and Weld-Sealing

The water resistance of the seams was evaluated under a hydrostatic pressure of 1.055 mmH_2O for a duration of one minute. The results in Table 6 indicate that when process parameters such as air pressure [Mpa] were at their highest or lowest levels, and speed [m/min] was at its maximum, both the stitch-sealing and weld-sealing joints failed to meet the required water resistance. This was observed in both pre-wash conditions and after 10 washing cycles**.**

Experiments 3, 12, and 14 show that the water resistance of both stitch-sealing and weld-sealing joints decreased after 10 washing cycles. This demonstrates that the water resistance of the joint may be affected by usage (simulated by the washing process in this study).

Based on the average results across the experiments, the weld-sealed joints consistently yielded better water resistance than the stitch-sealing joints.

Table 7. Tensile strength results of stitch-sealing and weld-sealing

No.	X_1	X_2	X_3	Tensile strength [N]	
	[°C]	[m/ min]	[MPa]	***Stitch-sealing***	***Weld-sealing***
1	1	1	-1	452.4 ± 75.6	336.8 ± 21.4
2	1	-1	1	490.2 ± 104.8	327.4 ± 15.2
3	-1	1	1	369.4 ± 101.2	331.6 ± 11.0
4	-1	-1	-1	446.0 ± 117.0	337.6 ± 15.4
5	-1.68	0	0	303.0 ± 48.3	335.8 ± 8.8
6	1.68	0	0	402.6 ± 74.1	352.4 ± 19.7
7	0	-1.68	0	293.2 ± 49.2	342.4 ± 22.2
8	0	1.68	0	336.0 ± 63.2	338.6 ± 13.8
9	0	0	-1.68	323 ± 112.6	288.6 ± 32.8
10	0	0	1.68	345.6 ± 79.1	302.6 ± 16.9
11	0	0	0	274.0 ± 63.2	270.2 ± 11.1
12	0	0	0	292.6 ± 17.1	304.4 ± 14.9
13	0	0	0	295.0 ± 19.2	302.8 ± 15.0
14	0	0	0	297.8 ± 18.3	305.0 ± 14.6
15	0	0	0	291.3 ± 18.4	303.5 ± 15.2

Results of Tensile Strength of Stitch-Sealing and Weld-Sealing

Analysis of sealing process parameters on joints tensile strength

The experimental results for tensile strength are presented in Table 7, revealing distinct trends for the two joining methodologies. For stitch-sealed joints, an increase in temperature (Experiments 5 and 6), speed (Experiments 7 and 8), and air pressure (Experiments 9 and 10) consistently resulted in an enhanced the strength of the stitch-sealed joints. Conversely, for the weld-sealed joints, while increasing temperature (Experiments 5 and 6) and air pressure (Experiments 9 and 10) improved the strength of the weld-sealed seam, an increase in speed (Experiments 7 and 8) led to a reduction in the tensile strength of the joint.

Overall, the stitch-sealed seams exhibited a superior average bond strength (490 N) compared to the weld-sealed seams (352 N).

Modeling and analysis of stitch-sealed joint strength (Y1)

To quantitatively analyze the relationship between the sealing process parameters—Temperature (X1), Speed (X2), and Air pressure (X3)—and the tensile strength of stitch-sealed seams (Y1), a quadratic regression model was established as follows:

$$Y_1 = 290.11 + 29.88X_1 + 13.37X_2 + 5.65X_3 + 15.35X_1X_2 + 41.98X_1X_3 - 1.92X_2X_3 + 38.86X_1^2 + 28.75X_2^2 + 18.91 X_3^2 \quad (1)$$

From (1), the linear effects of the process parameters (Xi) on tensile strength (Y_1) are evaluated by their corresponding coefficients (a_i). The largest absolute coefficient, $a_1 = +29.88$, corresponds to temperature (X_1), identifying it as the most significant linear factor. The positive sign indicates that increasing the temperature leads to a substantial increase in the bond strength of stitch-sealed seams. The coefficient $a_2 = +13.37$ suggests that speed (X_2) also has a positive linear effect on tensile strength. In contrast, the much smaller coefficient for air pressure ($a_3 = +5.65$) implies its linear influence on the seam strength is negligible compared to that of temperature and speed.

The interaction effects between two parameters (X_{ij}) are assessed via the a_{ij} coefficients. The large positive coefficient for the temperature-pressure interaction ($a_{13} = +41.98$) is particularly noteworthy, indicating a strong synergistic interaction between temperature (X_1) and air pressure (X_3). The positive signifies that to maximize tensile strength (Y_1), a simultaneous increase in both temperature and pressure is required. A similar, though less pronounced, synergistic interaction is observed between temperature and speed (X_1X_2), as shown by its positive coefficient ($a_{12} = +15.35$), suggesting that a concurrent increase in these two parameters also enhances bond strength.

Based on this analysis and corroborated by 3D response surface plots, Fig.4 (a) – (c), and interaction plots, Fig.5 (a) – (c), optimizing the bond strength of stitch-sealed seams necessitate operating in a high-temperature, high-pressure regime while adjusting the speed accordingly. However, it is critical to calibrate these parameters appropriately to prevent seam degradation, as excessive temperature or pressure could lead to bond failure.

Table 8. Fit statistics values of sealing process parameters and stitch-sealed seam tensile strength

Std. Dev.	73.56	**R²**	0.5964
Mean	347.47	**Adjusted R²**	-0.1299
C.V. %	21.17	**Predicted R²**	-50.5134
		Adeq Precision	2.6264

Table 9. ANOVA for quadratic model of stitch-sealed joint strengt

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	39992.59	9	4443.62	0.8211	0.6253
A-X1	4960.08	1	4960.08	0.9165	0.3824
B-X2	915.92	1	915.92	0.1692	0.6978
C-X3	255.38	1	255.38	0.0472	0.8366
AB	628.33	1	628.33	0.1161	0.7471
AC	3956.55	1	3956.55	0.7311	0.4316
BC	8.57	1	8.57	0.0016	0.9698
A²	18701.83	1	18701.83	3.46	0.1221
B²	8888.35	1	8888.35	1.64	0.2562
C²	8627.16	1	8627.16	1.59	0.2624
Residual	27058.46	5	5411.69		
Lack of Fit	26708.27	1	26708.27	305.07	< 0.0001
Pure Error	350.19	4	87.55		
Cor Total	67051.05	14			

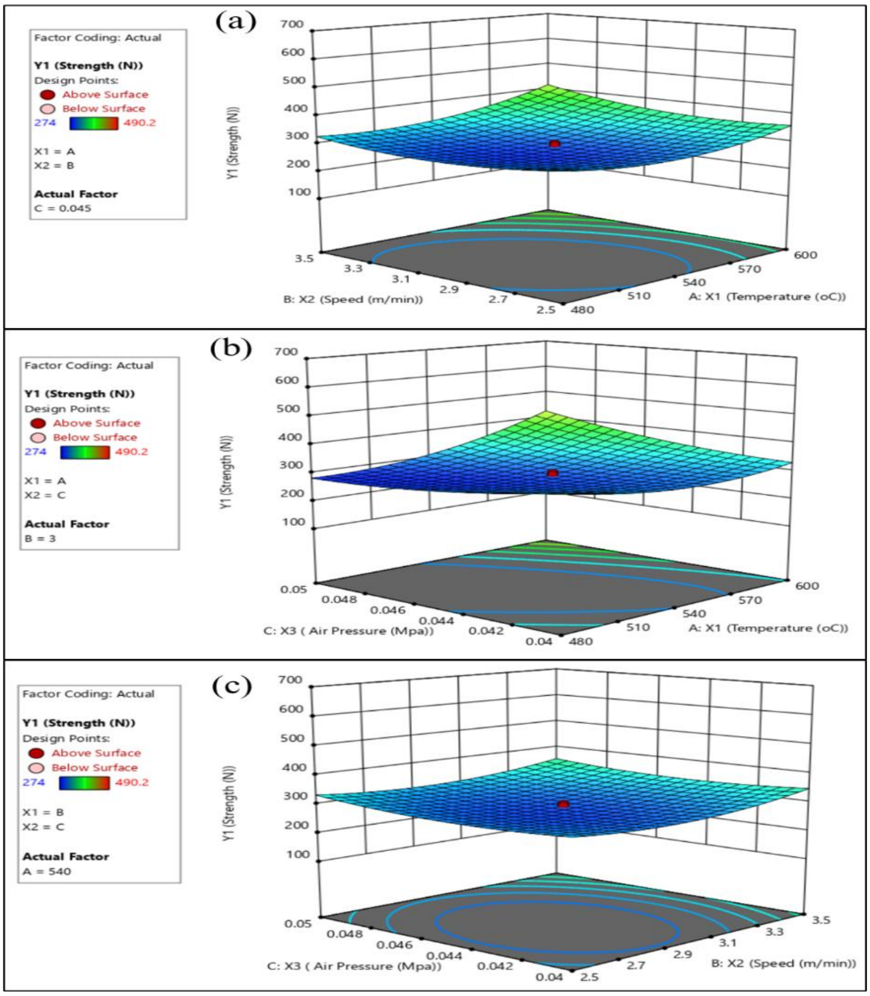

Figure 4. 3D-graph response of stitch-sealing tensile strength Y1 [N] at different levels of: (a) Temperature - X1 [°C] and Sealing speed - X2 [m/min], (b) Temperature - X1 [°C] and Air pressure - X3 [MPa], and (c) Sealing speed - X2 [m/min] and air pressure - X3 [MPa].

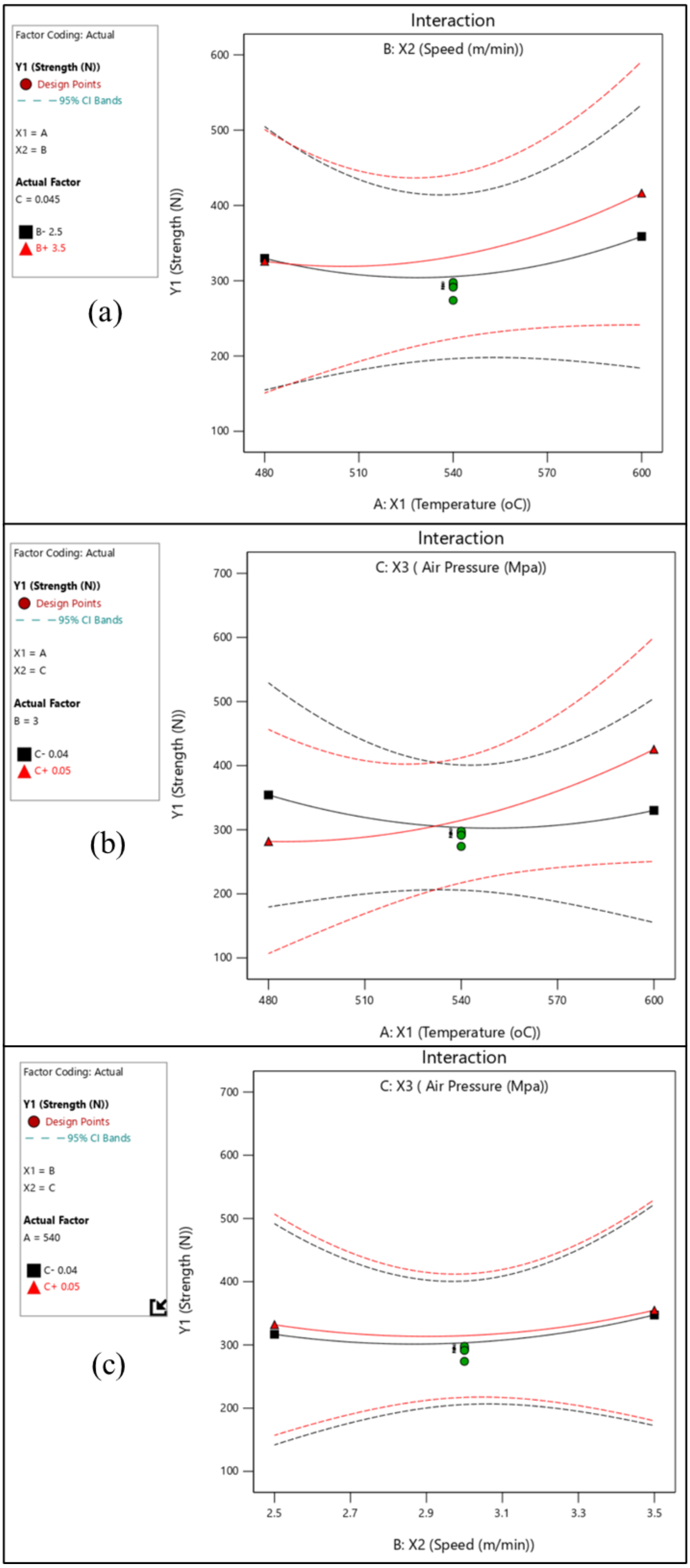

Figure 5. Interaction plot of stitch-sealing tensile strength Y_1 [N] at different levels of (a) Temperature - X_1[°C] and Sealing speed – X_2 [m/min], (b) Temperature - X_1[°C] and Air pressure – X_3 [Mpa], (c) Sealing speed – X_2 [m/min] and Air pressure – X_3 [Mpa].

Table 10. Fit statistics value of the relationship of the sealing process parameters to the weld-sealed seam tensile strength

Std. Dev.	13.64	**R^2**	0.8792
Mean	318.65	**Adjusted R^2**	0.6618
C.V. %	4.28	**Predicted R^2**	0.5141
		Adeq Precision	5.7596

Table 11. ANOVA for quadratic model of weld-sealed joint strenght

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	6775.52	9	752.84	4.04	0.0691
A-X1	137.78	1	137.78	0.7402	0.4289
B-X2	7.22	1	7.22	0.0388	0.8516
C-X3	98.00	1	98.00	0.5265	0.5006
AB	144.06	1	144.06	0.7740	0.4193
AC	9.32	1	9.32	0.0501	0.8318
BC	90.26	1	90.26	0.4849	0.5172
A^2	3711.62	1	3711.62	19.94	0.0066
B^2	3262.30	1	3262.30	17.53	0.0086
C^2	0.8821	1	0.8821	0.0047	0.9478
Residual	930.66	5	186.13		
Lack of Fit	17.93	1	17.93	0.0786	0.7931
Pure Error	912.73	4	228.18		
Cor Total	7706.18	14			

Modeling and analysis of weld-sealed joint strength (Y2)

In the experiments to analyze the effect of sealing parameters on the weld-sealed seam tensile strength, the C.V. value of 4.28% is generally considered very low, indicating that the variation in the data is small compared to the mean value (318.65). This implies that the experiments are highly repeatable and precise.

Similarly, a quadratic regression model was developed to elucidate the relationship between the process parameters and the tensile strength of weld-sealed joints (Y_2):

$$Y_2 = 297.18 + 4.98X_1 - 1.19X_2 + 3.5X_3 + 7.35X_1X_2 - 2.04X_1X_3 + 6.23X_2X_3 + 17.31X_1^2 + 17.42X_2^2 - 0.19X_3^2 \quad (2)$$

According to (2), the largest absolute linear coefficient is $a_1 = +4.98$, corresponding to temperature (X_1), which suggests it is the most influential linear factor. The positive value indicates a direct relationship where higher temperatures increase the tensile strength of the weld-sealing. The coefficient $a_3 = +4.93$ also shows a positive linear effect of air pressure (X_3) on bond strength. In contrast, the coefficient $a_2 = -1.19$ is negative, indicating an inverse linear relationship for speed (X_2); that is, decreasing the speed promotes higher tensile strength. However, the magnitudes of these linear coefficients are minor compared to the quadratic coefficients for temperature ($a_1^2 = +17.31$) and speed ($a_2^2 = +17.42$). This finding suggests that the tensile strength of weld-sealed seams (Y_2) is not predominantly governed by the linear effects of individual parameters but rather by the non-linear (quadratic) effects of temperature and speed.

Regarding interaction effects, the positive coefficient $a_{12} = +7.35$ indicates a synergistic interaction between temperature (X_1) and speed (X_2), implying that a concurrent increase of both is beneficial for tensile strength. Likewise, the interaction between speed and air pressure (X_2X_3) is also synergistic ($a_{23} = +6.23$). Conversely, the coefficient for the temperature-pressure interaction ($a_{13} = -2.04$) is negative, indicating an antagonistic relationship. This suggests that to increase tensile strength, one parameter must be increased while the other is decreased (e.g., increasing temperature while decreasing pressure, or vice-versa).

In conclusion, the analysis, in conjunction with 3D response surface plots, Fig. 6 (a) – (c), and interaction plot, Fig. 7 (a) – (c), indicate that optimizing the tensile strength for weld-sealed joints requires setting temperature and speed at their optimal extreme levels within the experimental domain.

The analysis reveals that the optimal sealing parameter sets for achieving maximum tensile strength differ significantly between the two joining methods. For stitch-sealing, the highest tensile strength was achieved under conditions of high temperature, low speed, and high pressure (as demonstrated in Experiment 2). In contrast, the optimal tensile strength for weld-sealing was obtained at a very high temperature, while maintaining both speed and pressure at intermediate levels (Experiment 6).

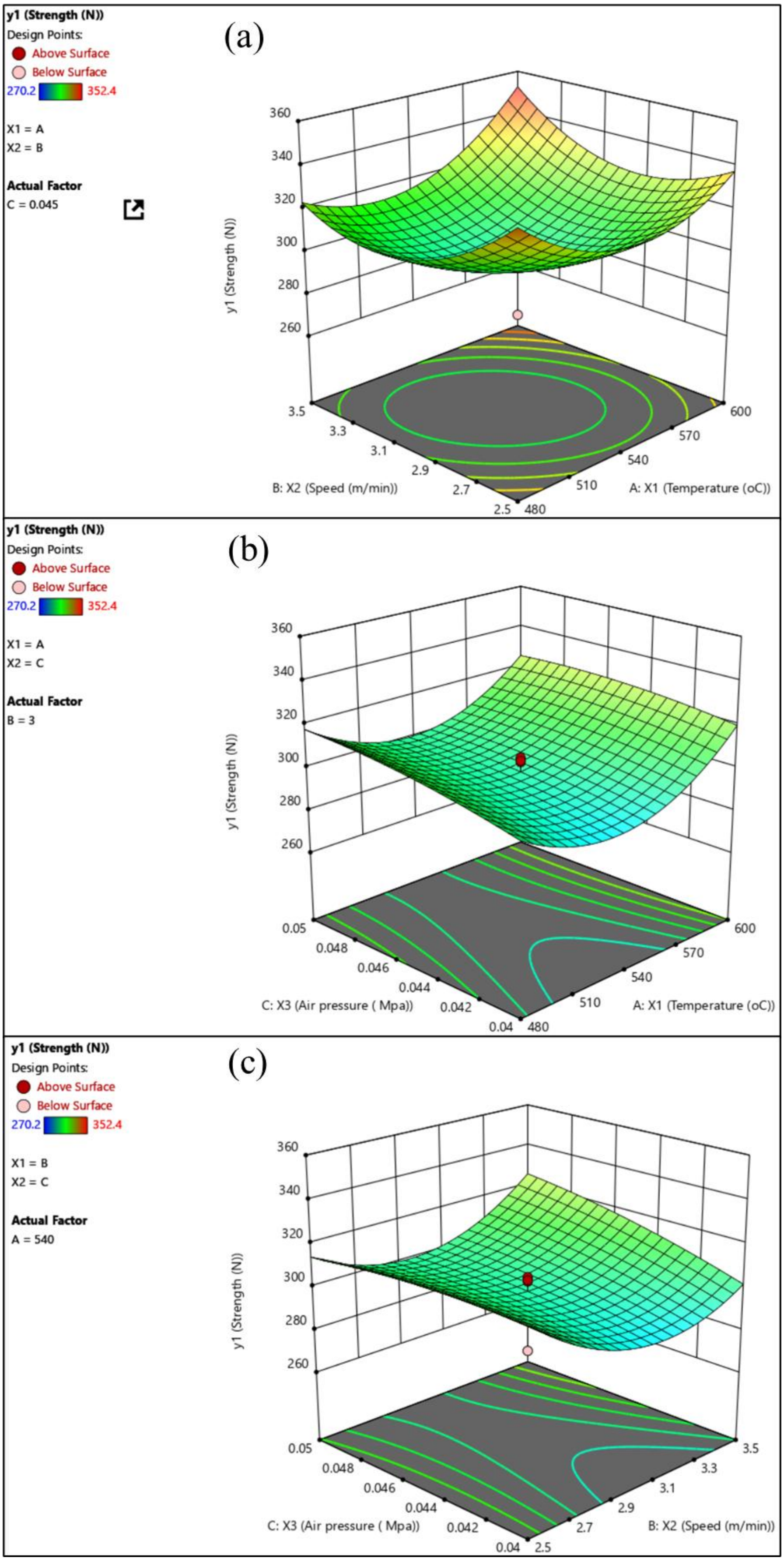

Figure 6. 3D-graph response of weld-sealing tensile strength Y1 [N] at different levels of (a) Temperature - X1 [°C] and Sealing speed - X2 [m/min], (b) Temperature - X1 [°C] and Air pressure - X3 [Mpa], and (c) Sealing speed - X2 [m/min] and Air pressure - X3 [MPa].

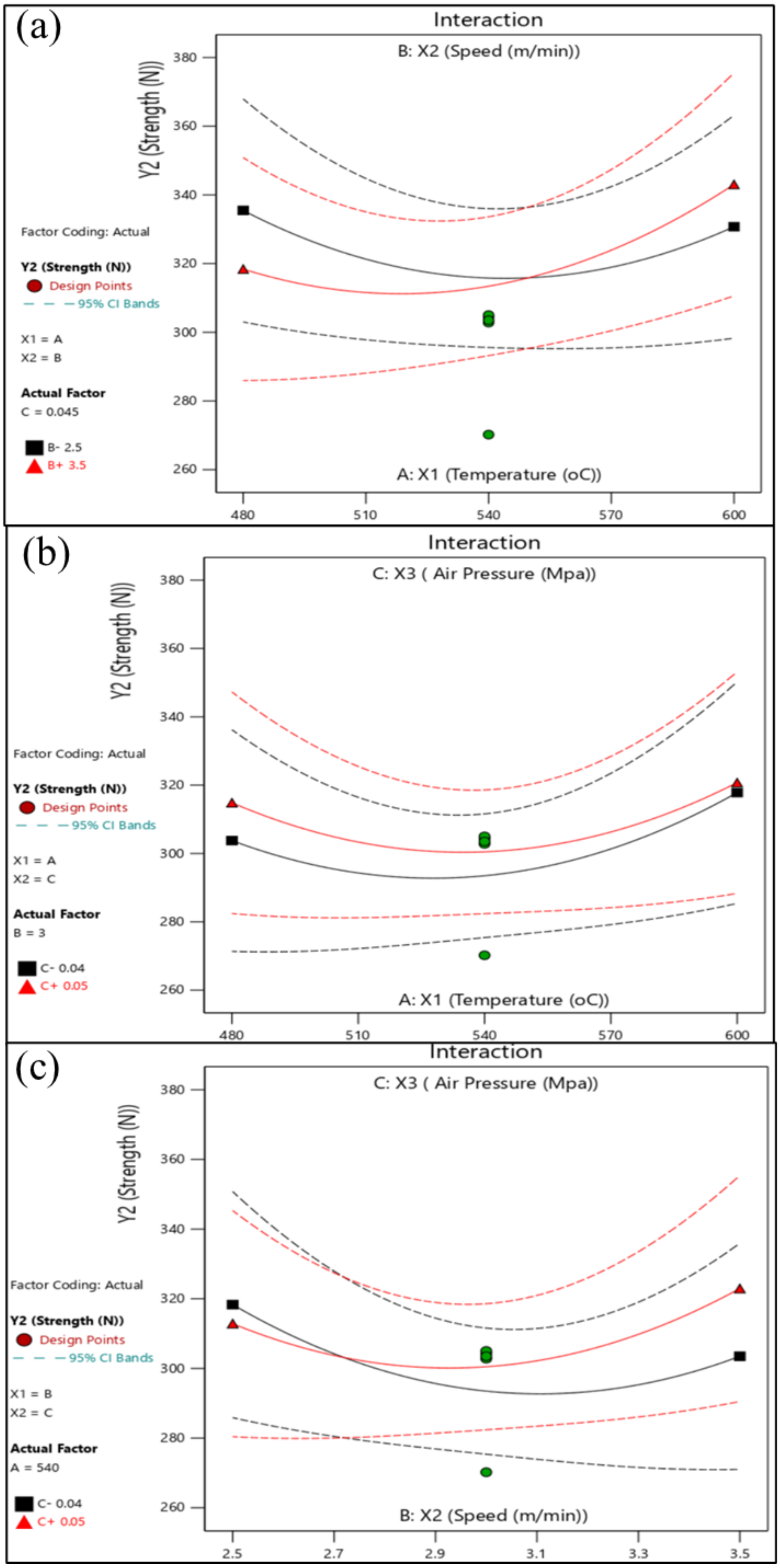

Figure 7. Interaction plot of weld-sealing tensile strength - Y1 [N] at different levels of (a) Temperature - X1 [°C] and Sealing speed – X2 [m/min], Temperature - X1 [°C] and Air pressure – X3 [Mpa], and (c) Sealing speed – X2 [m/min] and Air pressure – X3 [MPa].

This comparative analysis indicates that, from the perspective of optimizing bond strength, the weld-sealing process offers superior process stability and repeatability for large-scale manufacturing compared to the stitch-sealing method.

CONCLUSION

This study provided a systematic comparison between stitch-sealing and ultrasonic weld-sealing techniques applied to three-layer waterproof fabrics commonly used in high- performance apparel. Through the application of Box-Wilson Central Composite Design, the effects of key sealing parameters temperature, sealing speed, and air pressure were evaluated in relation to seam thickness, hydrostatic water resistance, and tensile strength. Ultrasonic weld-sealing consistently produced thinner seams and demonstrated superior water resistance, particularly after repeated laundering, indicating greater long-term waterproof integrity and enhanced wearer comfort. Stitch-sealing outperformed in terms of tensile strength, making it more suitable for applications demanding high mechanical durability. Among all variables, temperature had the most dominant influence on joint performance, followed by sealing speed and air pressure. Significant two-factor interactions, especially between temperature and air pressure, further contributed to joint integrity.

Based on these findings, the application of the jointing methodologies can be optimal due to the aim of the application. For applications where absolute waterproof integrity is the primary objective (medical protective garments or high-performance rainwear), the ultrasonic weld-sealing technique is superior, with the sealing parameter of higher sealing temperatures and moderate speeds to ensure hydrostatic resistance. Conversely, for applications where mechanical durability is paramount (industrial workwear), the stitch-sealing method is recommended, with moderate temperature and higher pressure for sealing parameters.

Future studies should explore the sealing performance across various fabric types and real-world usage conditions. Additionally, integrating simulation-based modeling and techno-economic analysis will enhance process optimization and industrial scalability.

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RESEARCH ON SHAPE MEMORY PROPERTIES OF WOOL YARN AND WOOL KNITTED FABRIC AFTER DESCALING TREATMENT BY ULTRASONIC

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ABSTRACT

Wool is one of the most widely used proteinic material for textile products due to its outstanding desirable properties including excellent thermal insulation, breathability, flame retardancy and comfort properties. Moreover, wool has shape memory capability, so it is good candidate for thermo-regulating clothes. However, wool fibers have a surface structure of overlapping cuticle cells known as scales which significantly affect fiber properties. This paper investigated the appearance, strength, extension and the shape memory behavior of the wool yarn and also the wool rib knitted fabric before and after descaling its cuticle cells using calcium carbonate nano powder (CCNP) powder with the concentration of 2 g/l, 5 g/l, and 10g/l in ultrasonic bath. The shape memory behavior of wool yarn, and rib knitted fabric were examined by changing between the warm-humid (temperature of 28°C; humidity of 90%) and the cold-dry condition (temperature of 8oC; humidity of 20%). The results showed that the increase of CCNP concentration improved the descaling effect, which resulted in less sharp morphology of scales on the wool fiber surface. Wool yarn breaking strength and elongation tended to increase due to the increase of CCNP concentration, while the value of CV (%) decreased. Moreover, the results demonstrated that the length of wool yarn did not change much for both original and treated yarns while descaled fabric possessed higher shape memory ability than untreated fabric, especially in vertical direction with 100 % of the original value, and the horizontal shape memory ability was in range of 93.8 % to 97.6 %.

KEYWORDS

Calcium Carbonate Nano Powder, Knitted Fabric, Shape Memory Ability, Ultrasonic, Wool Fibre.

INTRODUCTION

knitted fabric thermal comfort properties. For more detail, the results showed plain knitted fabric with loose structure and the fabric knitted with single-ply yarn possessed the lowest thermal resistance value and the highest relative water vapor and air permeability value. A. Majumdar [4] investigated the thermal properties of different knitted fabric structures made of blend fibers (100% cotton, 50:50 cotton: bamboo and 100% bamboo) to manufacture three types of knitted structures that were plain, rib and interlock. The paper demonstrated that thermal conductivity of knitted fabrics depending on the material ratio and knitted structure. This value reduced as the proportion of bamboo fiber increases. And the thermal conductivity and thermal resistance values of interlock fabric was the maximum followed by the rib and plain fabrics. Moreover, the water vapor permeability and air permeability of knitted fabrics increases while the bamboo fiber ratio increased.

Shape memory polymers are considered as stimuli-responsive materials which possessed double-shape possibility [5]. This kind of polymer could be returned to desired permanent shape from their shape in a predefined way from temporary shape if they exposed to an appropriate stimulus such as temperature. Application in textile field of shape memory polymer was carried out for recent years [4,6-9] to improve the function of textile products. Shape memory polymer fabrics can flexibly respond to environmental stimuli, make corresponding changes in morphological/fabric structure, presenting outstanding advantages and bringing garment an intelligent thermal-moisture management [6-7]. Judit Gonzalez Bertran et al. had studied shape memory polymers in the form of filament yarns integrated in the fabrics [8]. In the research, the shape memory polyurethanes (SMPUs) woven with reversible thermodynamic properties produced using weft SMPU filament yarns interlaced into polyester (PES) fabrics. The different ratios of weft SMPU filament yarns (PES/SMPU 1:0; 3:1; 1:1; 1: 3, and 0:1) were investigated. Then the fabric thermodynamic properties such as thermal resistance, permeability index, shape memory effect, and mechanical performance were examined and

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compared to the 100% PES reference fabric. The results showed that SMPU-based fabrics developed were classified as highly breathable with water vapor resistance < 6 m^2Pa/W and thermally comfortable (water vapor permeability index < 0.3). The fabrics with weft SMPU filament yarns had temperature stimuli at Tg, while there was not thermodynamic behavior for 100% PES woven fabric. According to the authors the reason was the improvement in thermal protection against increase of ambient temperature, while still maintain good moisture management properties for the ratio PES/SMPU 0:1. Among many shape memory polymers applied on textile industrials, the thermal and hygrothermal capability of wool materials make this kind of textile material considered as natural shape memory polymers. Jinlian Hu et all. [5] have reviewed the fundamental concept of the shape memory polymers and the fundamental aspects of the shape-memory effect to discuss the shape memory behavior of wool materials. Moreover, the authors have investigated the effects of synthetic shape memory polymers on the thermal and hygrothermal of the woven wool fabrics to show the shape memory behavior of treated wool. According to Crawshaw [10], the shape memory behavior of wool materials may be explained by their structure. As known, wool fiber is surrounded by cuticle cells which overlap in one direction and which consist at least of four layers, the epicuticle, the A-layer and the B-layer of the exocuticle, and the endocuticle. The cuticle surrounds a compacted mass of cortical cells of spindle form aligned with the fiber axis and with their fringed ends inter digitating with each other. Both cuticle and cortical cells are separated by the cell membrane complex comprising internal lipids and proteins. This cell membrane complex is the component between the cells that guarantees strong intercellular bonding via proteins generally called desmosomes. The cross-sections of the cortex cells showed the presence of macrofibrils oriented in the direction of the fiber axis and embedded into the intermacrofibrillar matrix which contains cytoplasmic residues and nuclear remnants [10-11]. The scale, which is a big obstacle for wool in a wide range application in textile, can be removed easily by chlorinated chemicals, but it is toxic for users and environment. Some recent researches have investigated new and clean method for wool treatment to reduce the scale and to obtain the suitable characteristic for destinated application [12-15]. Salwa Mowa and Rania El-Newash [12] had improved garment appearance and performance wool fabric by using bio-treatment (two commercial proteases) and chemical wool treatments by softener based on poly amino siloxane (PAS). The authors had studied the physical and mechanical properties of treated wool fabric as descaled surface of bio-treated wool. The research reported that the improve in drapability, drape coefficient, smoothness, yellowness index, and electrical conductivity of the treated wool fabrics. Honglian Cong et al. have studied the influence of the treatment with oxygen low-temperature plasma on the knitted woolen fabrics for sportswear [13]. Nine groups knitted fabric with different technical characteristics were investigated by the changes in the surface morphology and chemical composition of wool fibers before and after plasma treatment. The paper has demonstrated that the anti-felting, bursting strength and moisture absorption of the knitted woolen fabrics were improved. The reason was explicated by scales in the wool fiber surface were seriously etched after oxygen low-temperature plasma treatment. Meanwhile, the fabric showed less time to dry. Wool descaled method using calcium carbonate particles was investigated [14, 15]. Ghasemi et al. [14] studied a descale method using calcium carbonate Nano particles (CCNP) with diameter of 60 nm based on abrasion effect in an ultrasonic bath. In the research woolen samples (fiber and yarn) were sonicated with different concentration (2, 6 and 10g/l) of CCNP. Tensile properties of the yarns, directional friction effect of the fibers and SEM images of the fibers were examined. The authors reported that sonicated CCNP treatment of wool yarn reduced its tenacity, extension and work of rupture and increased its coefficient of friction. The reason was the descaling of wool samples in comparison to the raw wool. The authors also explained that abrasion of thin layer from surface of the fibers changing the sharpness of the scales. The results showed that, scales were observed clearly changing at the CCNP concentration of 6 g/l and they were nearly removed at the concentration of 10g/l. Jinlian Hu et al. [9] reported the advantage of descaled wool yarn in thermo-regulating textile application due to the change in pore size of knitted fabric. The research showed that knitted descaled woolen fabric had actually water-responsive pore ability due to changing stitch shape and can be considered as a seasonal garment material with body sweat acting as a stimulator for thermoregulation. According to the authors, descaled wool knitted fabric can provide a cooling sensation during sweating due to the water-responsive switching (opening/closing) of the knit stitches. The results also demonstrated fabric pore area increased by more than 70% at 100% water absorption, and the air permeability of the knitted descaled woolen fabric increased significantly to 60% with increasing water absorption. However, the detail of wool fiber descaling process was not mentioned.The aim of this research was examination of shape memory characteristics of wool yarn and the wool knitted fabric descaled by the abrasion effect of CCNP in combination with ultrasonic energy.

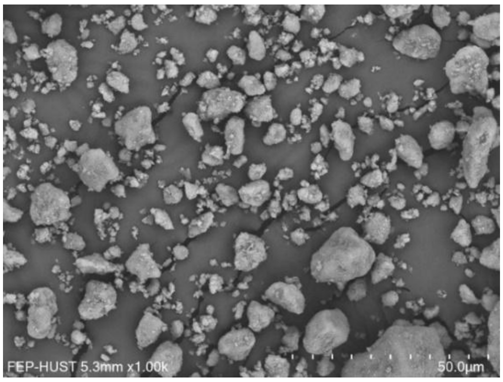

Figure 1: SEM image of calcium carbonate nano powder used to descale wool yarn.

MATERIAL AND METHODS

Materials

Original wool yarn Ne 40/1 without descaling was supplied by Xinao Company (China). Calcium carbonate nano powder (CaCO3 nano powder) (CCNP) with particle size in range of 500 nm ÷ 50 nm, which was used for abrasion in descaling process, was presented by Vietchem Company (Vietnam).

Methods

Shape memory characteristics of wool yarn

Original wool yarn was descaled by $CaCO_3$ nano powder, using an ultrasonic bath of Mujigae at 40^{o}C and 40 Hz for 20 minutes. $CaCO_3$ nano powder was dispersed in distilled water at different concentrations of 2, 5 and 10 (g/l). After the descaling process, the yarn sample was rinsed carefully with distilled water to eliminate the residual powder and then was dried at 45 °C for 1 hour. The morphology of scales on wool yarn surface before and after descaling treatment was observed by a scanning electron microscope of JEOL at the voltage of 5kV. The change in the sharpness of the wool fiber scales was defined by angle formed from two tangent lines to the two sides of the scale. The breaking strength and elongation of wool yarn before and after descaling treatment was determined according to ISO 2062:2009 testing standard. The shape memory behavior of wool yarn was evaluated according to the change in yarn length by altering environment temperature and humidity. For all yarn samples (original yarn and yarn descaled with 2 g/l, 5 g/l and 10 g/l of $CaCO_3$ nano powder), an original length L_o of 50 (mm) was marked on the yarn that was storage at cold-dry chamber (temperature of 8^{o}C; humidity of 20%) for 24 hours. After that, the yarns were moved into a warm-humid chamber (temperature of 28°C; humidity of 90%) for 30 minutes and then the temporary length L_t was measured. The elongation of yarn *E* [%] was determined by equation (1):

$$E\ [\%] = \frac{L_t - L_o}{L_o} \times 100 \qquad (1)$$

From the warm-humid chamber, the yarn was moved back to the cold-dry chamber (temperature of 8 °C; humidity of 20%) and after 30 minutes of storage there, the memorable length L_m was determined. The shrinkage of yarn S (%) was determined by equation (2):

$$S\ [\%] = \frac{L_t - L_m}{L_t} \times 100 \qquad (2)$$

And the shape memory ability of yarn *M* (%) was calculated by the equation (3):

$$M\ [\%] = \frac{L_m}{L_o} \times 100 \qquad (3)$$

Shape memory characteristics of wool knitted fabric

To evaluate the shape memory behavior of wool yarn fabric, rib 1:1 knitted fabric was made from original wool yarn (plied by 4) on a flat knitting machine of Singer (knitting gauge G7). The rib knitted fabric was then treated by descaling process at different concentration of $CaCO_3$ nano powder (2 g/l, 5 g/l and 10 g/l), similarly to the wool yarns treatment.

Shape memory behavior of rib knitted fabric was expressed by the change in wale spacing (for horizontal direction) and course spacing (for vertical direction) measured by ASTM D3887, when the environment switched between cold-dry (temperature of 8°C; humidity of 20 %) and warm-humid (temperature of 28°C; humidity of 90%) condition, as was conducted for wool yarns in the section 2.2.1. The measurement of all samples were taken immediately after the changing cold- warm-humid condition. The horizontal elongation E_h [%], horizontal shrinkage S_h [%] and horizontal shape memory ability M_h [%] were deduced from original wale spacing W_o, temporary wale spacing W_t and memorable wale spacing W_m by equation (4)-(6) below:

$$E_h\ [\%] = \frac{W_t - W_o}{W_o} \times 100 \qquad (4)$$

$$S_h [\%] = \frac{W_t - W_m}{W_t} \times 100 \qquad (5)$$

$$M_h\ [\%] = \frac{W_m}{W_o} \times 100 \qquad (6)$$

The vertical elongation E_v [%], vertical shrinkage S_v [%] and vertical shape memory ability M_v [%] were deduced from original course spacing C_o, temporary course spacing C_t and memorable course spacing C_m by equation (7)-(9) below:

$$E_v\ [\%] = \frac{C_t - C_o}{C_o} \times 100 \qquad (7)$$

$$S_v [\%] = \frac{C_t - C_m}{C_t} \times 100 \qquad (8)$$

$$M_v\ [\%] = \frac{C_m}{C_o} \times 100 \qquad (9)$$

Each dimensional measurement was triplicated to get the average value.

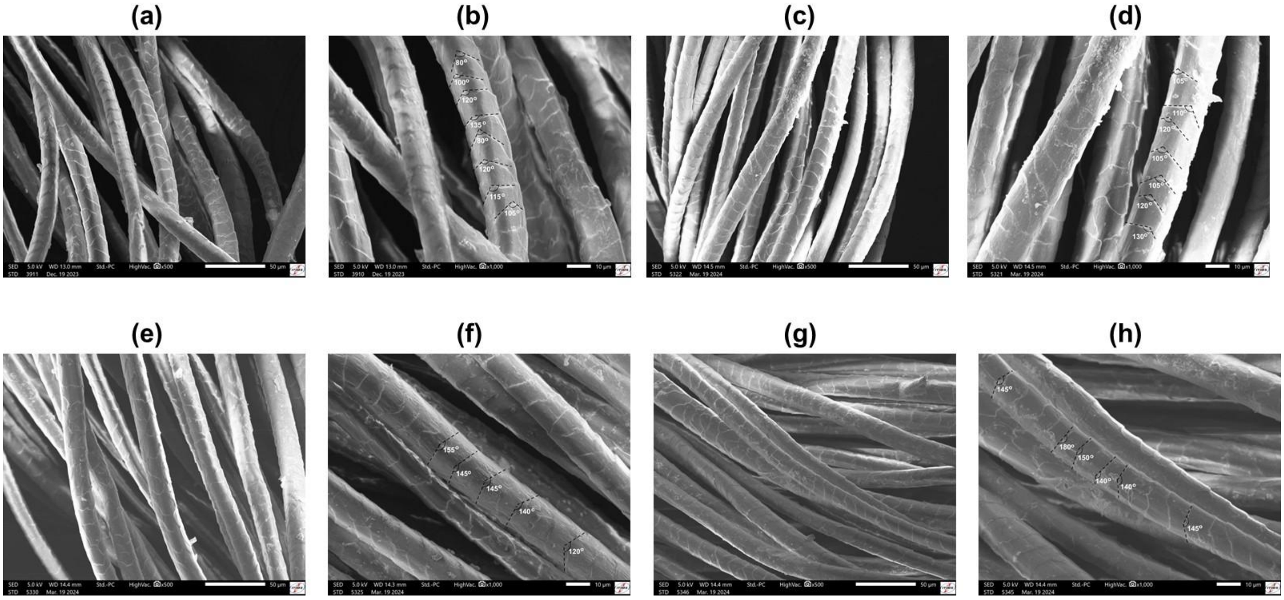

Figure 2. SEM images of wool yarn before descaling treatment (a, b); descaled with nano powder concentration of 2 g/l (c, d); 5 g/l (e, f); 10 g/l (g, h).

RESULTS AND DISCUSSION

Influence of nano powder concentration on wool descaling ability

The effectiveness of the ultrasonic descaling process with calcium carbonate nano powder (CCNP) was evaluated through the change in the sharpness of the wool fiber scales, specifically the angle formed by the two tangent lines to the two sides of the scale. **Chyba! Nenalezen zdroj odkazů.** presented a series of scanning electron microscope (SEM) images that illustrated the impact of calcium carbonate nano powder (CCNP) abrasion on the surface morphology of wool fibers. The images in **Chyba! Nenalezen zdroj odkazů.**(a-b) showed the surface of the initial wool fiber, where the scales were clearly observed with an average angle of approximately 105º.

As the CCNP concentration was increased, the abrasive effect became more pronounced. At a concentration of 2 g/l (**Chyba! Nenalezen zdroj odkazů.**(c-d)), the edges of the scales became less sharp, with the average scale angle increasing to approximately 115º. This tendency became clearer with higher CCNP concentrations, intensifying at 6 g/l with an average angle of 140º (**Chyba! Nenalezen zdroj odkazů.**(e-f)), and finally resulting in a nearly flat surface at 10 g/l with an average angle of 150º (**Chyba! Nenalezen zdroj odkazů.**G-H).

The images demonstrated that the sonification of CCNP caused an abrasive treatment that effectively modified the scales of the fiber. This effect intensified with the increase in CCNP concentration because the edges of the scales were worn and gradually lost their sharpness. The scales' loss of sharpness after descaling changed the mechanical properties of the descaled yarn, such as breaking strength and elongation, and the properties of the fabric knitted from these yarns.

Influence of nano powder concentration on breaking strength and elongation of wool yarn

The Figure 1 showed that the descaling treatment using calcium carbonate nano powder (CCNP) significantly increased the breaking strength of the wool yarn. An increase of approximately 28% was observed, from 133.4 cN for untreated yarn to 170.0 cN for yarn treated with 2 g/l of CCNP. As the CCNP concentration was increased from 2 to 10 g/l, the yarn breaking strength remained relatively stable, ranging from 160 to 170 cN. These findings contrast with a previous study by A. Ghasemi, which reported a decrease in breaking strength with increasing CCNP concentration.

The observed increase in breaking strength may be attributed to an increase in the homogeneity of the fiber's surface due to the abrasive action of the descaling process. This improved homogeneity allows the exerted force to be distributed more evenly along the fiber, thus increasing the yarn's overall breaking strength.

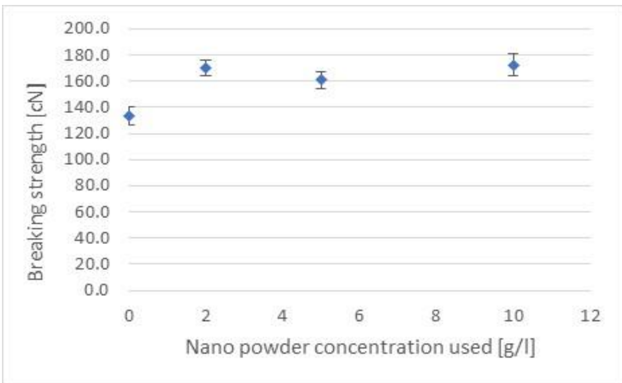

Figure 1: Breaking strength of wool yarn before and after descaling treatment with calcium carbonate nano powder.

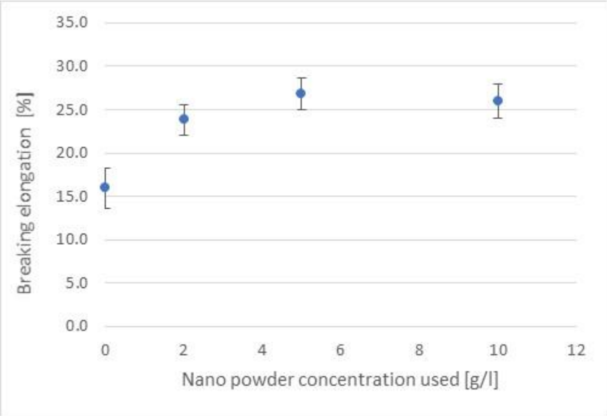

Figure 2: Breaking elongation of wool yarn before and after descaling treatment with calcium carbonate nano powder.

In contrast, in a non-homogeneous structure, force tends to concentrate at the weakest point, leading to premature breakage at a lower value than the system's expected breaking strength.

Furthermore, the decrease in the coefficient of variation (CV) for the breaking strength of the descaled yarn provides additional evidence of this enhanced homogeneity. The CV value for the untreated yarn was 16.3%, whereas it was lower for the treated yarns, ranging from 10% to 15%. This reduced deviation in the breaking strength values for the treated yarn supports the hypothesis that the descaling process leads to a more uniform fiber structure.

Figure 2 illustrates the breaking elongation of wool yarn before and after descaling treatment with calcium carbonate nano powder (CCNP). The data reveals a similar trend to that observed for breaking strength. The descaling treatment resulted in a substantial increase in the yarn's breaking elongation, rising by approximately 1.5 times from 16.0% for the untreated yarn to 23.8% for the yarn treated with 2 g/l of CCNP. When the CCNP concentration was increased from 2 g/l to 10 g/l, the breaking elongation remained relatively stable, falling within the range of 24% to 27%. The increase in breaking elongation is hypothesized to be a result of the abrasive action of the CCNP and ultrasonic treatment, which creates a more homogeneous fiber surface. This improved homogeneity allows for a more even distribution of force during stretching, thereby increasing the time to force distribution and, consequently, the breaking elongation. Further supporting this hypothesis is the significant decrease in the coefficient of variation (CV) for breaking elongation following the treatment. The CV for the untreated yarn was 46.5%, whereas it was markedly lower for the treated yarns, ranging from 22% to 24%. This reduction in the CV confirms that the descaling treatment contributes to a more uniform yarn surface. Overall, the descaling treatment improved both the breaking strength and breaking elongation of the yarn while also making it more uniform. These enhanced properties are a favorable outcome for the application of this treated wool yarn in knitted products, where good strength and elongation are essential for comfort and durability.

Influence of nano powder concentration on shape memory behavior of wool yarn

Table 1 showed the influence of nano powder concentration on the shape memory behavior of wool yarn. The data, which compared the yarn's temporary condition (warm-humid) to its initial cold-dry condition, recorded only a little change in yarn length. A slight increase in shrinkage was observed as the CCNP concentration was increased from 2 g/l (2.2%) to 5 g/l (2.8%) and 10 g/l (3.0%) during the change from the warm-humid to the cold-dry condition. Generally, the shape memory ability (*M*%) for all yarn samples, both untreated and treated, was quite good, ranging from 98.0% to 98.8%.

Influence of nano powder concentration on shape memory behavior of wool knitted fabric

Tables 2 and 3 detailed the shape memory behavior of the wool knitted fabric. The results indicated that the fabric elongated under warm-humid conditions and shrunk under cold-dry conditions in both the horizontal (wale spacing) and vertical (course spacing) directions.

Table 1: Influence of nano powder concentration on the change in yarn length.

Nano powder concentration [g/l]	0	2	5	10
Original length L_o [mm] *Storage in cold-dry condition for 24 hours*	50.0 ± 0.0	50.0 ± 0.0	50.0 ± 0.0	50.0 ± 0.0
Temporary length L_t [mm] *Expose to warm-humid condition for 30 min*	50.5 ± 0.2	50.5 ± 0.0	50.6 ± 0.0	50.5 ± 0.0
Memorable length L_m [mm] *Back to cold-dry condition for 30 min*	49.1 ± 0.1	49.4 ± 0.1	49.2 ± 0.3	49.0 ± 0.2
Elongation *E* [%] by equation (1) *Change from cold-dry (original) to warm-humid (temporary) condition*	1.0 ± 0.4	1.0 ± 0.0	1.2 ± 0.1	1.0 ± 0.0
Shrinkage *S* [%] by equation (2) *Change from warm-humid (temporary) to cold-dry (memorable) condition*	2.8 ± 0.3	2.2 ± 0.1	2.8 ± 0.5	3.0 ± 0.5

Shape memory ability M [%] by equation (3) *Compare the memorable to original dimension*	98.2 ± 0.2	98.8 ± 0.1	98.4 ± 0.5	98.0 ± 0.5

Table 2: Influence of nano powder concentration on the change in wale spacing.

Nano powder concentration [g/l]	0	2	5	10
Original wale spacing W_o [mm] *Storage in cold-dry condition for 24 hours*	3.2 ± 0.1	4.1 ± 0.1	4.1 ± 0.1	4.2 ± 0.1
Temporary wale spacing W_t [mm] *Expose to warm-humid condition for 30 min*	3.4 ± 0.0	4.3 ± 0.1	4.3 ± 0.1	4.4 ± 0.1
Memorable wale spacing W_m [mm] *Back to cold-dry condition for 30 min*	3.0 ± 0.0	3.9 ± 0.1	3.9 ± 0.1	4.1 ± 0.1
Horizontal elongation E_h (%) by equation (4) *Change from cold-dry (original) to warm-humid (temporary) condition*	6.2 ± 1.9	4.9 ± 1.6	4.9 ± 1.5	4.8 ± 0.1
Horizontal shrinkage S_h (%) by equation (5) *Change from warm-humid (temporary) to cold-dry (memorable) condition*	11.8 ± 1.0	9.3 ± 1.4	9.3 ± 0.9	6.8 ± 1.1
Horizontal shape memory ability M_h [%] by equation (6) *Compare the memorable to original dimension*	93.8 ± 1.0	95.1 ± 0.1	95.1 ± 1.6	97.6 ± 1.3

Table 2: Influence of nano powder concentration on the change in course spacing

Nano powder concentration [g/l]	0	2	5	10
Original course spacing C_o [mm] *Storage in cold-dry condition for 24 hours*	1.9 ± 0.0	1.8 ± 0.0	1.8 ± 0.0	1.7 ± 0.0
Temporary course spacing C_t [mm] *Expose to warm-humid condition for 30 min*	1.9 ± 0.0	1.9 ± 0.0	1.9 ± 0.0	1.8 ± 0.0
Memorable course spacing C_m [mm] *Back to cold-dry condition for 30 min*	1.8 ± 0.1	1.8 ± 0.0	1.8 ± 0.0	1.7 ± 0.0
Vertical elongation E_v (%) by equation (7) *Change from cold-dry (original) to warm-humid (temporary) condition*	0.0 ± 1.8	5.6 ± 1.9	5.6 ± 1.9	5.9 ± 2.0
Vertical shrinkage S_v (%) by equation (8) *Change from warm-humid (temporary) to cold-dry (memorable) condition*	5.3 ± 2.0	5.3 ± 1.8	5.3 ± 1.8	5.6 ± 1.9
Vertical shape memory ability M_v [%] by equation (9) *Compare the memorable to original dimension*	94.7 ± 1.9	100.0 ± 0.0	100.0 ± 1.8	100.0 ± 0

It could be seen that the wool knitted fabric elongate by warm-humid condition and shrinkage by cold-dry condition horizontally. The horizontal elongation E_h [%] was higher for un-treated wool knitted fabric (6.2%) and for the descaled fabric samples, the nano powder concentration seemed to not affect the horizontal elongation, the value of E_h [%] was around 4.8 ÷ 4.9 % for the wool knitted fabric descaled with 2 g/l, 5 and 10 g/l of calcium carbonate nano powder. Similarly, in the cold-dry condition, the horizontal shrinkage S_h [%] was also higher for un-treated wool knitted fabric (11.8 %). However, in this state, the nano powder concentration influenced on horizontal shrinkage of descaled wool fabric, the value of S_h (%) was lowest (6.8 %) for the fabric treated with 10 g/l of nano powder. The horizontal shape memory ability [Mh%] was consistently good, ranging from 93.8% to 97.6%, with the best was the fabric treated with 10 g/l of CCNP (97.6 %).

Table 3 showed a similar trend for the vertical direction, though the magnitude of change was much less. The vertical elongation in the warm-humid environment was in the range of 0% to 5.9%, and the vertical shrinkage in the cold-dry environment was in the range of 5.3% to 5.6%. Notably, the descaling treatment had a more obvious effect on the vertical dimension. The untreated fabric did not elongate vertically, while the descaled fabrics elongated by 5.6% to 5.9%. Consequently, the vertical shape memory ability (M_v) of the treated fabric was increased from 94.7% to 100%.

In general, the wool knitted fabrics demonstrated a high degree of dimensional recovery, with horizontal shape memory ability (M_h) ranging from 93.8% to 97.6% and vertical shape memory ability (M_v) ranging from 94.7% to 100%. The shape memory ability of the wool knitted fabric increased in both the horizontal and vertical directions after the descaling treatment. Notably, the vertical shape memory ability reached 100% for all wool knitted fabrics descaled with nano powder at concentrations of 2, 5, and 10 g/l.

It was observed that while the change in environmental conditions had a negligible effect on yarn length (as shown in Table 1), the wale and course spacing of the wool fabric underwent distinct changes. Hu J. et al. [9] reported that immersing wool fibers in water led to a significant decrease in fiber diameter and an increase in length (approximately 16%), with the dimensions almost fully recovering after complete drying. Their study on single-jersey wool fabric showed that after water immersion, both wale and course spacing increased, and the total fabric area expanded by about 20% compared to the dry state, with a near-complete recovery upon drying. In the current study, the change in moisture from a cold-dry to a warm-humid environment may not have been as impactful as direct water immersion, which could explain the insignificant change in yarn length noted in Table 1. Additionally, the chemical descaling agent (chlorination) used by Hu J. et al. [9] likely provided a more potent effect than the mechanical descaling method employed here. Nevertheless, the combination of moisture and temperature changes in this study was sufficient to alter the spatial configuration of the knitted loops, leading to an increase in both wale spacing (Table 2) and course spacing (Table 3). This clearly indicates that the ultrasonic descaling treatment with CCNP made the wool fabric more sensitive to changes in temperature and humidity.

It should be noted that, in comparison to the untreated fabric, the descaled wool knitted fabric exhibited greater sensitivity to environmental temperature and humidity changes in the vertical direction but less in the horizontal direction. The change in the sharpness of the wool fiber scales could be the reason of the tendency. The more concentration of CCNP the more scales' loss of sharpness. As consequence, the friction between the yarn decreased that may help the fabric returned easily to initial dimension. For thermoregulating applications, it is not only important for the fabric to return to its original shape but also for its dimensions to change significantly to accelerate thermoregulation within the microclimate zone, thereby ensuring wearer comfort during environmental transitions. Consequently, a wool rib-knitted fabric with high course density and low wale density should be considered for the design of thermoregulating apparel.

CONCLUSION

The research investigated shape memory behavior of Ne 40/1 wool yarn and wool rib knitted fabric before and after the descaling treatment. A non-toxic descaling treatment was used that based on the abrasion effect of calcium carbonate nano powder (CCNP) in ultrasonic bath.

In the scope of research (Ne 40/1 wool yarn and rib fabric knitted by this wool yarn plied by 4), with three levels of CCNP concentration used that were 2 g/l, 5 g/l and 10g/l, the increase of CCNP concentration helped to strengthen the descaling effect, which resulted in less sharp morphology of scales on the wool fiber surface. Moreover, descaling treatment also helped to increase the breaking strength and elongation of wool yarn while the CV values decreased.

With the stimuli was humidity and temperature of surrounding environment, the length of wool yarn did not change much for both original and treated yarns. However, the wool rib knitted fabric tended to elongate by warm-humid condition and shrinkage by cold-dry condition in both horizontal and vertical direction. Especially, the descaling treatment had obvious effect on the shape memory behavior of wool rib knitted fabric in vertical direction. In the warm-humid condition, untreated fabric did not elongate while descaled fabric elongate vertically with the course spacing increase by 5.6 %, 5.6 % and 5.9 % for the CCNP concentration of 2 g/l, 5 g/l and 10 g/l, respectively.

In this research, generally, the shape memory ability of wool rib knitted fabric was quite good in both directions, up to more than 93%. Descaled fabric exhibited higher shape memory ability than untreated fabric, especially in vertical direction, where the course spacing could return to 100 % of the original value. This presents an opportunity to develop thermo-regulating textile products using wool yarn that has been environmentally descaled with calcium carbonate nano powder and ultrasonic energy.

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EXPLORATION OF LASEM BATIK MOTIFS THROUGH A FITTING TOOL "ARBATULA" APPLICATION BASED ON AUGMENTED REALITY

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ABSTRACT

Lasem batik is one of the prestigious cultural products of Rembang Regency, with distinctive motifs including Sekar Jagad, Latohan, and Watu kricak. Lasem batik faces an existential crisis due to declining interest among the younger generation in preserving it. Various efforts have been made, one of which is by academics who have made Lasem batik a research topic by adapting digital technology as a representation of the lives of the younger generation. The most basic preservation of Lasem batik can begin with the introduction of motifs through fashion, in line with current trends. This became the basis for the author to conduct exploratory research on Lasem batik motifs through the Fitting Tool application based on Augmented Reality technology. Both have been applied in the fashion industry, but have never been applied to Lasem batik motifs. This research uses a Research and Development method that is oriented towards innovative product development and descriptive presentation. Data collection was conducted through observation, interviews, and documentation at the Lasem Batik Cooperative, supported by a literature review of journals and books on Lasem batik. The main result of this research is the "ARBatula" application prototype, which simulates an Augmented Reality-based fitting tool to display Lasem batik motifs on 3D fashion through markers with several features such as gender selection, motif selection, and mode selection. The results of this research are expected to attract the attention of the younger generation in an effort to preserve the existence of Lasem batik through a technological and fashion approach.

KEYWORDS

ARBatula, Augmented Reality, Batik, Fashion, Fitting Tool, Lasem, Motif.

INTRODUCTION

Lasem is an area on the north coast of Rembang Regency where Cheng Ho stopped in 1413 [1], to the point of being called "Little China or Little China" [2][3]. Its strategic geographical position made Lasem a stopping point for visiting ships in the past, which had an impact on the development of batik with its distinctive color composition, motifs, and decorative patterns [4][5]. Lasem batik is known as one of Indonesia's cultural heritages resulting from the acculturation of Javanese, Chinese, Arabic, Indian, and European cultures [6]. China, in particular, has a strong influence on the textile industry in Southeast Asia, especially batik [7]. Lasem batik is not just a textile, but a cultural artifact rich in heritage and identity with high historical, aesthetic, and symbolic value [8]. This was reinforced by UNESCO's designation of batik as a Masterpiece of the Oral and Intangible Heritage of Humanity on October 2, 2009 [9][10][11][12]. Lasem batik is not only a cultural icon, but also a leading commodity [13], which originated from home-based industries, along with other regions such as Solo, Cirebon, Pekalongan, Semarang, Yogyakarta, Pati, Surabaya, and Madura [14][15][16]. To this day, batik making remains the livelihood of Lasem's residents [17][18].

Despite its popularity as a cultural icon, the current condition of Lasem batik is worrying. The Lasem batik industry is experiencing a decline amid the rise of Western fashion trends due to globalization [19], as well as urbanization [20]. The heyday of Lasem batik occurred in 1970 [21], with 144 industries [22], decreased to 120 industries in 2017 [23], and become 78 industries in early 2024 [24]. Public appreciation has also declined, making it difficult to regenerate the younger generation, who prefer to work in modern sectors, both inside and outside Rembang [25]. The problem of transferring batik skills from experienced craftsmen to the younger generation has yet to be solved and continues to this day [26]. The Lasem batik production process takes a long time, while the younger generation prefers instant gratification [27].

Based on the author's observations and interviews on May 31, 2025, at one of the Lasem batik artisan groups, only women aged 50 and above still have the

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motivation to continue batik making. The existence of Lasem batik, which maintains the writing technique to preserve its quality and authenticity [28], also faces the threat of imported batik, which offers lower prices [29]. The decreasing number of batik artisans has resulted in minimal exploration and innovation in existing batik motifs. Motif variations are limited and tend to be repetitive and stagnant, highlighting the need for more innovation in creating new motifs [30]. If old motifs continue to be used without change and the spirit of batik making is not passed on to the younger generation, it will be difficult to regenerate batik artisans and the cultural heritage of Lasem batik could become endangered in the future [31].

The various issues above are interrelated and point to one main issue, namely the challenge of preserving Lasem batik. Preservation and inheritance must be carried out to maintain the values, norms, and cultural products of batik for the younger generation by adapting to the current environment [32], Amidst the rapid globalization and development of digital technology, Lasem batik artisans and business owners are predominantly middle-aged, or what is known as "Generation X." The conventional learning process in the past was oriented towards books, pictures, and writing [33], This is one of the factors limiting this generation's knowledge and skills in utilizing digital technology. Meanwhile, the younger generation, consisting of millennials (Generation Y) and Generation Z, were born and raised in an era of rapid growth in digital media, making them adaptable to technologies based on artificial intelligence, the internet, virtual reality, and wireless technology [34].

Generation X is the group born between 1961 and 1980, millennials were born between 1981 and 1995, and Generation Z were born between 1996 and 2010 [35]. Based on 2020 census data, Indonesia's population composition is dominated by Generation Z and Millennials in first and second place, with 74.49 million and 69.9 million people, respectively [36]. Collaboration between Lasem batik artisans or business owners from Generation X and Millennials and Generation Z can create strong and diverse synergies, with the potential to generate rapid business growth, rich innovation, broader marketing, and sustainability [37].

Digitalization and rapid technological developments have also driven the expansion of batik into a fashion trend related to current clothing styles, as a form of self-expression and representation of national identity [38]. The younger generation (especially Generation Z) is highly curious and inquisitive, and readily follows varied and dynamic fashion trends [39]. Since long ago, batik has also been developed into a fashion product because of its economic value. This is an opportunity to introduce and pass on Lasem batik, which can begin with the exploration and development of old or new motif designs as an attraction for the younger generation [40]. The introduction and exploration of Lasem batik motifs are very important, because the younger generation in Rembang Regency, especially in Lasem, are not yet fully aware of its uniqueness as a heritage with high artistic value [41]. The fashion approach is one method that can be applied in line with the characteristics of the younger generation.

On the other hand, digital technologies such as Augmented Reality, Virtual Reality, Artificial Intelligence, Interactive 3D, Metaverse, and the like, are beginning to be adapted in various fields, including fashion, giving rise to the term digital fashion [42]. Some of these include: Augmented Reality-based virtual fitting to enhance the sneaker shopping experience [43][44], App-based virtual fitting for fashion e-commerce that utilizes data such as weight and height for body measurements [45], NFT-based virtual fashion through websites as a form of digital innovation to reduce clothing waste [46], Augmented Reality-based fashion design interface using deep generative models to visualize clothing designs in real time based on input images [47], Digital fashion based on virtual technology through the principles of holographic photography imaging as a new way to interact with consumers [48], Augmented Reality-based Smart Fitting application for virtual clothing model trials that displays various categories, colors, and sizes [49], as well as clothing designs using a Generative AI approach that offers customization and user engagement for real-time styling [50].

The various examples of digitization above are still general in nature and none of them have used Lasem batik as the subject of experimentation, making them potential subjects for research. Given the urgency of preserving Lasem batik for the younger generation amid the inevitable application of digital technology, and as a first step, the researcher conducted research focusing on the development of "ARBatula" as a prototype application fitting tool to explore Lasem batik motifs based on Augmented Reality technology. "ARBatula" is the name of the application, which is an acronym for "Augmented Reality Batik tulis Lasem" (Lasem Handmade Batik Augmented Reality). It is only fitting that Lasem batik artisans, potential heirs, and other related parties embrace various digital technologies as a new way of interacting with fashion cultural heritage [51].

This is relevant to efforts to digitize cultural heritage from the local to the global level, which take advantage of trends in technology and media

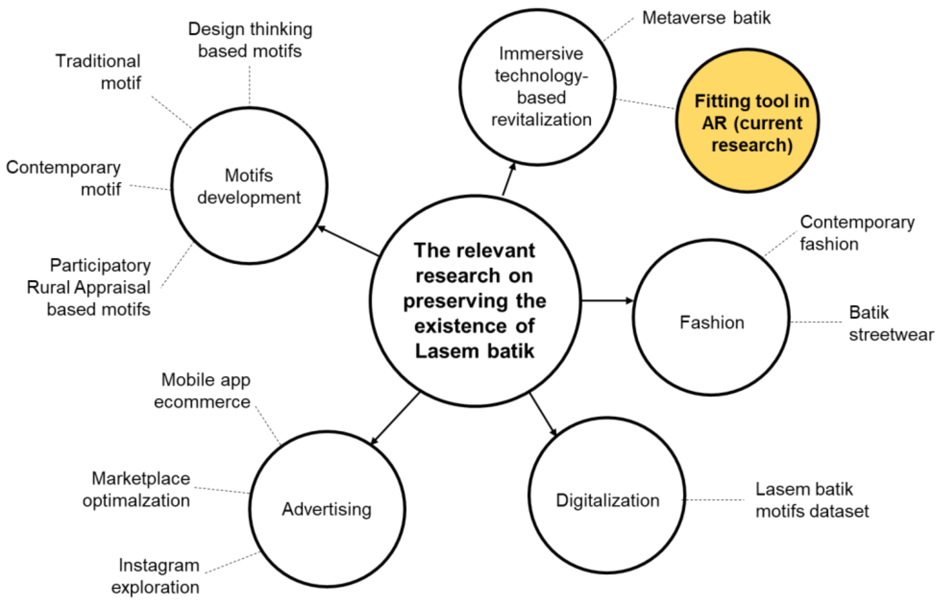

Figure 1. Mapping of research relevant to the topic of Lasem Batik.

development. The preservation of digital-based cultural heritage has become a focus for researchers in order to improve accessibility, create institutional collaboration, and improve restoration and conservation efforts to ensure that cultural and digital integration is maintained [52]. Preservation can be achieved through Digital Twin Technology, which transforms public access to cultural heritage through virtual tourism, Augmented Reality, or immersive digital museums to create interactive cultural heritage experiences and ensure that cultural heritage remains intact for future generations [53]. Augmented Reality, Virtual Reality, and 3D Modeling are the most widely used types of technology for preserving cultural heritage [54].

Some examples include the Olympia archaeological site and the old town of Chania in Greece, which use outdoor augmented reality to bring to life archaeology, artifacts, and ancient monuments that have been destroyed, such as the glass mosque; or Qasr al-Abd Palace in Jordan, which offers smartphone-based augmented reality as a guide for visitors [55]. The preservation of cultural heritage in Indonesia also utilizes similar technologies, some of which include: preserving the traditions of the archipelago (landmarks, traditional foods, dances, and traditional clothing) through interactive cultural experiences packaged in smartphone applications [56], displaying virtual 3D objects of sculptures or statues from East Kalimantan [57], introducing artifacts from the North Sulawesi Provincial Museum in virtual 3D form [58], and reconstructing the story of Borobudur reliefs through a digital book application [59]. The above studies show that the synergy between cultural heritage preservation and digital technology, especially Augmented Reality-based technology, is the right choice from various aspects.

RELEVANT RESEARCH AND NOVELTY

Relevant research on Lasem batik

The critical condition of Lasem batik has become a concern for several parties, ranging from the government, academics, practitioners, to investors [29][60]. Academics, in particular, have conducted various studies in an effort to preserve Lasem batik. Research related to motif development includes: exploration of batik motifs depicting bouquets of kawis fruit [61], designing contemporary batik motifs based on the cultural aesthetics of Lasem batik motifs [62], study on the development of Lasem Rembang hand-drawn batik motif designs [63], interpretation and implementation of Latohan motifs in Lasem batik [64], designing new motifs through Participatory Rural Appraisal (PRA) [31], and exploration of Lasem batik motifs through Design Thinking [30]. Research related to promotion and advertising efforts, including: UI-UX design for Lasem batik e-commerce based on mobile applications [25], Utilizing e-commerce to increase sales of Lasem hand-drawn batik MSMEs [65], as well as the use of Instagram social media as a means of promoting Lasem batik fashion [13]. Research that highlights Lasem batik as fashion includes: the application of Lasem batik in contemporary clothing designs [66], as well as ideas for designing women's streetwear based on acculturation in Lasem batik [67]. Lasem batik became the subject of research from the perspective of digital and virtual technology, namely: the adaptation of the metaverse as a form of readiness for Lasem batik MSMEs [68]. Recently, Lasem batik has also been the subject of research in the development of a compilation dataset of batik fabric product photos, as a visual reference and mapping of Lasem batik based on motif images [69]. These relevant studies can be grouped into five major themes, namely: motif development, advertising, batik fashion, digitization, and revitalization based on immersive technology.

The various relevant studies above have one thing in common, namely adapting digital technology and platforms. In addition, the above description shows that the development of a fitting tool application to explore Lasem batik based on Augmented Reality has never been done by other researchers. This is a novelty or state of the art of research that raises Lasem batik as a topic and object of research. Figure 1 shows a mapping of relevant studies discussing Lasem batik, while also showing the position of this study, which falls into the category of revitalization based on immersive technology. The adaptation of Augmented Reality technology has the potential to explore batik motifs in line with fashion trends that are relevant to the younger generation.

Relevant research on augmented reality batik and similar fashion products

Augmented reality is a variation of a virtual environment in the form of computer-generated digital information, whether it be images, audio, video, or even touch or haptic sensations, overlaying it in the environment in real time [70]. Its use in batik products and various fashion items has been explored by previous researchers. Its implementation has led to the Virtual Try-On system, which is a fashion textile modeling system or technique that allows potential buyers to try on or change various virtual clothes that are attached to a real human body using computer vision techniques, and displayed on a monitor or other device screen. The Virtual Try-On system has several advantages for both potential consumers and fashion producers, including [71]. Creating an inclusive experience in trying on virtual clothing comfortably and conveniently at home, encouraging potential customers to quickly and accurately assess and decide on the suitability of the product they want to buy, and reducing the potential for order cancellations due to incorrect sizes or clothing model choices. Virtual Try-On in the fashion world has become a major focus and has been proven to have significant benefits in overcoming production redundancy issues to reduce clothing waste [72].

The application of Virtual Try-On in the form of Augmented Reality on batik products (slow fashion) has been carried out by two groups of researchers from Indonesia in 2022 and 2025. The first was the initial development of a Virtual Try-On platform for batik fashion based on Mobile Augmented Intelligence Technology, which utilizes three hand gestures: a point gesture to point and activate batik motifs, a grab gesture to select and pull motifs, and a release gesture to remove motifs on 3D fashion models [73]. The result is a prototype application for mapping batik motifs onto 3D fashion models attached to virtual mannequins, rather than onto the user's body in real time. The second is Augmented Reality for Virtual Try-On of East Kalimantan batik through the Tiktok application [74]. The result is a virtual mapping of Lai batik motifs onto a 3D fashion model on the user's body, which can display front, side, and back views according to the orientation of the user's body position. In addition, the visualization and shape of the fashion model are differentiated based on gender.

The use of Virtual Try-On has also expanded to other fashion products, such as glasses, watches, sneakers, and casual clothing (fast fashion). Researchers from Nepal have developed an Augmented Reality-based Virtual Try-On system for glasses on a web platform that utilizes a webcam to display virtual glasses based on the shape and size of the user's face [75]. The principle of operation is to capture the face and follow the position of the user's face (head straight or tilted), similar to how AI cameras work, which are now a default feature on smartphones. Major companies such as Prada and Warby Parker have long been using this technology to promote their eyewear products. Researchers from Stanford University have developed "GlamTry," a virtual try-on for watches, using watch photo data that is extracted and turned into a virtual object that can appear on the user's arm through body detection [76]. As implemented by Rolex and Baume & Mercier to promote their luxury watches, researchers at Hanyang University have developed "ARShoe," a virtual try-on product for sneakers that can display products based on photos of the user's feet [44]. This has also been done by researchers from Beihang University, who have developed Virtual Fitting for sneakers on online shopping applications [43]. Both have similarities in displaying 3D sneaker objects based on the position and direction of the feet and the length of the feet based on camera capture results. A large company that has utilized this technology is Nike.

Virtual Try-On paling banyak diadaptasi untuk produk baju kasual, baik yang bersifat eksperimental maupun implementatif. Peneliti dari Mesir mengembangkan “FITMI”, Virtual Try-On berbasis web untuk merevolusi belanja online secara realistik [77]. Website menyediakan menu untuk mengunggah foto fashion atau memotret langsung dari kamera sebagai input data visual, hal ini juga berlaku untuk foto pose pengguna. Hasilnya yaitu tampilan produk fashion pada foto pengguna yang diunggah sebelumnya. Peneliti dari Saudi Arabia mengembangkan “Smart Fitting”, Virtual Try-On berbasis smartphone yang bisa menampilkan produk fashion beragam bentuk, model dan warna berdasarkan data pindai tubuh pengguna melalui kamera [49]. Metode yang diterapkan dalam “Smart Fitting” yakni overlay virtual fashion model juga diterapkan pada hampir semua Virtual Try-On sejenis yang telah dilakukan peneliti lainnya. Hal ini tidak terlepas dari sifat real-timedan kemudahan akses.

Perusahaan yang telah menerapkan ini dalam produk fashionnya diantaranya: H&M, Zalando, dan Levi Strauss & Co.

Berbagai penelitian relevan di atas menunjukkan bahwa Virtual Try-On menjadi sarana eksplorasi sekaligus promosi beragam produk fashion yang telah mendunia. Meskipun sudah diterapkan untuk fashion batik, namun belum ditemukan penelitian Virtual Try-On produk batik Lasem. Hal ini menjadi temuan baru yang berpotensi dikembangkan sebagai upaya melestarikan batik Lasem melalui eksplorasi motifnya, yang secara tidak langsung juga memperkenalkan dan mempromosikannya dengan pendekatan digital.

RESEARCH METHOD

This study uses a Research and Development (R&D) approach with a structured development model oriented towards innovative product development and descriptive presentation. Descriptive research is research conducted to ensure and enable researchers to describe the characteristics of issues of concern in real conditions and situations. In this context, researchers understand the issues or phenomena surrounding Lasem batik based on facts and field conditions. The purpose of descriptive research is to obtain a complete profile or description of relevant aspects of an interesting phenomenon that occurs in an individual, organization, industry, or other matters.

Data collection was conducted through observation of Lasem Batik MSMEs, interviews with MSME managers, and literature studies on relevant research that highlighted Lasem batik as the object of study. Data from these various methods was taken into consideration in the development of the fitting tool application. The research was conducted in several systematic stages that combined cultural studies, visual exploration, digital technology development, and evaluation. The main objective of this method was to produce a prototype of an interactive fitting tool application that was not only functional, but also had cultural and educational value.

The initial stage began with a preliminary study through observation, interviews, literature studies, and documentation of Lasem batik, including: motifs, dyeing techniques, cultural values, and current challenges. The exploration and documentation of Lasem batik motifs was carried out by taking motif samples, photographing them, and converting them into digital assets for design purposes. The results of the information gathering are taken into consideration for needs analysis, namely identifying the needs, challenges, and opportunities for developing a fitting tool as an effort to explore batik motifs based on Augmented Reality. Device requirements and target audiences need to be presented to ensure relevance to the research focus.

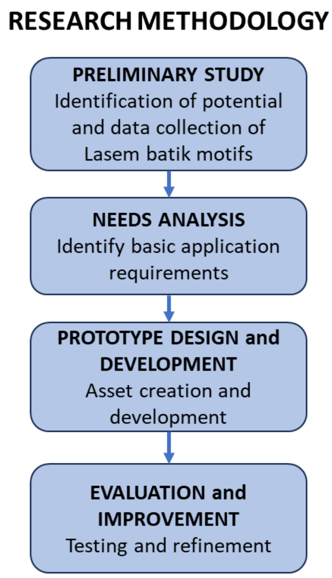

Figure 2. Research method steps.

After determining the requirements analysis and target audience, a flowchart of the fitting tool application prototype was mapped out and the user interface was designed. The prototype was developed using interactive application technology (Blender, Unity, or similar programs), with the integration of batik motif libraries. At this stage, users can select motif designs and see a real-time visualization of the motifs on products such as clothing. After development was complete, an evaluation (testing) of the interface and navigation flow was conducted, which served as the basis for improvements and refinements to the application prototype.

RESULTS AND DISCUSSION

Identification of potential and collection of data on Lasem batik motifs

Lasem batik still has enormous potential to be introduced more widely, especially to the younger generation. The author's observations of one of the Lasem batik cooperatives in May and June 2025 resulted in the documentation of ten motifs, which were selected based on the preferences of batik craftsmen. The documented motifs are four types that are quite popular, namely: Sekar Jagad, Truntum, Gringsing, and Lereng. These motifs are local motifs unique to Lasem that were developed independently by the cooperative, not well-known acculturated motifs such as Burung Hong and Naga. This aims to promote local motifs so that there is no imbalance with acculturated motifs. In addition, it also provides an opportunity for Lasem batik artisans to develop new motifs in an effort to enrich the repertoire of Lasem batik motifs.

Figure 3. Observation of the batik-making process and documentation of ten Lasem batik motifs.

Figure 4. Interview with the head of the Lasem batik cooperative regarding efforts to introduce motifs.

Figure 3 shows the author's observation of artisans making batik motifs on a piece of cloth. Artisans are challenged to create motifs that are different from those they have made before. This is aimed at creating novelty. Artisans may make old motifs, but they must be accompanied by new motifs to produce a variety of motif combinations. The more complex the motif, the more expensive the price. The ten batik motifs above are examples of motifs with two to three images and three color combinations. The fabrics produced by the Lasem batik cooperative consist of three types based on color, namely: two colors, three colors, and more than three colors. Batik with two colors has the lowest price, three colors has a medium price, while more than three colors has the highest price.

The author interviewed Mrs. Sri Wahyuni, chairperson of the Lasem batik cooperative, and learned that batik artisans are on average over 50 years old and still maintain traditional methods in motif creation, sales, and presentation or exhibition of Lasem batik. Catalogs are used to display motif collections, including photos, names, and prices. Artisans do not yet have the knowledge or experience to use digital media or technology in the batik industry. The catalog they have is also the output of the 2016 Work Study Program, which has not been updated to date. This medium is not relevant to the younger generation, who are more familiar with digital media than conventional media. The Lasem batik cooperative must see the opportunities and potential that exist, namely introducing and showcasing the Lasem batik collection through its motifs by utilizing digital technology that is adapted and used in the world of fashion, namely an Augmented Reality-based fitting tool.

Needs analysis

Relevant research shows that there has been no introduction of Lasem batik motifs through Augmented Reality-based fitting tools. On the other hand, the potential and use of Virtual Try-On as an implementation of Augmented Reality is important in various fashion products. As stated by the author at the end of Introduction, one relevant way to preserve Lasem batik for the younger generation is through pattern recognition. This is a major consideration in the development of a fitting tool in the form of Virtual Try-On to explore Lasem batik patterns in 3D fashion models that can be accessed in real-time based on the working principles of Augmented Reality. Of the ten batik motifs observed and documented by the author, there are four Sekar Jagad motifs used for the application content. Sekar Jagad is a motif that is often made by craftsmen, as well as one of the famous and original motifs typical of Lasem. This motif has a main visual in the form of a flower interspersed with kricak (small stone fragments), latoh (seaweed), vines, or tumpal.

The selection of Virtual Try-On as an Augmented Reality-based fitting tool development is relevant to the needs and behavior of consumers from the millennial and Generation Z groups as digital native generations. Consumer behavior is the study of individuals, groups, or organizations related to the consumption of products or services based on important decisions ranging from choosing, buying, using, to evaluating them in order to fulfill needs or desires [78]. The use of Virtual Try-On for consumers has the potential to increase the entertainment value of the online shopping experience and enhance the overall consumer experience [79]. On a broader scale, namely digital marketing campaigns, Augmented Reality integrated with social media applications (such as TikTok) can increase consumer engagement and trust, strengthen brand preference and loyalty, and encourage purchase intent [80][81][82].

The potential and benefits of Virtual Try-On are not only enjoyed by people in Western countries (Europe and America), but also in Eastern countries (Asia). The existence of Virtual Try-On for consumers in India, Bangladesh, and Indonesia provides the same benefits, namely influencing purchasing decisions, creating unforgettable experiences, increasing consumer loyalty to brands, which ultimately helps countries to grow collectively in terms of technology [83][84][85][86]. This means that the use of Virtual Try-On is not only beneficial on a small scale for fashion manufacturers and consumers, but on a larger scale it also demonstrates a country's progress and readiness to adapt to technology.

Prototype design and development

The fitting tool application to be developed is a Virtual Try-On prototype based on Augmented Reality that can be accessed using an Android smartphone. Batik craftsmen are not accustomed to using technology or digital products, so an easily accessible application is needed to avoid difficulties. The application works by adapting the marker-based Augmented Reality model popularized by Siltanen [87][88].

The fitting tool was designed through six stages. First, four of the 10 motifs photographed during observation were selected. The four motifs were Sekar Jagad with different color variations and motif images. The first motif depicted yellow flowers and peacocks with a black background. The second motif depicted white flowers with a red background. The third motif depicted red and white flowers with a black background. The fourth motif depicts bright pink and white flowers with a dark blue background.

The second stage involves digitally mapping the visual data of the motifs using Adobe Photoshop graphics processing software. This software has features and functions for simple 3D object processing. This is also known as texture mapping or warp texturing. Each visual motif data is analyzed based on a specific pattern, cut, and arranged in such a way that it is suitable for texturing on a 3D fashion model. The mapping and texturing results are saved in png format. The challenge in this stage is placing the main flower motif as the foreground on the 3D fashion model.

The third stage is the creation of a 3D fashion template that will be used as an area for digitally mapping batik motifs to visualize virtual fashion shirts. The author chose Blender, a specialized 3D object software, to accommodate this need. The 3D fashion model was created with medium polygons to keep the file size small while maintaining a smooth shape. The 3D fashion object was saved in gITF/GLB format so that it could be accessed for designing an Augmented Reality-based application.

The fourth stage is the design of the user interface and graphics needed in the application. The user interface includes navigation buttons, while the graphics consist of the application's start screen and the User Manual display. These assets were designed using Adobe Illustrator and Photoshop software and saved in png format in accordance with the characteristics of the application's requirements.

The fifth stage is the development of the application using Unity3D multimedia software. The program code is written to synchronize the user interface, texture mapping, and 3D virtual fashion so that it can display a virtual shirt that maps the Lasem batik motif. The final compilation of the application is in .apk format so that it can be installed and accessed using a smartphone.

The sixth stage is the creation of a QR code using AR Code, as a marker to bring up a virtual 3D shirt. Marker-based augmented reality has the technical advantage of being simpler and easier to implement because it only displays virtual objects based on QR codes to avoid the potential distraction of unnecessary objects. Meanwhile, the markerless model does not require a QR code, but it must be supported by sensor features such as GPS and inertia to determine the position and orientation of objects, which results in higher smartphone specifications. In addition, the markerless model is also prone to unnecessary visual distractions that can interfere with the main object.

The application, which has been compiled and installed on a smartphone, is ready to use, but all 3D asset data, textures, and information are accessed offline. For more details, the application design, starting from the name, form, function, and tools used for its development, is presented in Table 1.

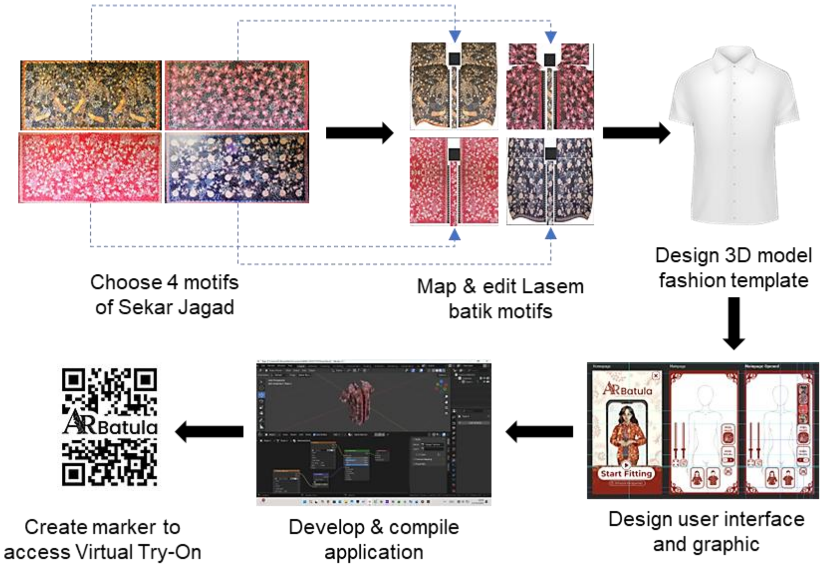

Figure 5. Application design and development process.

Table 1. Application design details and tool requirements.

Criteria	**Specifications / Scope**	**Description**
Developed products	"ARBatula"	"ARBatula" is an acronym for "Augmented Reality Batik tulis Lasem" (Lasem Handmade Batik Augmented Reality). This name was chosen for its ease of pronunciation, and has never been used for any other digital product.
Product form	Fitting tool application in the form of Virtual Try-On based on Augmented Reality	The implementation of Virtual Try-On as an Augmented Reality-based fitting tool application has been widely used, based on relevant research presented previously.
Functional requirements	Pattern recognition and mapping in 3D fashion	Introducing Lasem batik motifs with a digital approach through fashion visualization that is relevant to millennials and Generation Z.
Development device	Notebook	• Prosesor Core i5-10210U • 8GB RAM • Operating system Windows 10 • SSD M2 PCIe 512 GB • GPU Intel Graphic HD & NVIDIA GeForce MX230 2GB • Display 14" FHD (1920x1080)
Development software	Virtual Try-On design	• IDE: Unity 3D LTS 2020.3.x • Compiler: Xcode 13 • AR Library: ARFoundation 4.1 & ARKit 4
Test device platform	Smartphone	• Device: Samsung Galaxy A25 5G • Chipset: Exynos 1280 (5 nm) • OS: Android 14 • CPU: Octa-core (2x2.4 GHz Cortex-A78 & 6x2.0 GHz Cortex-A55) • GPU: Mali-G68 • Main camera: 50 MP, f/1.8, 27mm (wide), 1/2.76", 0.64µm, PDAF, OIS • Sensor: Gyroscope

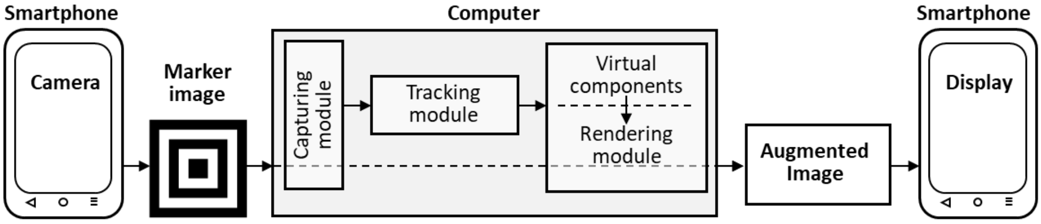

Figure 6. Marker-based Augmented Reality model on "ARBatula".

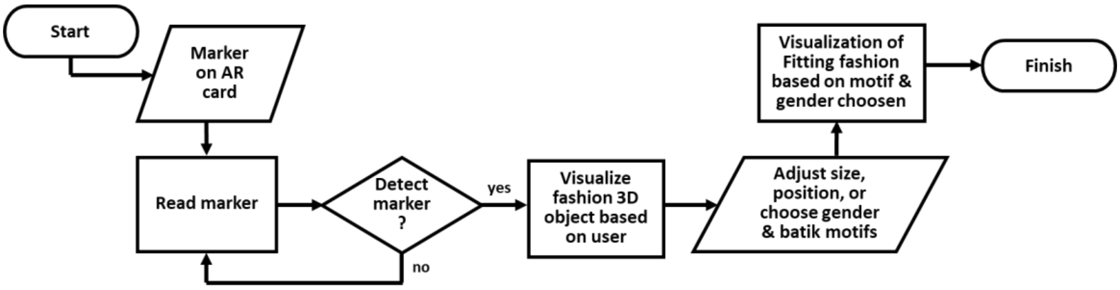

Figure 7. The "ARBatula" workflow.

Figure 8. The initial display of "ARBatula" and the tutorial User Guide.

Figure 9. The process of fitting scan markers on male (left) and female (right) models.

Figure 10. Final appearance of the fitting on men (left) and women (right).

Table 2. Recommendation Matrix for Improvement of the fitting tool application "ARBatula".

No	Problems Found	Impact	Recommendation for Improvement	Priority
1	The camera is a little slow to activate when starting the fitting	Lower user experience, users have to wait	Optimize camera initialization, perform camera module pre-loading	High
2	Objects were slightly blurred in some experiments	Reduced fitting quality, less clear display	Add an auto-focus feature or a notification when an object is not in focus	High
3	Batik motifs appear with a pause (slow loading)	Users feel the application is less responsive when changing motifs	Apply caching or preloading for 10 batik motifs	Medium
4	Adjustment of shirt size lacks precision	Unrealistic fitting results, the size looks unnatural	Improve the scaling algorithm, add more detailed step sliders	High
5	Male/female models are sometimes slow to change	Slightly disrupts the flow of use, but is still usable	Optimize model rendering with image compression or preload	Medium
6	Storage of fitting results is limited to the default format	Users do not have the option of file quality/format as needed	Add format options (PNG/JPEG) and storage resolution	Low

The Virtual Try-On prototype works as shown in Figures 6 and 7. The process begins with input from a smartphone camera pointed at a marker image in the form of a card. The marker contains digital data in the form of a 3D virtual shirt object. When the marker is scanned, the application prototype is computerized from the module. The module is part of the Augmented Reality application with specific functions. The capturing module functions to take, capture, and read digital data of Lasem batik motifs presented in the form of a QR code. The tracking module functions to detect and track markers to determine the position of virtual objects. If the marker is not detected, the process returns to read marker (capturing & tracking module). If the marker is detected, it proceeds to the Rendering module stage. This stage combines the results of the capturing and tracking processes to produce an augmented image that combines the real world with virtual elements, namely a 3D visualization of a Lasem batik-patterned shirt. When the fitting object appears on the screen, users can change the size and position of the object as needed, as well as select the gender and motif variants available. The display results can be viewed on the smartphone screen in camera mode, in the form of a fashion fitting visualization based on the selected pattern and gender. The results can be saved to the smartphone gallery in jpg image format.The "ARBatula" fitting tool application is designed and packaged as simply as possible for easy user access. On the initial screen, there are two menus: "Start Fitting" and "Instructions for Use." Users can simply press the "X" button on the top right of the screen or press the "Back" button on their smartphone to exit the application. If users are accessing the application for the first time, it is highly recommended that they follow the Instructions for Use, which contains four step-by-step tutorial images. The first step is to prepare the QR code by hanging it on a lanyard to display the 3D fashion model on the model. After that, press "Start Fitting" to enter the main camera on mode display. Once in active camera mode, point and adjust the model's body so that the upper half of the body is within the camera frame. Finally, the application is ready to use with buttons that can be accessed as needed. Illustrations of each step can be accessed by swiping the screen to the right or left as desired.

Testing the "ARBatula" Fitting Tool

The "ARBatula" application can be used to display male and female fitting tool models. As explained in the tutorial above, the application can run when the user attaches a marker using a lanyard. The smartphone is pointed at the model and the distance is adjusted so that the body parts appear in a medium shot, as shown in Figure 9. When the marker is read by the camera, the dark red Sekar Jagad patterned 3D fashion model automatically appears as the default, followed by a menu navigation that users can access, including: pattern selection, pattern mapping mode selection, gender, and saving the fitting results.

Users can change the Lasem batik motif using the "Select Motif" button on the right side. There are four Sekar Jagad motifs that can be selected to change the appearance, including the default motif. To change the batik mapping mode, users can access it via the "Select Mode" button. At the bottom, there is a Select Gender button to change the mode from male to female or vice versa. The application is designed so that when the user is male, a shirt model appears. Conversely, if the user is female, a blazer model appears. Finally, there is a Camera button at the bottom right to capture the screen image or save the fitting results to the gallery. The fitting results not only provide a simulation of the fashion design for users when making clothes from Lasem batik fabric, but also serve as a reference for tailors regarding the planning of clothing patterns that match the desired motif shape to highlight the characteristics of the motif.

Evaluation and Improvement

Evaluation of the "ARBatula" Prototype was carried out using the User Acceptance Test (UAT), which is the last testing stage in the software development cycle. In this UAT, end-users or clients test the application to ensure that the application: matches the business needs that have been defined at the beginning (requirements), functions properly in an environment that is close to real conditions, and is ready to use. UAT was conducted involving 5 client representatives and 10 end-users. The test scenarios covered the main features of the application, including: image capture, gender selection (Male/Female), batik motif, fashion mode, size adjustment (slider), and saving fitting results. From the UAT results, most of the evaluations showed results that were in line with expectations. There are some minor findings, such as a camera that is a little slow to activate, batik motifs that are somewhat late to display, or fitting sizes that are less precise in some experiments, but still get the status of "Pass with notes" because it does not hamper the main function of the application. In general, the UAT results from all users stated that the application can be used properly according to the initial needs.

Based on feedback from UAT participants, the application was accepted, with a few minor improvement recommendations as summarized in Table 2. The main recommendations given were to improve the responsiveness of the camera when starting the fitting, speed up the loading time of batik motifs, and add a finer size adjustment feature to make the fitting results look more realistic. Despite these minor notes, the application as a whole is considered feasible to use and ready to enter the wider implementation stage.

Table 3. Virtual Try-On Benchmarking: ARBatula, Batik Kalimantan Timur, Smart Fitting, and Zalando

Comparisons	**ARBatula**	**East Kalimantan Batik**	**Smart Fitting**	**Zalando**	**Conclusion**
Fashion items	Lasem hand-drawn batik	Lai Batik	Casual	Casual	ARBatula highlights batik as a unique local cultural product of Lasem, which has never been researched before in terms of virtual try-on.
Accessories	Smartphone	Smartphone	Smartphone	Smartphone	The four virtual try-ons are accessible via smartphone.
How Augmented Reality works	Scan marker	Scan marker	Markerless	Markerless	ARBatula chose to use markers to reduce visual distractions, without worrying about the appearance of unnecessary virtual objects.
Menu in the application	Star Fitting, Instructions for Use, and Exit (three pages)	Scan Marker in the Tiktok app (multi-page)	Login/Register, Try On Cloth, Send Reviews, View Ratings, View Feedbacks (multi page)	Search/Choose fashion product, Choose Size, Create Own Board, etc (multi page)	ARBatula presents a concise menu of only three pages to make it easier for users and directly leads to the fitting tool without being affiliated with a specific application (stand-alone).
Virtual fashion display models	Attaches to the user's body	Attach to the user's body	Sticks to the user's body	Attach to avatar	Zalando has a different way of displaying virtual fashion, namely through user avatars. This actually has the potential to reduce accuracy.
Variety of virtual fashion items and their advantages	Two clothing models: men's and women's. Options to select gender, batik motif, batik pattern, change size using a slider, and save fitting results	Two clothing models: men's and women's, with one motif. Can display virtual fashion from the front, side, and back	Various models of casual women's clothing. Can choose various colors in virtual fashion	Various men's and women's fashion models. Multiview: can rotate virtual fashion 3600	ARBatula presents variations of men's and women's fashion based on user detection and offers a fairly complex display option that remains easily accessible within a single app view without having to switch screens, namely by selecting four different motifs with two mode variations. This is a unique feature offered and aligns with its purpose for exploring batik motifs.

Benchmarking between "ARBatula" and similar Virtual Try-Ons

The ARBatula application has been designed as an effort to introduce Lasem batik motifs digitally to the younger generation, packaged in a Fitting Tool in the form of a Virtual Try-On based on Augmented Reality. As explained in second chapter, Virtual Try-On is a technology that has been widely adapted for modern fashion products, and has only been applied three times to batik fashion, including the one done by the author. To provide a comprehensive overview, the author compares four Virtual Try-On products, namely: ARBatula, East Kalimantan batik Virtual Try-On (the result of batik clothing research), "Smart Fitting" (the result of casual clothing research), and Zalando (Zalando's professional Virtual Try-On). This comparison was conducted to highlight the differences, advantages, and disadvantages of each Virtual Try-On.

Potential for Sustainability and Cultural Relevance

The design and development of the ARBatula application is the first step in digitizing Lasem batik motifs using a Virtual Try-On approach based on Augmented Reality. Although its current importance lies in its role as an effort to preserve local culture, this application can still be developed further in the future, particularly in the commercialization of products and the ethical consumption of Lasem batik as slow fashion on a wider scale. The results of this research are currently limited to batik artisans, potential consumers within the scope of the batik cooperative, and academics. In the future, it is hoped that there will be further research on the development of the ARBatula application that can be integrated with the marketing or sales system owned by the Lasem Batik Cooperative. This has been done by professional fashion brands, so it may be beneficial to many parties, including batik craftsmen, the government, academics, design or multimedia practitioners, business partners, tailors, fashion designers, and the community or potential consumers. As a result, artisans affiliated with the Lasem batik cooperative can sell both fabric sheets and ready-to-wear garments digitally through Virtual Try-On, and can develop derivatives of Lasem batik fabric, such as scarves, headscarves, wallets, bags, and even shoes.

CONCLUSION

The implementation of the "ARBatula" application prototype as an effort to preserve Lasem batik through the exploration of motifs in the form of Augmented Reality-based fitting tools has been successfully carried out. Although there are shortcomings in the way the application works that need some adjustments based on testing, the output of this research is accepted and in accordance with the problems and objectives set at the beginning of the research. Fashion is the right approach and is suitable for the target audience, namely the Gen Z and millennial groups. Based on the recommendation table above, another main point to note is that the presentation of 3D fashion models tends to be formal and needs to adjust to fashion trends that are relevant to the Gen Z and millennial groups. This prototype can be developed better so that it really becomes a real solution that has an impact on the preservation of Lasem batik, and is expected to have an economic impact on Lasem batik entrepreneurs or craftsmen. Further development of the results of this research can combine the online shopping feature with the fitting tool feature, so that it can be widely applied.

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AIMS AND SCOPES

“Vlakna a Textil” is a peer-reviewed scientific journal serving the fields of fibers, textile structures and fiber-based products including research, production, processing, and applications.

The birth of this journal is connected with three institutions, Research Institute for Man-Made Fibers, Svit (VÚCHV), Research Institute of Chemistry of Textiles (VÚTCH) in Žilina and Department of Fibers and Textiles at the Faculty of Chemical Technology, Slovak Technical University in Bratislava, having a joint intention to provide, utilize and deposit results obtained through the research, development and production activities dealing with the aforementioned scopes. „Vlákna a Textil“ journal has been launched as a consequence of a joing of existing magazines „Chemické vládkna“ (VÚCHV) and „Textil a chémia“ (VÚTCH). Their tradition should provide a good framework for the new journal with the main aim to create a closer link between the basic element of the product - fibre and its fabric - textile.

Since its founding in 1994, the journal introduces new concepts, innovative technologies and better understanding of textile materials (physics and chemistry of fiber forming polymers), processes (technological, chemical and finishing), garment technology and its evaluation (analysis, testing and quality control) including non-traditional applications, such as technical textiles, composites, smart textiles or garment, and nano applications among others. The journal publishes original research papers and reviews. Original papers should present a significant advance in the understanding or application of materials and/or textile structures made of them.

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