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CONTENT

EXPERIMENTATION OF MANGO LEAF EXTRACT (*MANGIFERA INDICA L.*) FOR NATURAL DYE MATERIALS FOR BATIK FABRICS

HAMIDAH, MIDA[1]; ABDULLAH, FARID[1]; SOBANDI, BANDI[1*]; PAWITAN, ZAKIAH[1]; SYA'BANY, DEWI M. [1]; B. SUKARMAN[2]; HASNAWATI, HASNAWATI[2] AND PANDANWANGI, ARIESA[3]

[1] Universitas Pendidikan Indonesia, Jl. Dr. Setiabudi No. 229, Bandung, 40154, Indonesia
[2] Universitas Negeri Makassar, Jl. Dg. Tata Raya, Parangtambung, Makassar, 90224, Indonesia
[3] Universitas Kristen Maranatha, Jl. Surya Sumantri No.65, Bandung, 40164,

ABSTRACT

The use of natural dyes is an effort to reduce the impact of environmental pollution on the production process of batik that uses synthetic colors. This experimental study aims to explore the stages and results of the natural color dyeing of mango leaf extract by using different fixator variables and batting processes. Batik cloth is dyed three times in a solution of mango leaf extract as a dependent variable, then fixed with a lime solution ($Ca(OH)_2$), an alum solution ($Al_2(SO_4)_3K_2SO_424H_2O$) and a ferrous sulfate solution ($FeSO_4.7H_2O$) as an independent variable. Results of the study: 1) The stages of the process of dyeing plain and patterned batik cloth with Mango Gedong Lip Batik leaf extract with a fixator of lime solution, alum, and ferrous sulfate solution are carried out through the following stages: processing the fabric and dye of mango leaf extract, writing motifs with canting caps, dipping batik fabric, fixing batik fabrics with fixators, and releasing wax from batik fabric; 2) The results of dyeing plain and patterned batik cloth with Gedong Gincu Mango leaf extracts with lime solution fixators tend to be brown; alum fixation produces original colors; and ferrous sulfate fixators produce colors that tend to be blackish-green. The dyeing results on plain batik fabrics have stronger color intensity than the dyeing results on patterned batik fabrics because they undergo the nglorod process (separation of batik wax from batik fabric) with hot water added with sodium carbonate auxiliary substances (Na_2CO_3). Research recommends that artisans utilize plant waste to promote the green industry.

KEYWORDS

Experimentation; Mango Leaf Extract; After-Mordanting; Natural Dyes; Batik Fabric; Green Industry.

INTRODUCTION

Pollution of batik wastewater produced by batik companies is one of the serious environmental problems in Indonesia [1] [2]. Water resources are very important for the development of a region because they function as the main source for drinking, agriculture, and industry. Water pollution caused by natural and antopogenic activities is a major threat to global public health [3]. More than 80% of the waste generated by human activities is dumped into rivers and oceans without any treatment, resulting in environmental pollution and more disease. 80% of diseases and 50% of child deaths worldwide are related to poor water quality [4].

Liquid waste from the batik production process usually contains colorful particles and has high levels of dissolved and suspended particles such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD) [5]. To minimize this waste, several wastewater treatment efforts have been made at several batik companies through wastewater treatment plants (WWTPs), including using horizontal subsurface flows that are built into wetlands, using activated sludge processes, and using anaerobic biological treatment followed by wetlands as adsorbent media for batik waste [6] [7]. Efforts to reduce waste have also been carried out through filtration and nanofiltration processes so that they can reduce the concentration and increase the pH of liquid waste before filtration [8-10].

The waste generated by the batik industry consists of gas, liquid, and solid waste. Liquid waste in the batik industry is the most commonly produced waste and has the potential to pollute the environment if not managed properly [11]. One of these environmental problems is the emergence of liquid waste from the batik industry in large quantities [12]. With many batik fabric products made by batik companies, there is

* **Corresponding author:** Sobandi B., e-mail: *bas@upi.edu*
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also a lot of waste generated from the manufacturing process [13].

Switching the use of synthetic dyes to natural dyes is one of the wisest solutions because the good use of natural ingredients will not have a bad impact on the environment [14]. The presence of natural dyes as a substitute material in the batik industry is a preventive solution to avoid environmental problems [15]. Natural dyes are more environmentally friendly and have been proven to produce lower emissions, so the use of natural dyes in the batik production process is highly recommended [16].

One of the ingredients that produces natural dyes for the dyeing process of batik fabrics is mango leaves from the Mango Gedong Gincu variety (*Mangifera indica var. Gedong*). This type of commodity is widely produced in Indramayu, Majalengka, and Cirebon Regencies, West Java Province [17]. The type of gedong variety of mango fruit has a half-mature maturity and a full-ripe maturity called Gedong Gincu Mango, which is one of the export fruit commodities from Indonesia. Gedong Gincu fruit is a type of fruit that is grouped at the level of full-ripeness [18].

Various studies on the use of mango leaves for food sources and medicines have been carried out by many researchers. In the food field, mango leaves are used in the development of active packaging to preserve food through chitosan film that has been enriched with mango leaf extract so as to physically protect food and actively resist oxidation [19] [20]. Furthermore, in the fields of health and pharmacy, it is known that mango leaves, as one of the tropical plants, can be used as the most important medicine in the world because they have effective bioactive substances [21]. Edible mango leaf extract has mangiferin content, which shows antioxidant, antiviral, anticancer, antidiabetic, immunomodulatory, hepatoprotective, and analgesic effects, and high polyphenolic compounds. It has a long history as a medicinal ingredient [22] [23]. Mango leaves with bioactive compounds have medicinal properties that have the potential to improve human health because they have phytochemical evidence as bioactive phenolic and contain flavonoids as anti-inflammatory, antioxidant, antidiabetic, and antitumor [24-27]. Clinically, mangiferin content can be used effectively to treat obesity in humans [28]. Mango leaf extract (*Mangifera indica* L. var. *gadung*) grown in Indonesia contains secondary metabolites that have the potential to be antibacterial agents [29]. Mango leaves also contain bioactive compounds that have the potential to be antibacterial, such as mangiferan, flavanoid, and saponin, which can be used to overcome skin disorders in the form of acne and have the potential to be an anti-Candida albicans formulation and ointment to protect the skin [30] [31].

Studies on mango leaves in agriculture relate to diseases and the maintenance of mango plants. Research related to mango leaf diseases includes the following: AI-based modeling research has been carried out to detect and classify mango leaf diseases effectively and efficiently [32]. The study of early mango leaf disease using feed-forward neural networks and hybrid metaheuristic feature selection showed that the results of the artificial neural network approach were better than the convolutional neural network that could be implemented by farmers using smartphones in the field [33]. Automated approach to diagnosing mango leaf disease using the improved and optimized DenseNet architecture [34]. Meanwhile, in the field of mango plant maintenance, studies have been carried out related to the balance of mineral nutrients in mango leaves during the flowering period, which affects mango trees and fruit production [35].

The results of studies related to the use of mango leaves have also been carried out in the fields of technology and environmental conservation. In the field of electrochemical and surface technology, the use of 1 M HCl solution with mango leaf ethanolic extract is known to inhibit the corrosion of light steel so that the rate of iron anodic solution and the rate of cathodic hydrogen evolution reaction decrease efficiently [36]. Mango leaf studies related to environmental conservation include the following: Juicy mango leaf extract is used as an agent for the biosynthesis of silver nanoparticles (AgNPs). Used catalytic and mercury detectors for wastewater management systems and activated carbon synthesis mango leaves are used for ultra-sensitive detection of toxic heavy metal ions and energy storage applications [37] [38]. Mango leaves as biochar derived from agricultural waste biomass are a cheap raw material for the complete removal of CV dyes in the concentration of toxic cationic textile dyes [39].

Various studies on mango leaves from various disciplines, such as those described above, have been carried out by many previous researchers, such as in the fields of food and medicine, agriculture, and plant maintenance, as well as in the fields of technology and environmental conservation. However, the author has not found many studies that specifically discuss the benefits of mango leaves, especially the Gedong Gincu Mango Leaf variety, as a natural dye for environmentally friendly batik fabric warming materials. For this vacancy, the researcher has conducted an exploration and will explain the benefits of leaf waste as one of the natural dyes in batik fabric that can be developed by batik craftsmen and entrepreneurs in Indonesia.

The objectives of writing the paper are: 1) to analyze the stages of the dyeing process of plain and patterned batik cloth with Batik Gedong Mango leaf extract with a fixator of lime solution, alum solution, and ferrous sulfate solution; 2) to find the difference between the dyeing results of batik cloth and the dyeing results on plain and patterned fabrics with

Gedong Gincu Mango leaf extract material with fixators of lime solution, alum solution, and ferrous sulfate solution. Research encourages batik artisans to utilize plant waste, especially mango leaves, as an alternative to environmentally friendly natural dyes. Further research is needed related to the difference in color intensity in plain fabrics and patterned fabrics with the process of bleaching (removing wax from batik fabrics).

MATERIALS AND METHODS

Materials and tools

The materials used in this study are natural leaf materials, primisima batik fabric, and several fixator materials. The natural dye used is the Mango Gedong Gincu leaves (Fig. 1). This mango variety grows a lot in Majalengka Regency and Indramayu Regency, West Java Province, Indonesia, as a superior product of the region.

In addition to using natural dyes from Gedong Gincu Mango leaves, in this experiment, the researcher used a "mori primissima" type of fabric medium whose specifications are presented in Table 1. This fabric is used as a medium to draw or write batik motifs by scratching or applying a barrier to the color of hot wax with canting tulis or a canting cap.

Table 1 above has informed the results of the Primisima fabric test with detailed data, as follows: a) fabric weight: 111.70 g/m^2; b) fabric thickness: 0.24 mm; c) fabric composition consists of: 80% cotton and 19.77% rayon; and d) known fabric construction: warp density: 42.52/cm; welf density: 30.91/cm; warp thread number: 14.37 tex; weft thread number: 13.75 tex; and face webbing: plain.

Some of the fixator materials used include: lime solution ($Ca(OH)_2$), aluminum solution ($Al_2(SO_4)_3K_2SO_424H_2O$), and ferrous sulfate solution ($FeSO_4.7H_2O$), which works for directors and color amplifiers or lockouts. In addition to the main ingredient, there are also auxiliary ingredients such as Turkey Red Oil (TRO) for the process of soaking the fabric before dyeing it in natural dyes so that the color absorbs optimally and soda ash/Sodium Carbonate (Na_2CO_3), which is used for the ngelorod process (the release of batik wax from batik fabric).

Figure 1. Natural color material of Mango Gedong Gincu leaves.

Research methodology

This study uses an experimental method to explore the natural color of Gedong Gincu Mango leaves. The variables in the study are differences in fixators and differences in the dyeing process of batik fabrics (some are dyed on plain batik cloth and some are dyed on fabrics that are already patterned with batik) using canting stamps.

The material exploration stage was carried out in Rajagaluh Lor Village, Rajagaluh District, Majalengka Regency. For the process of stamping batik cloth with the Mangga Gedong Gincu batik motif as a typical Majalengka batik motif, the researcher collaborated at the HertyElit Batik Gallery. The material of the solution of Gedong Gincu Mango leaf extract was the dependent variable, while the fixator was in the form of lime solution, alum solution, and ferrous sulfate solution as independent variables.

Working procedure

The steps taken by the researcher in this study are: a) cotton fabric processing (soaking cotton fabric with TRO solution); b) processing of natural dyes from Gedong Gincu Mango leaves by mashing them using a blender; c) boiling of natural ingredients of Mango Gedang Gincu leaves into an extract solution; d) the process of dyeing batik cloth with a solution of mango leaf extract of gedong lipc as much as 3 times each dyeing process; e) the color fixation process with lime solution, alum solution, ferrous sulfate solution; and e) the wax removal process using hot water added to a solution of soda ash/Sodium Carbonate. The steps of the work procedure are visualized in Fig. 2.

Table 1. Mori fabric test results.

No.	Tests		
	Type	Method	Results
1	Fabric weight [g/m^2]	SNI ISO 3801:2010	111.70
2	Fabric thickness [mm]	SNI ISO 5084:2010	0.24
3	Fabric composition (%)	SNI 08-0265-89	Cotton 80.23% Rayon 19.77%
4	Construction: - Warp density [1/cm] - Weft density [1/cm] - Warp thread number [tex] - Weft thread number [tex] - Face Webbing	 SNI ISO 7211-2:2010 SNI ISO 7211-5:2010 SNI ISO 7211-1:2010	 42.52 30.91 14.37 13.75 Plain

Source: Test results at the Bandung Textile Center [46].

Table 2. Results of dyeing mango leaf color extract on batik fabric

No	Dyeing Process	Types of Fixatives		
		Lime Solution ($Ca(OH)_2$)	**Alum Solution** ($Al_2(SO_4)_3K_2SO_424H_2O$)	**Ferrous sulfate Solution** ($FeSO_4.7H_2O$)
1.	Dyeing on fabrics without batik motifs (plain fabrics)			
2.	Dyeing on fabric using batik motifs (patterned fabrics)			

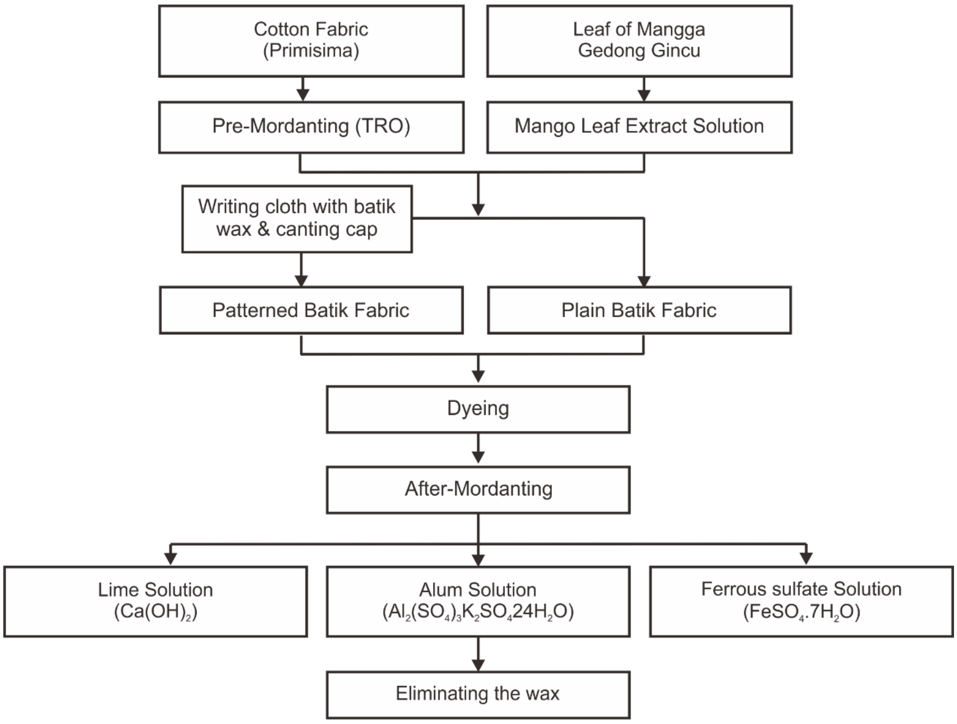

Figure 2. Experimental steps in research (adapted and developed from Sobandi et al., 2021) [40].

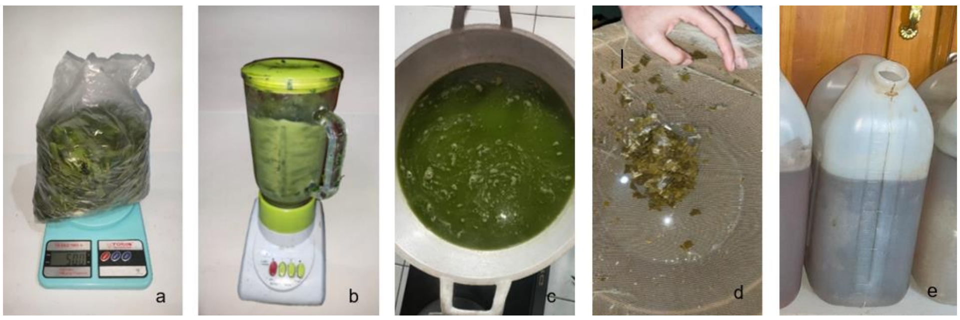

Figure 3. Mango leaf extract processing process.

Based on the experimental steps in the research presented in Fig. 2 above, it will be explained in detail as follows:

Preparation stage

In the preparation stage, there are two main steps consisting of fabric processing and natural dye processing: In the first step, the fabric to be used is first soaked with TRO solution (2 g/L) by soaking in cold techniques for 24 hours. After that, the Primisima batik cloth is rinsed with water and then dried. This stage aims to make the absorbency of the fabric to natural dyes more optimal. Furthermore, the curled batik fabric can be processed for stamping.

The second step is to make natural dyes from Gedong lip mango leaves. This natural color processing process is carried out through an extraction technique by boiling raw materials in a ratio of 1:10 (in this study using a ratio of mango leaf material of 0.5 kg to 5 liters of water).

Visually, Fig. 3 describes the stages of processing the natural color of mango leaves, with the following stages: a) preparing Gedong Gincu Mango leaves and weighing them as needed; b) smoothing the ingredients by cutting and blending so that the size becomes smaller; c) boiling the mango leaves until the amount of boiling water shrinks to half of the initial amount of water used; d) filtering the boiled liquid to separate the color extract from the rest of the pulp; d) storing the results of the extraction solution; this solution is ready to be used for the batik fabric dyeing process.

The process of writing fabric with canting stamp

The process of writing or applying batik motifs to batik fabric uses canting stamps. This process is carried out before the process of dyeing batik fabrics. In this study, the process of writing cloth was carried out on some batik fabrics (some other fabrics were not written with batik motifs, only plain fabric).

Dyeing process

The batik cloth that has been prepared in the previous process is then dipped in a solution of color extract from the leaves of Mango Gedong Gincu. The dyeing process is carried out gradually and repeatedly as needed, with the following stages: a) dip the batik cloth in a solution of mango leaf dye extract; b) lift the fabric from the dyeing solution, then drain the fabric until dry; c) the stages of the dyeing process are repeated again, like these stages. The dyeing process in this study was carried out three times with a predetermined dyeing time duration (about 30 minutes).

Fixation process

The fixation technique used in this study is final mordan fixation. This activity serves to determine the direction of the color and lock the color absorbed by the batik fabric so that it does not fade. In this study, the materials used were lime solution ($Ca(OH)_2$), alum solution ($Al_2(SO_4)_3K_2SO_424H_2O$), and ferrous sulfate solution ($FeSO_4$.7H2O) with a composition of 50 g/L of water each.

Wax removal process

The removal of the wax from the batik cloth is the final step of the batik process. The cloth that has been written or marked with batik wax using a canting stamp and dyed with natural dyes is boiled in boiling hot water on the stove at a temperature of 100 °C. The process of boiling batik fabric uses an auxiliary agent, sodium carbonate (Na_2CO_3) (5 g/L). This auxiliary substance serves to facilitate the removal of night candles from batik fabrics. After the process of ngloroding the batik cloth, clean the batik cloth with clean water and then dry it.

RESULTS AND DISCUSSION

Research results

The experimental process of dyeing batik fabrics has been carried out with two different treatments. The first process is carried out by dyeing on plain batik fabric, while the second process is carried out on batik fabric that already has batik motifs (see Table 2). Before the batik dyeing process in the second treatment, first the batik cloth that is still plain is written with a batik motif using a canting stamp with a Mangga Gedong Gincu motif (Fig. 4). The selection of canting caps with this motif aims to introduce and strengthen the identity of the typical batik motif that develops in Majalengka Regency, the district that produces the most Mangga Gedong Gincu.

The process of dyeing batik cloth using natural dyes made from Gedong Gincu Mango leaf extract. The results of dyeing plain fabrics and batik fabrics with the Mangga Gedong Gincu motif turned out to have different colors.

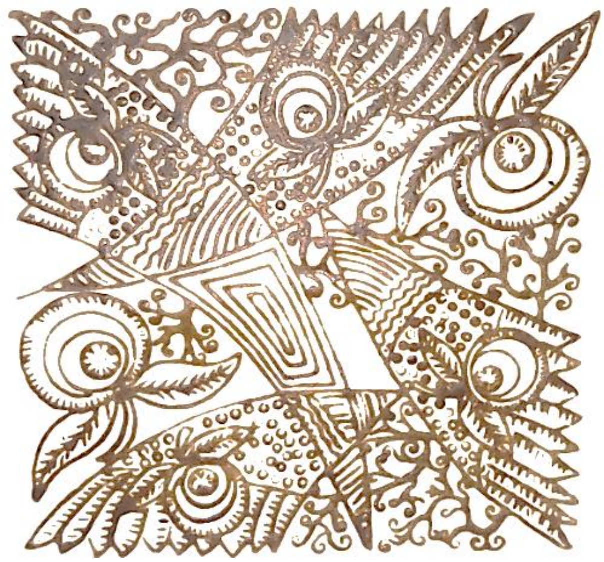

Figure 4. The result of the impression of the motif on the batik fabric using a canting stamp.

Table 2 above visualizes the comparison of the results of dyeing batik cloth with Gedong Gincu Mango leaf extract using different fixator materials, the dyeing results using lime solution fixators tend to be brown, the alum fixation produces a bright original color, and the ferrous sulfate fixator produces a color that tends to be blackish-green. Likewise, the results of dyeing colors on plain fabrics tend to have stronger color intensity than on batik fabrics that have been given batik motifs.

Based on the results of the color fastness to washing 40 °C and color fastness to rays: bright day, it is known that there are differences as presented in Table 3 below.

Table 3 displays the results of the test on the color fastness of Gedong Gincu Mango leaf extract on two types of fabrics, namely plain fabric and patterned fabric. This test was carried out on fabrics that were fixed with three different solutions, namely: lime solution ($Ca(OH)_2$), alum solution ($Al_2(SO_4)_3K_2SO_424H_2O$), and ferrous sulfate solution ($FeSO_4.7H_2O$). The test involved two main aspects: color fastness to washing at 40 °C and color fastness to bright light. The results of the color fastness test against washing at 40°C showed that plain fabrics generally showed a bad category (2–3) in fabrics that were fixated with lime solution and alum solution and a fairly good category (3). Meanwhile, the results of color fastness to washing at a temperature of 40 °C for patterned fabrics were found to be fabrics that were fixed with lime solution in the category of sufficient (3), fabrics that were fixed with alum solution in the category of good (3–4), and fabrics that were fixed with a solution of ferrous sulfate in the category of not good (2–3). Furthermore, the color staining value using fabric type medium (acetate, cotton, polyamide, polyester, acrylate, wool) showed that mango leaf extract provided a good category of color staining value (4–5), except for the cotton medium of patterned batik fabric dyed with lime solution and alum solution, which was better than plain fabric dyed with the same two solutions. Color-fading resistance to bright light during the day, light fastness values are known to have the same and different test results.

Table 3. Results of color testing of Gedong Gincu Mango leaf extraction on plain and patterned fabrics.

No.	Test Type	Test Results of Gedong Gincu Mango Leaf Extract						Test Method
		Plain Fabric			Patterned Fabric			
		Lime Solution ($Ca(OH)_2$)	**Alum Solution** ($Al_2(SO_4)_3K_2SO_424H_2O$)	**Ferrous sulfate Solution** ($FeSO_4.7H_2O$)	**Lime Solution** ($Ca(OH)_2$)	**Alum Solution** ($Al_2(SO_4)_3K_2SO_424H_2O$)	**Ferrous sulfate Solution** ($FeSO_4.7H_2O$)	
1.	Washing Resistance 40 ℃ Color Change Value Color Blemishes Value	2 - 3	2 – 3	3	3	3 – 4	2 - 3	SNI ISO 105-C06:2010 SNI ISO 105-A02:2010 SNI ISO 105-A03:2010
	- Acetate	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	
	- Cotton	4	3 – 4	3 – 4	4 – 5	4	3 – 4	
	- Polyamide	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	
	- Polyester	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	
	- Acrylate	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	
	- Wool	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	
2.	Color Resistance to Light: Day Light Ray - Resistant Value	3	4	3 – 4	3 – 4	3	3 – 4	SNI ISO 105 - B01:2010 SNI ISO 105 - A02:2010

Table 4. Comparison of the results of mango seed and mango leaf extraction dyeing on patterned fabrics.

No.	Test Type	Results of Natural Dyeing Test on Patterned Batik Fabric					Test Method
		Mango Seeds		Mango Leaf			
		Lime Solution ($Ca(OH)_2$)	**Ferrous sulfate Solution** ($FeSO_47H_2O$)	**Alum Solution** ($Al_2(SO_4)_3K_2SO_424H_2O$)	**Lime Solution** ($Ca(OH)_2$)	**Ferrous sulfate Solution** ($FeSO_47H_2O$)	
1.	Washing Resistance 40 ℃ Color Change Value Color Blemishes Value	4	4	3 – 4	3	2 - 3	SNI ISO 105-C06:2010 SNI ISO 105-A02:2010 SNI ISO 105-A03:2010
	- Acetate	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	
	- Cotton	4	3 – 4	4	4 – 5	3 – 4	
	- Polyamide	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	
	- Polyester	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	
	- Acrylate	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	
	- Wool	4 – 5	4 – 5	4 – 5	4 – 5	4 – 5	
2.	Color Resistance to Light: Day Light Ray - Resistant Value	3	3	3	3 – 4	3 – 4	SNI ISO 105-B01:2010 SNI ISO 105-B02:2010

Description: 1 = bad, 1-2 = bad, 2 = poor, 2-3 = not good, 3 = enough, good enough, 4 = good, 4-5 = good, 5 = very good

Patterned batik fabrics dyed with lime solution are known to be quite good (3–4) compared to plain fabrics; patterned batik fabrics dyed with alum are quite categorized (3) lower than plain fabrics (4); and there is a fairly good category similarity between fabrics dyed with ferrous sulfate solution on plain fabrics and patterned batik fabrics (3–4).

To see the contribution and significance of the research in this manuscript, it will be compared between the previous research (dyeing with mango seeds) and the results of the current mango leaf dyeing in terms of washing fastness and light fastness tests on patterned batik fabrics. The comparative data is presented in Table 4.

Table 4 above compares the results of color fastness testing on patterned fabrics dyed using extracts from mango seeds (previous research, which did not use alum solution fixators) [46] and Gedong Gincu Mango leaves. Testing was carried out using three types of solutions: lime solution ($Ca(OH)_2$), alum solution ($Al_2(SO_4)_3K_2SO_424H_2O$), and ferrous sulfate solution ($FeSO_4.7H_2O$). The test involved two main aspects: color fastness to washing at 40 °C and color fastness to bright light. The results of the color fastness test to washing at 40 °C in the color change value section showed that mango seed extract on patterned fabric had a color change value in category 4 with lime and ferrous sulfate solution fixators, compared to mango leaf extract, which only reached a value of 3 with lime solution fixator and a value of 2–3 with ferrous sulfate solution fixator. This shows that mango seed extract provides better color fastness for washing compared to mango leaf extract. Meanwhile, it was confirmed that the color staining value for all types of fabric mediums (acetate, cotton, polyamide, polyester, acrylate, and wool) was similar to the good category (4–5); even in the cotton medium, mango leaf extract with the lime solution fixator was better than mango seed extract.

Furthermore, from the results of the color fastness test to bright light during the day, the light fastness value was known: mango seed extract showed a fairly good light fastness value, namely 3 at the lime and ferrous sulfate.

Discussion

In general, the stages of dyeing batik cloth with natural dyes of Gedong Gincu Mango leaf extract are carried out in stages starting from: processing cotton fabrics, processing natural dyes from Gedong Gincu Mango leaves, making natural color extracts of Gedang Gincu Mango leaves, dyeing batik cloth with a solution of Gedong Gincu Mango leaf extract as many as 3 times each of the dyeing process, the color fixation process, and the wax removal process from the batik fabric (see Fig. 2). To produce natural color extracts from mango leaves, it is carried out through stages: preparing Gedong Gincu Mango leaf ingredients and weighing, smoothing the ingredients, making mango leaf extract, filtering the boiled liquid to separate the color extract from the rest of the pulp, and storing the results of the extraction solution (see Fig. 3).

Efforts to use and develop natural dyes derived from Gedong Gincu Mango leaves are considered appropriate to apply the 3R (Reduce, Reuse, Recycle) principle. Reduce means reducing the production of mango leaf waste that is widely produced by mango plants; reuse is meant to reuse mango leaf materials after their initial use; and recycle is intended as the process of converting waste materials into natural dyes to help reduce the use of natural resources and reduce negative impacts on the environment. This principle, in addition to aiming to reduce the amount of waste produced, also aims to reuse recyclable waste. In addition, mango leaves contain a lot of chlorophyll, which can produce color pigments for textiles that give them greenish-yellowish pigments with wavelengths of 540 nm and 640 nm [41].

The results of dyeing batik fabrics with different fixators and batik technique treatments have produced different color intensities. The data in Table 2 above informs us that the results of dyeing fabrics using a lime solution fixator ($Ca(OH)_2$) tend to produce colors that tend to lead to brownishness, the results of dyeing mango leaf natural dyes using an alum solution fixator ($Al_2(SO_4)_3K_2SO_424H_2O$) produce a more natural color that tends to be lighter in color, and the results of dye dyeing using a ferrous sulfate solution fixator ($FeSO_4.7H_2O$) tend to produce a darker fabric color, namely blackish-green color. The same thing was also found in the results of dyeing experiments using Gedong lip mango leaf extract on plain batik fabrics and motif fabrics that went through the process of batting with canting stamps. The color intensity of the dyeing results on plain fabrics (without batik motifs) appeared to be stronger than the dyeing results on patterned batik fabrics that underwent the nglorod process (the release of wax from the batik fabric), but the color intensity decreased. This condition is possible because it is boiled in hot water with the addition of soda ash / sodium carbonate (Na_2CO_3).

There was a color difference between the results of dyeing mango leaf extract on plain and patterned batik fabrics that were fixated with lime solution, alum solution, and ferrous sulfate solution. Through the color fastness test to washing at 40°C, the color change value showed that the results of dyeing mango leaf extract on patterned batik fabric fixed with lime and alum solution were better than plain fabrics. Different conditions were found in fabrics fixed with ferrous sulfate solution; the level of color fading resistance to washing at 40 °C was higher in plain fabrics than in patterned batik fabrics. Meanwhile, the color fastness test was conducted against bright light during the day, and the light fastness value is known to have various results. Patterned batik fabrics dyed with lime solution are known to be quite good compared to plain fabrics; patterned batik fabrics dyed with alum solution are in the sufficient category, lower than plain fabrics. The results of the fastness test to bright light in the day related to the light fastness value are known to have quite good category similarities between fabrics dyed with ferrous sulfate solution on plain fabrics and patterned batik fabrics (See Table 3). The findings from the results of this study need to be further studied.

The findings of the above study are in line with the results of previous studies, which stated that the potential of mangiferin yellow dye from mango leaves with the post-mordanting technique was confirmed as the best mordanting technique with the development of beautiful yellow to brown color gradation varieties with excellent fastness properties [42]. The dye extract material of Nigerian mango leaves (MLs) obtained from microwave extraction techniques (obtained through microwave-assisted and aqueous extraction techniques) confirms that mango leaf extract can be used to dye silk fabrics with various shades of yellow to brown as an abundant dyeing material, does not contain toxic materials, and can be sustainably used to dye silk fabrics on an industrial scale [43].

In general, the plant parts used as natural dyes for batik consist of tubers, roots, stems, leaves, and fruit peels [44]. The advantages of natural dyes include being cheaper, environmentally friendly, and producing distinctive colors [45]. Efforts to use natural colors for the dyeing process of batik fabric are an action that is not only healthy but also has added value in terms of economy, empowerment, and intergenerational inheritance efforts [46].

Mango is a fruit plant that grows widely and can be consumed. The quantity and quality of production are of utmost importance to meet the needs of the population [47]. The popularity of mangoes continues to increase due to their high nutritional and pharmaceutical value. Mangoes are unique because every part of the fruit, starting from the fruit, pulp, peel, seeds, leaves, and peel, can be used [48]. Dyes extracted from mango leaves produce more colorful ingredients than dyes derived from mango fruit extracts [49].

Based on the data in Table 4 above in the form of laboratory test results related to testing, namely color fastness to washing at a temperature of 40°C and color fastness to bright light in patterned batik fabrics (which have undergone the process of canting cap, color dyeing, and nglorod process), it is confirmed that the comparison is confirmed that mango seed extract provides better color fastness with lime and ferrous sulfate solution fixators with The value of 4 was compared to mango leaf extract using lime solution (value 3) and ferrous sulfate solution (values 2–3). The results of the color staining value test for all types of medium, such as acetate, cotton, polyamide, polyester, acrylate, and wool on batik fabric that uses mango seed extract and mango leaves in general, provide color staining values that have similarities, namely the good category (4–5). Meanwhile, the results of the color fastness test to bright light during the day confirmed the comparison that the quality of mango leaf extract resistance was better (value 3-4) than mango seed extract (value 3). The findings recommend that the two extract ingredients, namely mango seeds and mango leaves, with their advantages and disadvantages, can be used as dyeing materials for batik fabrics. The availability of mango leaf waste is more abundant because it is available throughout the year compared to the availability of mango seeds, which rely on by-products from mango fruit products. Thus, the author argues that mango leaf extract materials have more potential to be used and further developed in the dyeing process of batik fabrics in Indonesia.

The benefits of mango leaves are not only as an environmentally friendly natural dye for batik fabrics, but mango leaf extraction materials as a by-product of mango with the content of powerful antioxidant phenolic compounds such as mangiferin, flavonols, benzophenones, and gallotannis are highly appreciated in food, cosmetic, and pharmaceutical applications [50]. In addition, based on thermodynamic studies, it can be used as a green synthesis of silver nanoparticles carried out with mango leaf extract as a reducer, showing that the endothermic spontaneous reaction is an adsorbent suitable for development for textile wastewater treatment, with SDZA performing better than SZA [51].

CONCLUSION

Natural materials such as mango leaf waste in the surrounding nature can be used as a source of natural dye for dyeing batik fabrics. In addition to utilizing the diversity of natural potential flora, the use of Gedong Gincu Mango leaves as a source of natural dyes is also useful to foster awareness of life preservation and add economic value to the development of the green industry in the field of batik in a sustainable manner. The process of selecting natural color extraction materials and proper fixation can produce good colors that are environmentally friendly. The results of the experiment of dyeing Gedong Gincu Mango leaf extract on plain batik fabric are known to produce stronger color intensity than in patterned fabrics that undergo a wax removal process from batik fabrics. The findings of color reduction through the process of removing wax from batik fabric need further research. The research recommends the need to use natural dyes, such as those from Gedong Gincu mango leaves, through the extraction process in an effort to preserve the value of local wisdom and provide added value to batik craftsmen.

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HYBRID 3D WOVEN STRUCTURES FOR CONCRETE REINFORCEMENT UNDER IMPACT LOADING PART 1: DEVELOPMENT OF A BI-AXIAL CORE DESIGN

ORTEGA ARBULU, JUAN DANIEL*; NUSS, DOMINIK AND CHERIF, CHOKRI

Institute of Textile Machinery and High Performance Material Technology (ITM), Technische Universität Dresden, George-Bähr-Str. 3c, 01069 Dresden, Germany

ABSTRACT

Steel reinforced concrete (RC) is extensively used in the construction industry due to its high strength, durability, and versatility. Nonetheless, its resilience under dynamic loads, such as impact, remains particularly low. The research training group DFG GRK 2250 aims to significantly improve the impact energy absorption of existing infrastructures by applying thin layers of an innovative strengthening material composed of a strain hardening cementitious composite and a novel textile reinforcement. This paper investigated methods for manufacturing 3D hybrid woven fabrics with a core incorporating spatial elements in both the weft and warp directions, based on a bi-axial core design. The challenges associated with shaping spatial elements before and during the weaving process were discussed, with the latter proving to be the optimal choice when combined with carbon fiber towpregs. After developing the structural design, selecting the materials for each element, and establishing the fabric binding pattern, a demonstrator was successfully produced using a modified rapier weaving machine.

KEYWORDS

Woven cellular metals; 3D concrete reinforcement; Hybrid structure; Weaving technology.

INTRODUCTION

The most used building material in the world is concrete, a composite made of a cementitious matrix and solid filler aggregates. Even though concrete is cost-effective, versatile and has a high compressive strength, it is characterized by its brittle failure mode and low tensile strength. Consequently, it is conventionally reinforced with steel rebars (reinforced concrete - RC), mitigating crack initiation and propagation, and noticeable improving the overall mechanical properties under static loads [1]. Nonetheless, under dynamic loads, such as impact, it exhibits low resistance due to its poor energy absorption capabilities. Thus, other methods like continuous fiber reinforcement (textile reinforced concrete - TRC) or short fiber reinforcement (fiber reinforced concrete - FRC) are taken into consideration [2].

TRC replaces the conventional steel rebar or steel cages with either two- or three-dimensional grid-like layers of textile materials (continuous fiber reinforcement), such as carbon, alkali resistant glass or basalt [3] [4]. These have a substantially lower density and a higher tensile strength compared to steel. Furthermore, because they show excellent corrosion resistance, the need for a thick concrete cover, which is usually required for RC, is drastically minimized [5]. Thus, thinner structures with improved mechanical properties can be manufactured, which in turn positively affect the economy and the ecology (CO_2 emissions) [4], [6–8]. Despite these advantages, TRC faces some problems that are innate to the fiber materials themselves. Their high strength is usually coupled with low strain values (1 - 5%), meaning that little to no plastic deformation occur prior to failure. Consequently, even though these fibers have a great strength-to-weight ratio and can withstand noticeable higher tensile loads, their brittleness typically result in low energy absorption. Another crucial aspect for the performance of TRC is the bond between the textile material and the surrounding concrete, which ensures proper load transfer. It can be improved either chemically, with the use of more suitable sizing, or mechanically, through altering the surface topology of the reinforcement material (mechanical interlocking) [9], [10]. FRC, on the other hand, contains uniformly distributed, randomly orientated short fibers, that make up between 2% and 6 % of the total volume of the composite. They can be classified into micro fibers (5 - 20 mm in length and 0.02 - 0.20 mm in diameter),

* **Corresponding author:** Ortega Arbulu J.D., e-mail: *juan.ortega@tu-dresden.de*

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and macro fibers (30 – 65 mm in length and 0.4 – 1.2 mm in diameter). Commonly used fibers include those made from steel, glass and synthetic materials, like carbon, aramid, polypropylene, nylon, polyethylene, and polyvinyl alcohol [1] [11]. The benefits of FRC become apparent during the pre-cracking stage (stress transfer from the matrix to the fibers before macrocracks initiate), and during the post cracking phase (fiber bridging effect). The latter mechanism ensures effective stress transfer across pre-existing cracks, thereby controlling crack propagation rates and extending the structural integrity. Hence, because of its improved penetration, scabbing and fragmentation resistance, FRC is suitable for protective structures that have to withstand explosions and shock loads [12–15]. Therefore, it holds scientific value and interest to investigate the performance of a mineral-based composite that combines TRC and FRC for structural protection against impact events.

The Research Training Group GRK 2250 primarily focuses on the development of a composite material that acts as a thin protective layer on existing concrete structures. The constituents of this novel composite can be divided into two categories: the cementitious matrix and the textile reinforcement. The matrix is made of a special type of FRC, which is called strain-hardening cement-based composite (SHCC). It contains discrete synthetic microfibers (e.g. polypropylene) with a volume fraction up to 2%, which results in a high strain capacity, and a pronounced microcracking controlling behavior [16]. Due to the low strain-capacity of conventional two-dimensional grid fabric reinforcement (2DFT), e.g. carbon or glass [17] [18], a three-dimensional hybrid woven fabric (3DWT-M) was proposed and later developed at the Institute of Textile Machinery and High Performance Material Technology (ITM) at the TU Dresden (TUD). This novel reinforcement was manufactured on a modified rapier weaving machine Dornier HTVS4, and is based on the technology of three dimensional cellular woven structures for lightweight applications (metallic fiber based), also developed at the ITM [19] [20]. 3DWT-M synergizes the good mechanical properties of metallic fibers (e.g., tensile strength, ductility, workability) with the stiffness and high tensile strength of carbon fibers. It is characterized by a pyramidal metallic cellular core, that is achieved through a cleverly designed weaving pattern that utilizes preformed steel wires in weft direction (mono axial spatial reinforcement), and an in-plane reinforcement with carbon fiber tows at the upper and lower face of the structure. Moreover, high-speed tensile tests and impact tests show that 3DWT-M, in fact, perform better than 2DFT [21]. To gain a deeper insight into the behavior of 3DWT-M, a new in-situ sensor network was developed and integrated into the structure [22–24]. In addition, to improve the bond between the carbon fiber elements and cementitious matrix, profiled carbon fiber tows were later introduced [9] [10]. Nonetheless, due to the challenging scenario characterized by high impact energy, a thin protective layer, and complex interactions between different materials, it is essential to fully optimize the technologies and material-structural properties, particularly for the 3DWT-M. This paper therefore investigates the feasibility of enhancing the core structure from a mono-axial into a bi-axial spatial design (3DWT-B), and the results are illustrated using a demonstrator.

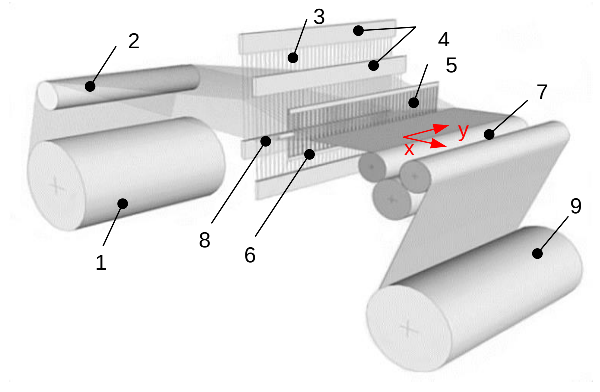
THEORETICAL BACKGROUND

Fundamentals of the weaving technology

A schematic with the basic set-up of a conventional dobby weaving machine is displayed in Fig. 1. A 2D woven fabric typically has two yarn systems: the warp yarn system, which runs in the direction of production (x), and the weft yarn system, which is perpendicular to it (y). Yarns in warp direction are stored either on a warp beam (1) or come directly from a bobbin creel. They are then individually guided by the back rail (redirection and force compensation component) into the healds (3), that are attached to the heald frames (4), and through the reed (5). The latter is integrated into the sley (6), sorts the warp yarns along the width of the fabric, and defines the warp density of the finished product. A dobby weaving machine can have up to 28 healds that individually move the attached warp yarn set either up (position I) or down (position 0), creating a space (weaving shed) to insert the weft yarns (b). There are different weft insertion systems available, but one of the most commonly used, delivering fast weaving speeds, high process stability, flexibility and efficiency, is the rapier system (single-, double-, or multi-rapier). During the beat up, the weft yarn is pushed forward by the reed (5), while the heald frames change position (shed change), and secure the yarn in the fabric edge. The take-off system (7) pulls the fabric at a preset speed and can be adjusted to produce different weft densities, which ultimately depend on the weaving pattern. Finally, the woven product is rolled on a storage beam (9). For 3D woven fabrics a linear take-off system is used instead (see Fig. 2(b)).

Reference structure

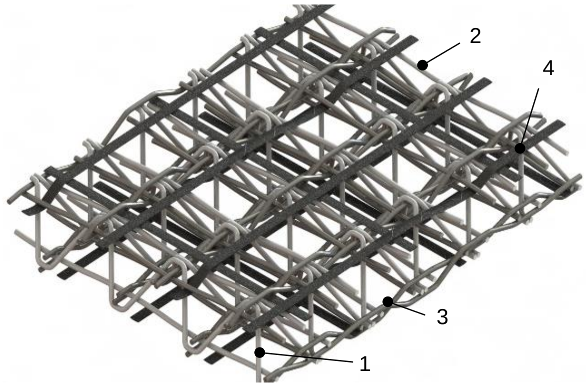
The reference structure (3DWT-M) described at the introduction is displayed in Fig. 2(a), and can be divided into three distinct sections: the core, and the upper and the lower face. The former is a woven cellular metal core, which is characterized by a pyramidal unit cell. This is achieved by inserting preformed steel wires (spatial element) in weft direction (1), that rest at an angle after the beat-up of the reed. The core is fixed due to the support of straight steel wires in weft (2) and binding wires in the warp (3), which form the upper and lower faces of



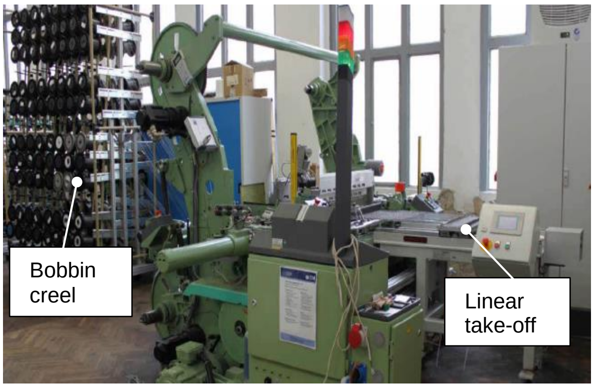
(a)

(b)

Figure 1. (a) Basic set-up of a weaving machine. (1) Warp beam, (2) back rail, (3) heald eye, (4) heald, (5) reed, (6) sley, (7) fabric take-off, (8) weft insertion system, (9) fabric storage, (x) warp direction or production direction, (y) weft direction [25]. (b) Weft yarn insertion and delivery on a double sided single-rapier system [26].



(a)



(b)

Figure 2. (a) CAD-Model of the reference structure. (1) Preformed steel wire, (2) weft wires, (3) binding wires in warp, (4) carbon fiber tow. (b) The modified rapier weaving machine Dornier HTVS4.

3DWT-M. Additionally, carbon fiber tows (4) (Teijin Tenax - E HTS40 F13 12K 800 tex) are woven into both faces, in weft and in warp direction, forming a grid-like pattern (12 mm x 15 mm). These were impregnated with a polyacrylate based sizing. Because of the subsequent application in concrete (thin layer), corrosion resistance is important; therefore, all the metallic elements are made of stainless steel wire (1.4301) with a diameter of 0.8 mm. For the core and the elements in the upper face, the wires have a higher tensile strength (approximately 1200 MPa). Conversely, elements in the lower face have a lower tensile strength, around 600-800 MPa, but a much higher elongation at fracture (about 35% higher). Thus, a structure with a gradient in mechanical properties is achieved, and as suggested by researches from previous studies, is ideal for energy absorption [27]. Moreover, it is imperative to highlight the open-cell architecture of 3DWT-M, which is necessary for the matrix (SHCC) to flow and properly cover all the elements of the reinforcement fabric. For this purpose, the fiber content of the matrix was also reduced from 2% to 1% [21]. The bond between the fibers and the concrete was then later enhanced by replacing the flat carbon fiber tows with profiled tows (Teijin Tenax-E STS 40 F13 48K 3200 tex carbon). These were manufactured in a profiling laboratory unit developed and built at the ITM [28]. Further, they have a polyacrylate-based impregnation agent (TECOSIT CC 1000), a polymeric dispersion with a solid content of approximately 50%, specially developed at CHT Germany GmbH (Tübingen, Germany) for an optimal compatibility with concrete. Pull out tests done in previous research showed a substantial increment in concrete bond strength compared non-profiled tows. The same investigation also shows, that the profiling of the tows results only in slight reduction in performance in quasi static tensile testing [9] [10].

MATERIALS AND MEHTODS

Requirements and restrictions

The requirements for the structure (see Fig. 4) are as follows:

· Spatial elements are to be implemented in weft and in warp direction (bi-axial core design).

· Upper and lower faces should absorb in-plane tensile and compressive forces, while the core should absorb compressive and shear forces.

· An Open cell structure is necessary to properly infiltrate 3DWT-B with the matrix (SHCC).

· A Periodic structure with same cell size, shape and regular distribution, because the striking location in a real scenario is unknown. Thus, the same mechanical properties along the whole fabric are needed.

· A Self-sustaining structure without the matrix to facilitate transport and assembly at the construction site.

· Corrosion resistant materials due to the later implementation in concrete (alkaline environment).

· A variety of fibers (metallic and synthetic) are needed to achieve a high strength and stiffness while possessing some ductility (gradient architecture and energy absorption).

· A reproducible and stable manufacturing process is desired.

After establishing the overall requirements, it is necessary to evaluate the cases for implementing spatial elements in warp direction (see Fig. 3). The first case (I) involves forming these elements prior to the weaving process separately, while the second case (II) involves forming them during the weaving process. Further, a distinction regarding the processed materials has to be made. While fiber-based materials can also be metallic, the term "fiber-based" used here refers specifically to synthetic fibers made either from natural or synthetic polymers [25]. The term "metallic" refers to monofilament metallic fibers with a diameter ranging between 0.02 mm up to 6.00 mm. The geometry of the cross section can also be other than round, e.g., rectangular. Similar to the preformed elements used in [21], metallic elements in case (I) can be shaped to the desired geometry through cold forming [29]. On the other hand, fiber-based materials, such as carbon fiber with a thermoplastic matrix, can be formed through thermoforming [30]. For case (II), three methods were taking into consideration, which involve using a pre-impregnated yarn and fully curing it after the fabric is woven: foulard, prepreg and powder coating. The foulard technique involves drawing a dry yarn through an impregnation bath that contains a set amount of rollers, which spread the yarn and improve the process quality [31]. The term "prepreg" describes a composite that consists, in this case, of a dry yarn that is pre-impregnated with a polymer matrix, and is then partially cured. Because heat accelerates the polymerization process, prepregs usually have to be stored at cool temperatures. In this way, the chemical reaction is drastically slowed down, and the prepreg can be stored for months or years before being used [32] [33]. The third method is a powder coating technology. In a continuous process, yarns are guided, spread, and coated with a powdered matrix, usually thermoset (epoxy), and then heated for the impregnation. Similar to the prepregs, the matrix is not fully cured, but due to the high initial glass transition temperature of epoxy powder, it does not have to be stored at cool temperatures [34–37].

Limitations for case (I):

· A feeding and guiding system into the weaving machine has to be designed to avoid undesired rolling, yawing and pitching of the spacer elements during the weaving process, specially between the machine components 1 and 5 (see Fig. 1).

· Necessary methods or technological modifications to the machine to regulate warp tension. Excessive warp tension can lead to deformation (metallic) or fracture (fiber-based).

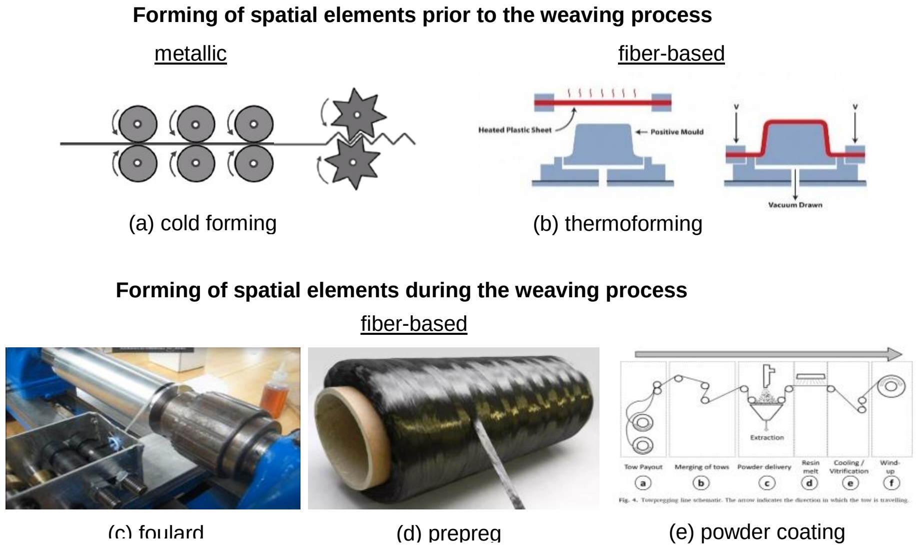


Figure 3. Forming of the spacer elements in warp direction. Forming prior to the weaving process: (a) cold forming [20], (b) thermoforming. Forming during the weaving process: (c) foulard [38], (d) prepreg [39], (e) powder coating [34].

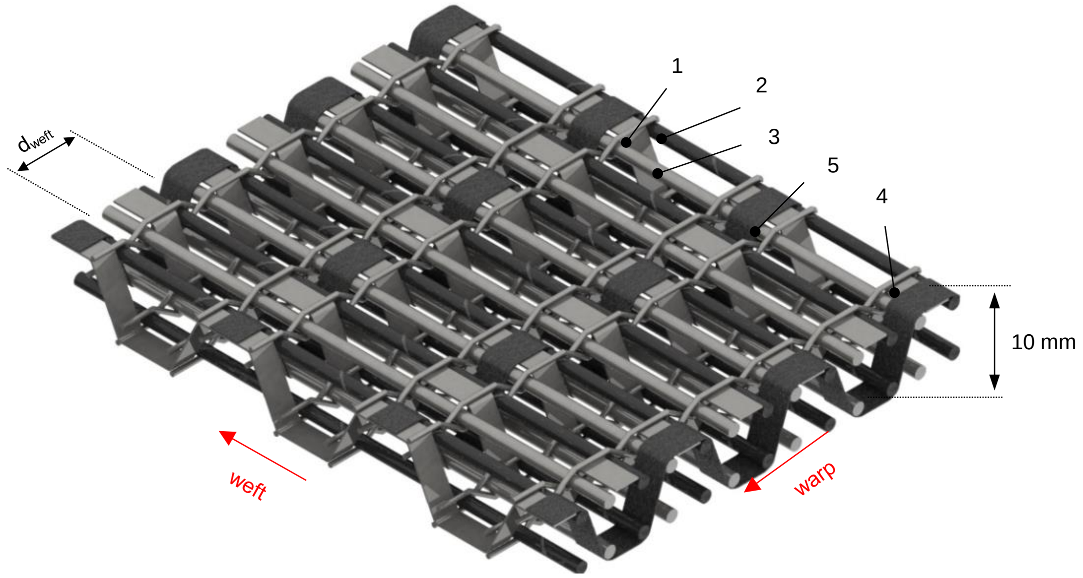


Figure 4. CAD-model of the novel reinforcement concept structure with spacer elements in weft and in warp direction. (1) Steel spatial element in weft, (2) carbon fiber profiled tow, (3) steel rod, (4) carbon fiber tow as spacer element in warp, (5) binding steel wire.

· Reduction of the shed geometry due to the height of the elements (instead of flat yarn) may lead to conflicts with the path of the rapier.

Limitations for case (II):

· Foulard: The impregnation bath process and design of the bath has to be carefully conceptualized. It has to be allocated between the bobbin creel and back rail, and should not interfere with the yarns and steel wires being delivered from the bobbin creel. Further, resin spilling on the machine may be a problem for the moving components of the weaving machine.

· Prepreg: Due to its pre-impregnated form, the stiffness might hinder the formability, and the tack might increase the friction with several machine components (back rail, healds, reed). Further, the shelf life in and out storage temperature is relevant for the mechanical performance of the composite.

· Powder coating: A powder deposit unit has to be developed first, as there are no known industrial suppliers for a finished powder impregnated yarn.

Technology, structural development and material selection

Using the Analytical Hierarchy Process (AHP) and the Weighted Sum Model (WSM), Case (II) - “Forming of spatial elements during the weaving process” and the method “prepreg” emerged as the optimal choice for enhancing the core of the 3D textile structure with a spatial reinforcement in warp direction. Relevant criterions were: tooling costs, material costs, manufacturing complexity, assembly effort, development costs, the number of suppliers. A structural model was then designed in SolidWorks based on the requirements outlined in Section 3.1, and is displayed in Fig. 4. It consists of three elements in weft direction (1-3) and two elements in warp direction (4-5). (1) and (4) build up the core, while (2), (3), and (5) form the upper and lower faces. (2) and (3) alternate on the sides of (1) and are held together with (5). (4) is woven along the weft elements, alternating between the upper and lower faces. Similar to a sandwich-structured composite, the upper and lower faces (2, 3, 5) are designed to take in-plane and bending forces, and the core (1, 4) shear and compressive forces. Furthermore, the open cell structure facilitates pouring and covering the entire reinforcement with concrete. An evaluation of the mechanical performance with and without the matrix (SHCC) is not the scope of this work, and is intended for later research.

The steel spatial element (1) is made of a flat stainless-steel wire (1.4016) with a cross section of 4.0 mm x 0.3 mm and a tensile strength of 984 MPa (Studer Biennaform). The 3D geometry was achieved through cold forming [20], and has a height of 10 mm. The profiled carbon fiber tows (2) were manufactured according to Section 2.2, and have a diameter of 2.2 mm. The rods are made from stainless steel (1.4301), possess a diameter of 2.0 mm and have a tensile strength of 928 MPa (Messinghaus Rehlken GmbH). A carbon fiber prepreg tow (towpreg) is used as a spatial element in warp (4), and has a width of 5.0 ± 0.5 mm. The dry yarn is a Toray T700-SC-24K-1650 tex, and the tensile strength of the cured towpreg is about 2880 MPa with an expected fiber volume fraction of 65% (Kümpers GmbH). Further, it has shelf life of 30 days at room temperature, and has a cure profile of 0.5 h at 120 °C, followed by 4.0 h at 140 °C. The binding steel wires for the top and bottom faces are the same as for the reference structure (Section 2.2)

Woven fabric development

Based on the modeled concept and the selected material, a weave pattern was developed and later converted into a binding cartridge, which must be provided to the weaving machine in a coordinated file. For this purpose, the cross section of the structure in warp must be displayed (see Fig. 5), and all included elements should be categorized individually: warp (K) or weft (S) direction, metallic (E) or carbon fiber (C) type, and planar (1) or spatial (2) form. Hence, for the weft direction: S-E-1, S-C-1, S-E-2, and for the warp direction: K-E-1 and K-C-2. Furthermore, the sequence of the smallest repeating unit in the weft (1-9) is identified and color-coded, and for each step in the sequence, the pull-off length (δ_0) of the fabric is set. The distance between each repeating unit in weft (d_{weft}) was set to 11 mm for one section and 16 mm for another section of the fabric (see Fig. 5 and Fig. 7). The warp density $\rho_{f,warp}$ was inferred directly from the CAD model (see Fig. 6), from which a tailored reed (STEVEN Reeds GmbH) was manufactured. Each of the elements in warp are then assigned to a heald frame. This results in the weaving pattern shown on the right of Fig. 5. The wires were best suited for the heald frames at the front (1 to 4) because the farther the heald frames are from the weaving reed, the larger the stroke required to form a proper shed geometry. Consequently, the wires would experience excessive bending, which is undesirable. Furthermore, circular heald eyes were used for the wires and double flat heald eyes (TWINTec) for the towpreg. Additional towpregs (P) are woven into a plain weave pattern on the top and bottom surfaces to stabilize and secure the edges of the fabric. After calibrating the weaving machine (Dornier HTVS4), a fabric sample (500 mm x 200 mm) was manufactured. It was then removed and put in an oven at 120°C for 0.5h and at 140°C for 4h to consolidate the towpreg.

CONCLUSIONS

The aim of this paper was to develop a novel type of woven reinforcement structure (bi-axial core design), while taking into account the constraints of the weaving technology and the requirements for its application in concrete under impact stress. The manufactured reinforcement fabric (3DWT-B) is shown in Fig. 7 before (left) and after (right) curing the towpreg. It can be observed that the carbon fiber towpregs were successfully integrated into the structure during the weaving process, and alternating between the upper and lower faces resulted in the desired spatial reinforcement (3D) in the warp direction. Depending on the pull-off length δ_0, the weft density $\rho_{f,weft}$ and the angle formed by the interlacing towpreg (α), which are proportional to each other, can

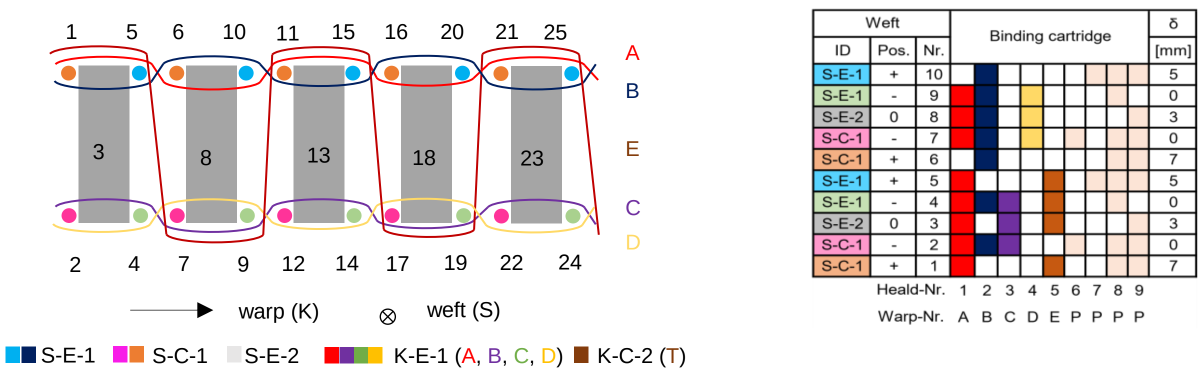


Figure 5. On the left a schematic representation of the woven structure: cross section in warp. S (weft), K (warp), E (steel), C (carbon fiber), I (1D), II (2D). On the right the resulting binding cartridge.

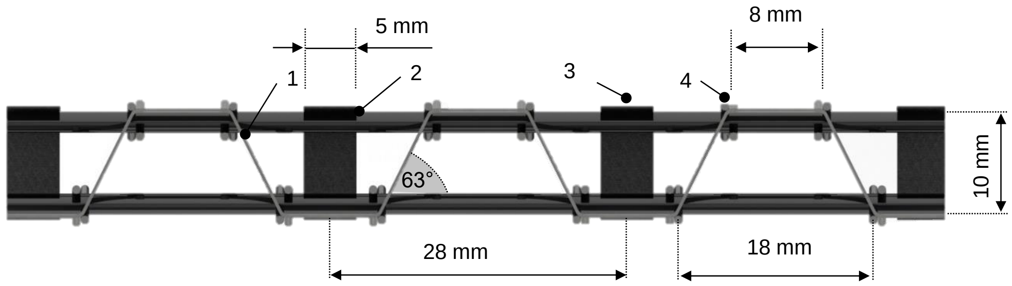


Figure 6. CAD model of the 3DWT-B concept: cross section in weft. (1) Steel spatial element in weft, (2) profiled carbon fiber tow, (3) carbon fiber towpreg as spacer element in warp, (4) binding steel wire.

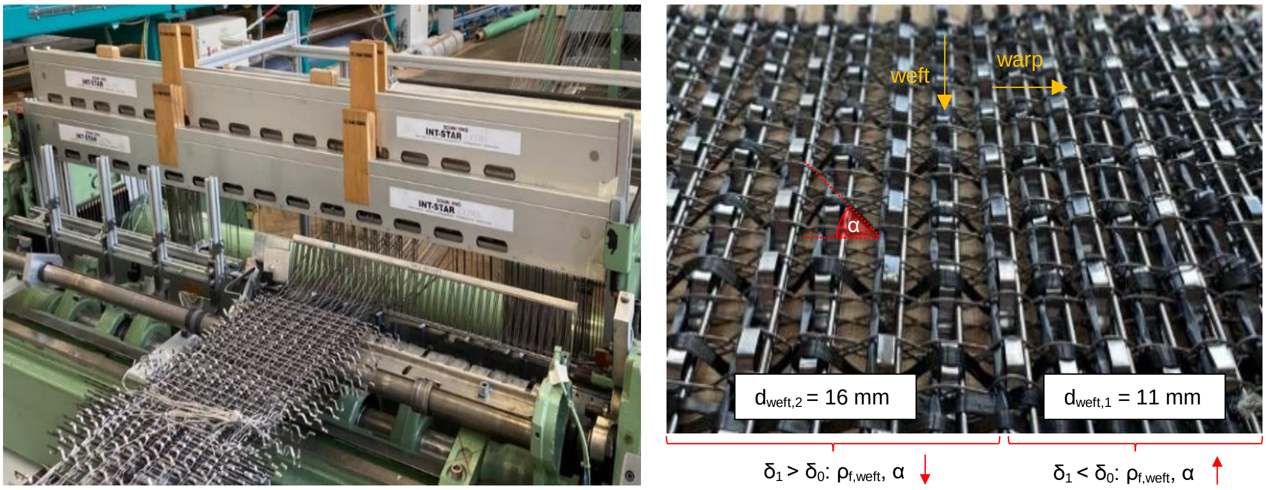


Figure 7. Manufacture of the novel reinforcement structure with the weaving machine Dornier HTVS4 on the left. Cured fabric on the right.

be increased ($\delta_1 > \delta_0$) or decreased ($\delta_1 < \delta_0$). The more acute α is, the less is the structural stability the towpreg provides across the thickness of the fabric. Additionally, the lower $\rho_{f,weft}$ may result in a reduced bending resistance of 3DWT-B in warp direction but increased flowability of the SHCC matrix into the fabric, due to the bigger gaps. The situation is inverse for a greater angle α and a higher $\rho_{f,weft}$. Thus, an optimal balance between the mechanical properties of the fabric and the flowability of the matrix into the structure has to be found. Poor casting of the SHCC into the reinforcement may result in air pockets and reduced mechanical performance of the mineral-based composite. It can also be observed that the geometry formed by the towpreg more closely resembles a sinusoidal shape rather than the trapezoidal geometry seen in the conceptualized CAD model (see Fig. 4). Moreover, the towpreg remained adhered to the structure after curing, but with repeated flexing, it started to detach locally until it could freely move sideways. This means that higher warp tension and additional elements in weft direction that press against the towpreg's surface may be beneficial for achieving the desired geometry. In that regard, if the warp tension is too high, friction also increases and may result in an undesired spreading of the yarn or even damage to it. Despite that, this work showed that it is a feasible to use carbon fiber towpregs with the forementioned weaving machine to enhance the core of the reinforcement fabric in warp direction. For future work it is necessary to conduct a study regarding the flowability of concrete into the reinforcement and the performance of the novel mineral-based composite.

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ADAPTIVE CLOTHING DESIGN FOR INJURED PEOPLE

BUKHANTSOVA, LIUDMYLA[1*]; LUSCHEVSKA, OLENA[1]; KOVALCHUK, DMYTRO[2]; ZACHARKEVICH, OKSANA[1]; KRASNIUK, LARYSA[1]; KOSHEVKO, YULIA[1]; KHASANOVA, OKSANA[1] AND BAZYLCHUK, OLEG[1]

[1] Khmelnytskyi National University, 11, Instytutska str., Khmelnytskyi, 29016, Ukraine
[2] Private enterprise “Adaptime”, 174/6, Chornovola str., Khmelnytskyi, 29016, Ukraine

ABSTRACT

Researchers have been paying increased attention to adaptive clothing as society's awareness of inclusivity and accessibility grows. This focus on adaptive clothing is particularly important for Ukraine, where there is a consistent need for products that cater to the needs of injured individuals. The research took a comprehensive approach to studying the issue. It involved engaging with hospital staff and patients with limb injuries to understand their exact requirements during treatment or rehabilitation after injuries. As a result of this collaboration, the gathered information became the foundation for creating men's clothing sets, which have been highly praised for their convenience and quality. This information can be used in future research on designing virtual adaptive clothing for individuals with limb amputations. The survey results can also assist clothing designers in effectively addressing the specific needs of consumers with limb injuries.

KEYWORDS

Adaptive design; Adaptive clothing; Injury; Disability; Virtual clothing; CLO 3D.

INTRODUCTION

According to the World Health Organization, 1.3 billion people live with significant disabilities, which represents 16% of the world's population or 1 in 6 individuals [1]. A portion of disabilities can be attributed to different types of injuries, whether intentional (caused by violence towards oneself or others) or unintentional (from road traffic accidents, sports, work-related risks, burns, falls, poisoning, etc.). Injuries result in about 5.8 million deaths worldwide every year – more than malaria, tuberculosis, and HIV/AIDS combined. However, hundreds of thousands of people suffer non-fatal injuries that can lead to various forms of disabilities [2].

According to a situation in Ukraine, the Office of the United Nations High Commissioner for Human Rights has confirmed that since February 22, 2022, a total of 19875 civil adults (an average of 542 people per month) and 1298 children have been injured. Men make up 60 percent of the adult casualties. 94% of adults were injured by explosive weapons with wide-area effects. It is important to note that the actual figures may be higher than reported [3].

Disabling injuries can result in either temporary or permanent disabilities. A temporary disability can be overcome with time or treatment. For example, a bone fracture can significantly impair the use of a limb but will heal over time with proper treatment. On the other hand, permanent disabilities cannot be overcome. These include limited mobility [4], hearing loss, and limb amputation [5].

Considering the high prevalence of disabilities in our society, it is crucial to find ways to integrate individuals with injuries into their daily activities. Most people with disabilities have special clothing needs. Although the market for adaptive clothing is insignificant in the apparel marketplace, it has the potential for further growth [6]. Therefore, adaptive apparel developers require specialized skills and knowledge to create high-quality products for individuals with disabilities.

Conceptually, adaptive apparel relates to modified or customized apparel that accommodates the needs of people with disabilities and/or impairments [7]. Several researchers have explored a wide range of specific issues related to individuals with disabilities, including those with various physical disabilities and their caregivers. This encompasses wheelchair users [8-10], people with rheumatoid arthritis [11] or muscular dystrophy [12], those with scoliosis [13], people with Down syndrome [14], and their respective caregivers [7] [11] [14].

Losing functionality in a limb can be incredibly stressful and can lead to negative consequences.

* **Corresponding author:** Bukhantsova L., e-mail: *bukhantsovalv@khmnu.edu.ua*
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Many amputees experience depression. Approximately 40% of amputees also experience anxiety, and roughly 20% experience depression. Some common challenges for amputees include loss of desire to live, apathy, difficulty accepting their new reality, social withdrawal, insomnia, and phantom pains [15]. Successful rehabilitation involves collaborating with doctors, therapists, and psychologists to adapt physically and psychologically to the new situation. Clothing also plays a significant role in this process.

Adaptive clothing can facilitate dressing and minimize awkwardness when accessing clothing and footwear. It can include features that aid rehabilitation, such as targeted compression or support for specific body areas. Adaptive clothing improves the quality of life for individuals with limb injuries undergoing treatment and long-term rehabilitation, positively impacting their physical and psychological well-being.

Modern adaptive clothing designs prioritize style [7] [16] and individuality, offering fashionable options that do not resemble medical attire. This contributes to positive self-perception and seamless social integration.

Perspective research on adaptive clothing should address the clothing needs of different age groups. This includes understanding the specific functional and aesthetic requirements at each stage of life and how these needs might change over time. There is also a need to examine the demand for gender-neutral adaptive clothing, identifying the obstacles and opportunities for such designs in the market.

Another critical area of research is the connection between adaptive clothing and self-identity or self-expression. This involves exploring how clothing choices mirror personal style, enhancing psychological well-being, self-esteem, and confidence by addressing psychological barriers.

Adaptive design research can utilize various qualitative, quantitative, and mixed methods. The mixed methods are more effective and may entail a combination of in-depth interviews and surveys, focus groups and surveys, in-depth interviews and experiments, or solely surveys [7] [17]. Combining methods helps comprehensively understand consumer needs and preferences [7].

Consumer reviews and feedback should assess adaptive design solutions for specific groups of people with disabilities. Recommendations regarding the effectiveness of adaptive clothing and its impact on quality of life and social inclusion should be based on experimental designs and actual data. Advanced data analysis techniques can reveal complex relationships and trends, enhancing the depth of research insights. To create more effective solutions, it's essential to involve people with disabilities and other stakeholders in the research process [7] [18].

When talking about adaptive design, it is crucial to say that it is primarily user-centered design, based on concentrating the design process on consumers' needs and limitations. Designer analysis and prototyping are central to the user-centered design framework, allowing users to engage with physical products in a real-world environment [7].

Another perspective method used in adaptive design is digital 3D Computer-Aided Design (CAD). A crucial feature of digital 3D CAD systems is their precision and digital prototyping, which allow designs to be created with minimal waste and directly start production from a digital model. This opens new opportunities for applying zero-waste design practices and allows for managing textile resources while allowing design experimentation [17] [19] [20]. One popular 3D software is CLO, which has 86 international companies listed as its users [21].

3D CAD systems were also used to prototype adaptive clothing digitally [22]. Researchers have used scanning technology, modelling, and reconstruction techniques to create a 3D body model sitting for virtual prototyping. This research showed how effective 3D CAD systems can be for virtually prototyping individual garments for paraplegics and how 3D tools can be used in adaptive design.

Ergonomic design [23] and new materials [24] [25] can improve comfort and functionality in adaptive clothing, meeting the needs of people with disabilities. Soft, stretchy textiles have been used in adaptive clothing production, offering enhanced comfort, pain reduction, body conformity, pressure alleviation, and minimized skin irritation. However, innovative features such as magnetic closures, adjustable fittings, shape memory alloys [26], and nano- [27] or e-textiles [28] can provide additional possibilities for adaptive clothing.

The researchers [8-14] have studied various challenges, focusing on specific types of disabilities and identifying specific apparel attributes that meet the functional and aesthetic needs of consumers with disabilities. Functional features encompass a diverse range of elements that enhance the performance and usability of garments, often leveraging cutting-edge technology and innovative materials to improve comfort, durability, and overall functionality [7] [29]. Using Velcro, magnetic fasteners, zippers, buttons, laces, adjustable parts (pants, sleeves, belts, cuffs), and elastic components simplifies the dressing process, especially for people with limited mobility or those needing assistance [14] [30] [31]. Additionally, adaptive clothing can have adjustable elements that can be customized to accommodate changes in body size and shape, allowing for variations due to swelling or weight fluctuations. The unique designs facilitate hygiene procedures without removing clothing, which is crucial for individuals in long-term body recovery. This comfort and independence in clothing enhance a customer's dignity, self-control, and confidence [31].

Meanwhile, aesthetic attributes pertain to the visual and design-related components (style, fit, and adaptability to specific needs and body types [29] [32]) that contribute to the overall visual appeal and suitability of clothing for individuals with disabilities. In the study [32], during the analysis of responses regarding satisfaction with clothing for girls with disabilities, it became clear that the girls' ability to express themselves and the aesthetic aspects of their clothing were crucial, showing the importance of allowing them to express their individuality and feel good about their appearance. Functional aspects of putting on and taking off garments, especially fasteners, were also identified as significant issues. Thus, researching the aesthetics and functionality of adaptive clothing is essential to ensure consumers' overall satisfaction and comfort.

The research aims are to create specialized clothing that addresses the individual needs of people with injuries. The future of research lies in the thorough development and effective implementation of adaptive design methods that cater to a wide range of disability types, including permanent or temporary physical impairments resulting from injuries. Additionally, it is essential to solve this issue with a comprehensive, user-centered design framework to dialog with apparel designers and consumers with disabilities. It will enable the creation of adaptive apparel that meets their specific needs and preferences concerning apparel design [7].

Our scientific research involves analyzing existing clothing, understanding common injuries, and developing functional solutions for adaptive clothing. The study's tasks include conducting surveys with patients, doctors, and rehabilitation specialists, creating virtual models and patterns for adaptive clothing, and evaluating the clothing sets with input from patients and experts.

METHODOLOGY

The research on adaptive apparel has mainly focused on the design processes and methodologies involved [7]. The research plan comprised four stages of the standard user-centered design process: planning, analysis, creation, and verification [33]. In the planning stage, our multidisciplinary team of experts has planned a survey and interviewed stakeholders.

During the survey planning stage, a team of experts, including researchers, a sewing business owner, a psychologist, and a rehabilitation specialist, collaborated to ensure that the survey questions were formulated accurately and clearly. The questionnaire underwent testing with two amputee patients who had completed treatment and were in the rehabilitation stage. Their feedback and suggestions were instrumental in enhancing the questionnaire.

For the adaptive design, we used a mixed-method study [18], which included surveys and experiments to comprehensively understand adaptive clothing for consumers. We employed analysis, synthesis, comparison, data generalization, explanation, a systematic approach, and description during the research. Stakeholders were divided into two categories: (S1, N_{S1}=30) the hospital staff and (S2, N_{S2}=20) the injured patients. These groups were determined based on their involvement in the treatment and rehabilitation process and the possibility of their use of adaptive clothing during this period. Group S1 consisted of doctors and rehabilitation specialists with varying experience working with injured patients. We created two surveys tailored to their roles, each containing two question blocks (Table 1).

In our survey, the main aspects affecting adaptive design for injured individuals were:

- the types of injuries in the current treatment and rehabilitation process;
- the percentage of limb loss after injuries;
- the garment elements for enhancing clothing functionality.

The questions QN5, QN12-QN13, and QN16-QN28 had visualizations (Fig. 1) to help the respondents precisely imagine the garment elements.

The next step involved conducting a detailed analysis of the survey results and forming essential conclusions. During the creation stage, the team developed multiple design solutions by leveraging 3D technologies and creating physical prototypes for testing. The final part of the design process involved evaluating the design and technology through user testing after two weeks of adaptive clothing utilization.

RESULTS AND DISCUSSION

General information about respondents (QB1)

We gathered data from 30 hospital staff members and 20 injured patients (men) and analyzed the survey results using Microsoft Power BI, a data visualization software.

The survey findings revealed that a significant majority (90%) of the hospital staff (S1) were under the age of 30 (Fig. 2). Our research suggests that this demographic has limited professional experience, typically less than two years. This can explain the rise in the number of injured individuals after 2022, leading to an increase in inexperienced rehabilitation specialists.

The hospital staff's opinion on common injuries (Fig. 3, a) shows they are combined arm and leg wounds. Specifically, 70% of injured patients used adaptive clothing during their treatment. Furthermore, 90% of the patients wore non-adaptive clothing, such as sports pants and T-shirts, during rehabilitation (Fig. 3(b)).

Table 1. Sample interview questions.

Question block	Stakeholders	Question Number (QN)	Sample Questions
General information about the respondents (QB1)	The hospital staff (S1)	QN1	Enter your age
		QN2	How many years of experience do you have working with injured patients?
		QN3	What are the most common injuries that your patients have?
		QN4	Did your patients use adaptive clothing?
		QN5	What are the most commonly used types of clothing by your injured patients in the rehabilitation process?
	The injured patients (S2)	QN6	Enter your age
		QN7	What injury do you have?
		QN8	Do you have a limb amputation?
		QN9	Which limb did you lose?
		QN10	Do you have casts on your limbs?
		QN11	Do you have bandages on your limbs?
		QN12	Do you require clothing with features that make dressing and undressing easier?
		QN13	Have you worn clothes with features that make dressing and undressing easier?
The requirements for adaptive clothing for the injured people (QB2)	The hospital staff (S1), the injured patients (S2)	QN14	Is adaptive clothing needed for injured people?
		QN15	If you have previously used adaptive clothes, please rate their convenience on a 5-point scale: "5" - very convenient, "4" - convenient, "3" - neutral, "2" - inconvenient, "1" - very inconvenient.
		QN16	What sleeve length would be convenient?
		QN17	Would it be comfortable to wear a shirt that can be transformed into a T-shirt by unbuttoning the lower part of the sleeve?
		QN18	Is it comfortable to wear clothes with a fastener along the sleeve?
		QN19	Would clothing with a fastener at the bottom of the sleeve and in the side seam be more convenient?
		QN20	Would using fasteners on the shoulders and sides for injuries be more convenient?
		QN21	Which fastener (-s) in adaptive T-shirts is (are) more convenient?
		QN22	Would using a garment with a zipper insert to expand the sleeve make the dressing process more accessible and convenient?
		QN23	Would wearing pants with a side seam zipper be convenient?
		QN24	What is the most comfortable position when fastening adaptive pants?
		QN25	Would pants that transform into shorts be comfortable for an injured person?
		QN26	Would wearing pants with a back zipper be convenient?
		QN27	Which fastener (-s) in adaptive pants is (are) more convenient?
		QN28	Would using pants with a zipper insert to expand the leg make the dressing process more accessible and convenient?

Figure 1. The example for question QN27 with pictures.

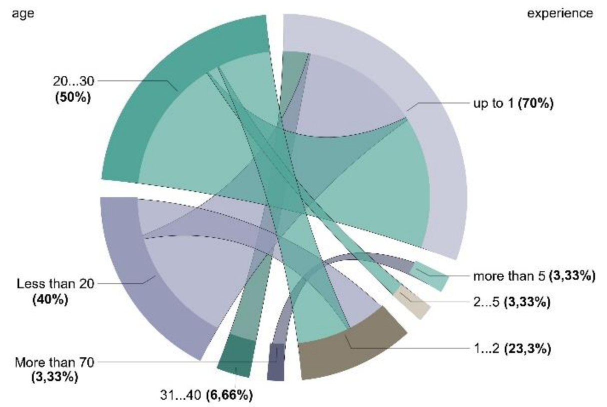
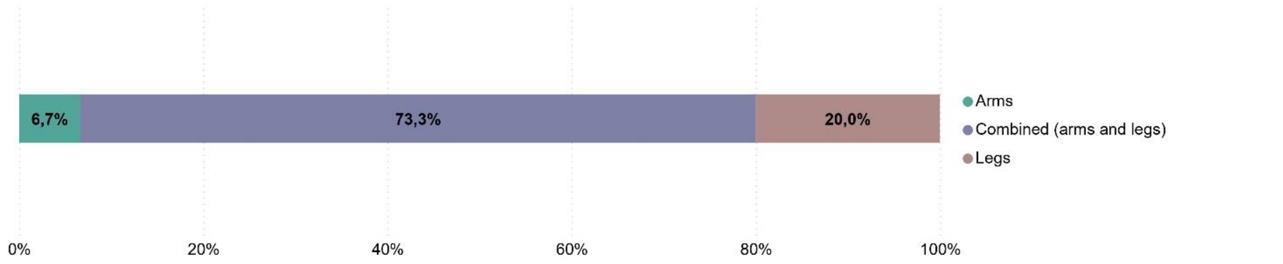


Figure 2. The hospital staff presentation by age and experience working with injured patients.

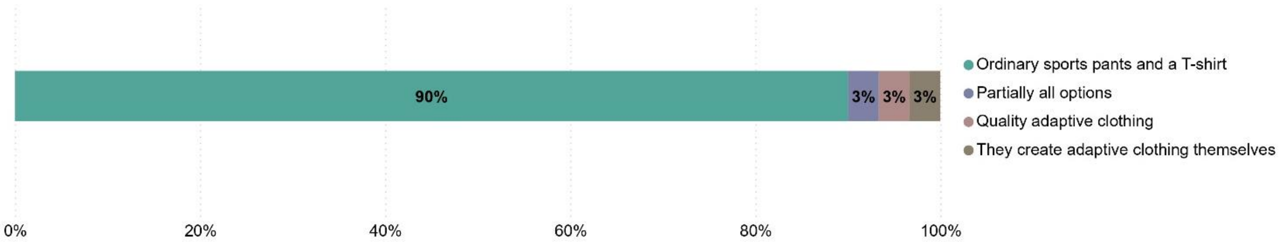
Half of the respondents in group S2 were between 20 and 40 (Fig. 4). Notably, 50% of the injured individuals utilized adaptive clothing in the treatment and rehabilitation. Furthermore, an overwhelming 95% of the respondents did not have casts on their limbs, and only 20% had bandages.

The information regarding the types of injuries and the proportion of limb loss resulting from those injuries is crucial for understanding the varying levels of restricted body mobility within the population and the associated challenges in creating adaptive clothing for this consumer group.

The survey analysis indicates that 20% of individuals experienced no limb injuries and maintained their body mobility despite other injuries. Additionally, some respondents (S2) reported limited mobility (25%) due to injuries to one arm or leg.



(a)



(b)

Figure 3. The hospital staff's opinion on common injuries (a) and the most used clothing of the wounded during rehabilitation (b).

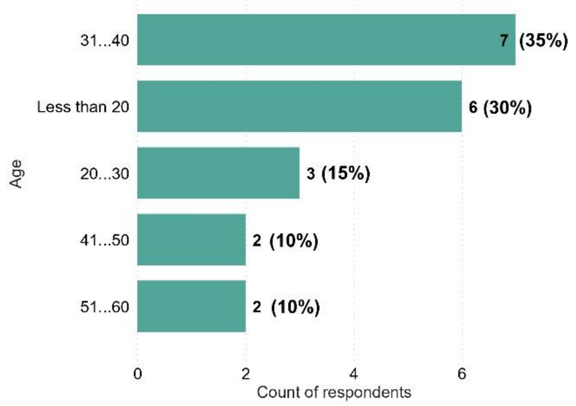


Figure 4. The injured patient's presentation by age.

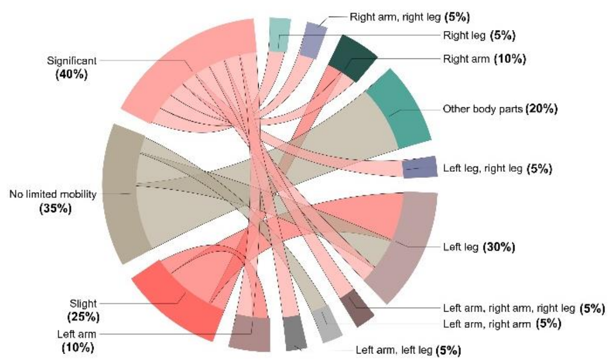


Figure 5. The relationship between limited body mobility and injury types.

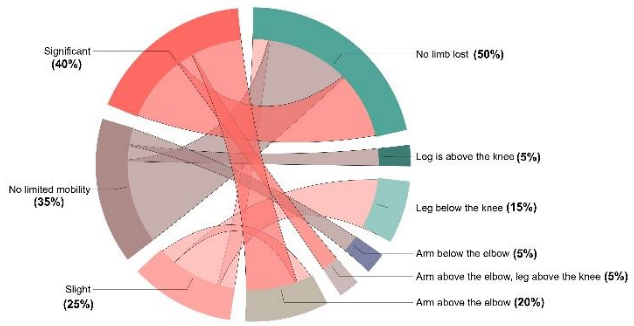


Figure 6. The relationship between limited body mobility and lost limbs.

Furthermore, the study revealed that 40% of people experienced significantly restricted mobility, with 20% of them having sustained combined limb injuries.

The relationship between limited body mobility and injury types is presented in Fig. 5. The research results show that 50% of respondents (S2) lost one or two limbs. 80% of patients with lost limbs had varying degrees of limited body mobility. However, some patients had significantly limited mobility without limb amputations (Fig. 6). The general data gathered about the participants in both groups (S1 and S2) has insights into the precise nature of the injuries sustained, the significant challenges in mobility faced by the injured individuals, and the urgent requirement for customized adaptive clothing to cater to their specific needs. This comprehension provides solutions to the hurdles associated with creating adaptive designs tailored to meet the needs of this particular consumer group.

The requirements for adaptive clothing for the injured people (QB2)

The second question block provides information regarding whether injured individuals require adaptive clothing. In a survey, 70% of hospital staff believed that adaptive clothing is essential for injured patients, citing the need for comfortable and convenient attire that accommodates medical equipment and assists patient care. Conversely, 30% thought that adaptive clothing is required only in specific situations, emphasizing the importance of flexibility and adaptability in providing tailored care to patients with diverse needs.

Question QN15 involves rating the convenience of the garments on a 5-point scale to evaluate the current adaptive clothing. According to the scale, "5" indicates that the garment was very convenient, "4" for convenient, "3" for neutral, "2" for inconvenient, and "1" indicates it was very inconvenient.

Fig. 7 and Fig. 8 depict the results of respondents S1 and S2 evaluating current adaptive clothing.

Hospital staff opinions regarding existing adaptive clothing indicate that 36.6% find it very convenient, while 3% consider it neutral. Amongst patients, only 15% perceive adaptive clothing as highly convenient. However, some respondents (S1 – 26.6%, S2 – 45%) did not provide an answer to this question. This could be because some staff members may not have observed the use of adaptive clothing, or some patients may not have had experience with these items before the survey.

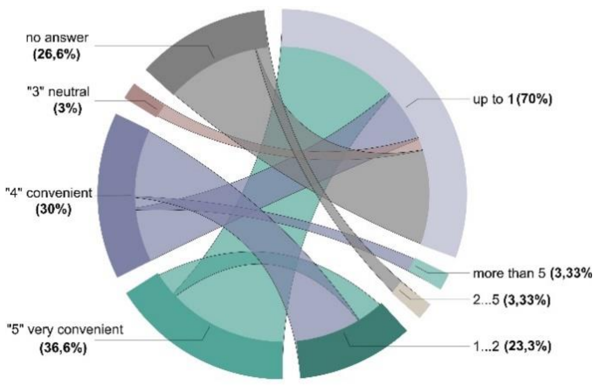


Figure 7. The relationship between evaluating existing adaptive clothing and hospital staff's experience.

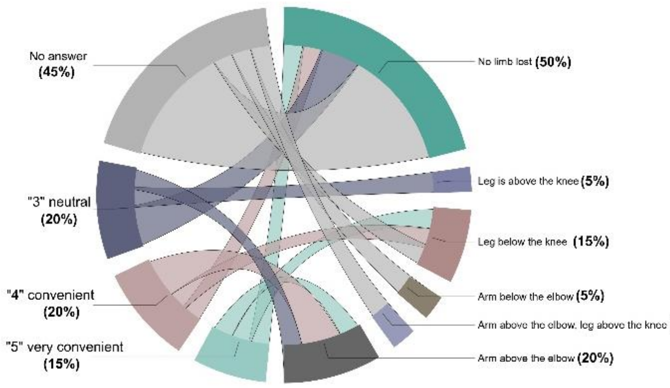
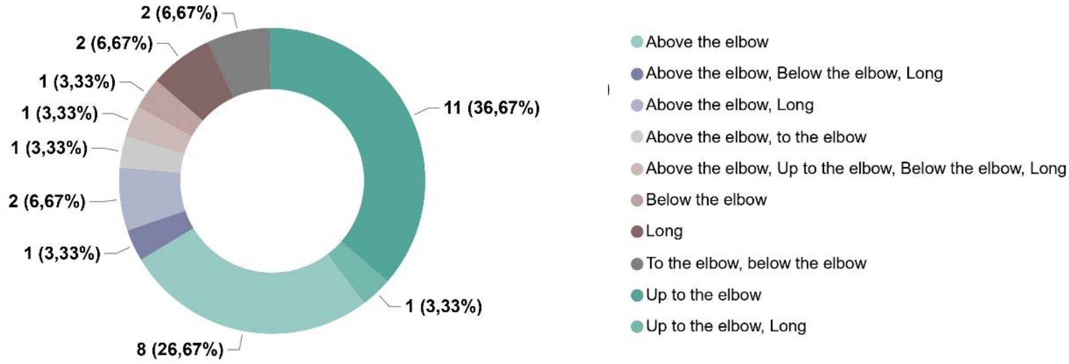
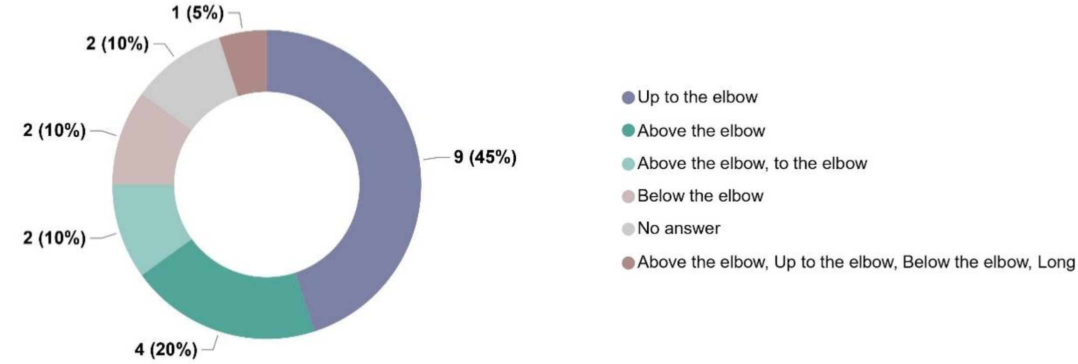


Figure 8. The relationship between evaluating existing adaptive clothing and availability of limbs.

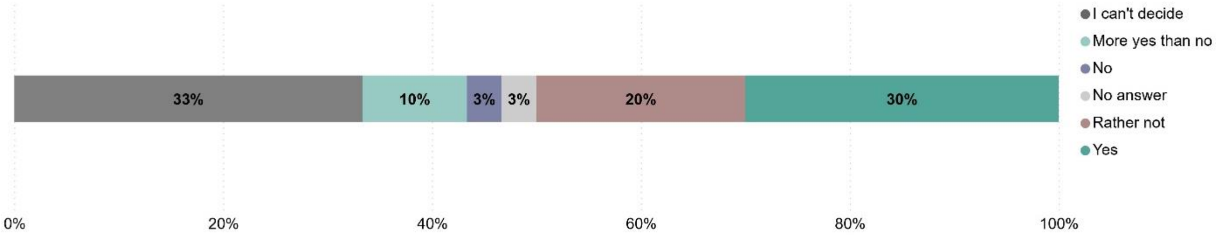


(a)

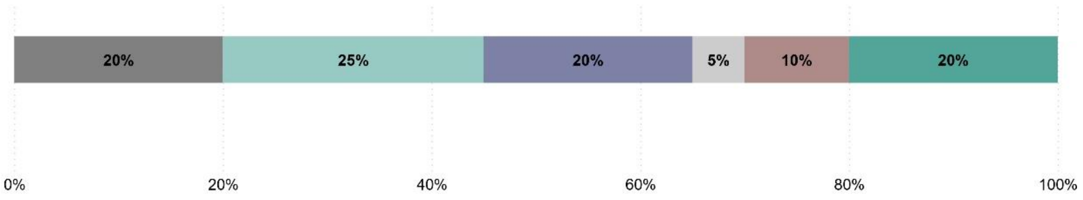


(b)

Figure 9. The preferred sleeve length of adaptive clothing by the insights from surveys S1 (a) and S2 (b).



(a)



(b)

Figure 10. The respondents' opinions about widening pants legs by zipper fasteners.

Questions QN16-QN28 focused on features that improve clothing functionality through the garment elements. Fig. 9 illustrates survey results for optimal sleeve length.

According to the survey, 10% of hospital staff and 25% of injured patients expressed that they found the idea of wearing a shirt that could be converted into a T-shirt by unbuttoning the lower part of the sleeve comfortable and convenient. Meanwhile, 3.33% (S1) of the respondents from one group and 20% (S2) from another group mentioned that they did not find this clothing design convenient. 16.67% of respondents in both groups haven't determined the answer.

Based on the survey results, 40% of respondents (S1) and 50% (S2) preferred clothes with a fastener along the sleeve, indicating that they find this feature comfortable. Additionally, 6.66% of respondents (S1) answered "No" when asked about their comfort level with this type of clothing.

Clothing with a fastener at the bottom of the sleeve and in the side seam would be convenient for S1 (26.67%) and S2 (45%). Various fasteners secure the garment's shoulders and sides. This design decision was approved by 60% (S1) and 50% (S2).

Our research identified more user-friendly fasteners for adaptive T-shirts: Velcro (S1 – 32%, S2 – 28%), zipper (S1 – 13%, S2 – 30%), and press stud (S1 – 25%, S2 – 20%); for adaptive pants: Velcro (S1 – 43%, S2 – 22%), zipper (S1 – 24%, S2 – 45%), and press stud (S1 – 30%, S2 – 30%).

Adaptive clothing incorporates elements that allow certain garment parts to expand, such as using a zipper fastener to extend the sleeves or legs. Our research revealed that 27% (S1) and 30% (S2) of participants expressed positive views about using zipper fasteners to make sweatshirts and hoodies more accessible and convenient. Meanwhile, 30% (S1) and 20% (S2) approved similar elements for pants (Fig. 10).

Our research found that the most comfortable ways to fasten adaptive pants are from the hip to the bottom (S1 – 41%, S2 – 30%) and from the top to the bottom (S1 – 35%, S2 – 30%). Fasteners from the knee to the bottom were preferred by 15% of S1 and 27% of S2. Additionally, 27% of S1 and 35% of S2 respondents preferred pants that can transform into shorts. On the other hand, 40% of S1 and 45% of S2 found pants with a back zipper to be inconvenient. However, 63% of S1 and 50% of S2 found pants with a zipper fastener in the side seams to be comfortable.

This information provides insights into the most common elements of garments that can be utilized in the adaptive design process.

Adaptive clothing design

The survey's results again affirm the pressing need for developing high-quality adaptive clothing that considers the specific requirements of patients, their caregivers, and medical professionals. The authors have put forward two sets of adaptive clothing designed to be worn together, catering to both summer and transitional seasons. These sets have been specifically designed to cater to the needs of men aged 18 and above, incorporating consumer preferences from our survey. Figure 11 presents a visual representation of the developed adaptive clothing sets.

A demi-season set consists of a hooded sweatshirt and pants (Fig. 11, a), a summer set of clothes consists of shorts and a T-shirt (Fig. 11, b), and a mixed set consists of a summer T-shirt and demi-season pants (Fig. 11, c).

The adaptive garments are loose-fit and designed to accommodate changes in injured patients' body sizes and shapes, allowing for variations due to swelling or weight fluctuations common during treatment and rehabilitation. The garment features additional Velcro openings in strategic locations, such as the side seams of the pants, T-shirt, hoodie, shoulder seams, and sleeve top, specifically designed for easy access to medical devices and catheters without requiring complete undressing. These deliberate design elements not only ensure unhindered access to medical interventions but also facilitate hygienic procedures without necessitating the removal of the garment, thereby playing a vital role in ensuring optimal care for patients undergoing long-term recovery.

Using the CAD Julivi, we developed patterns of adaptive clothing (Table 2). For men, we used sizes L—XL. The resulting patterns were dressed in 3D male models using Clo 3D Fashion Design Software to evaluate the fit of products and all design solutions of adaptive clothing from Fig. 11.

Knitted double-thread fabric (250 GSM) with an extensibility of 10% was used to produce experimentally developed adaptive clothing, namely, a hoodie, pants, and shorts. A plain cotton jersey fabric was used to produce a T-shirt. Accessories for fasteners were Velcro and laces for additional fixation of pants and shorts at the waist. After interview meetings with doctors and hospital patients, feedback on the newly designed adaptive clothing was given. These interviews suggested further expanding the legs and sleeves and adding another Velcro fastener location. They also emphasized the importance of using Velcro with high-quality adhesive properties.

After the recommended design alterations were incorporated, a specialized adaptive clothing batch was manufactured and distributed to hospital patients. Subsequently, a survey was conducted, involving in-depth interviews with nine male patients aged 20 to 45 who had been utilizing adaptive clothing for two weeks. Seven respondents reported having sustained leg injuries, while one patient had an arm injury, and another had a spinal injury, resulting in the inability to use both legs.

The survey asked participants to rate the convenience of developed adaptive clothing, the manufacturing quality, the textile quality, and the quality of the textile fastener on a five-point scale: "5" – very high quality/convenience; "4" – satisfactory; "3" – average; "2" – low; and "1" – poor quality/inconvenient. The survey results are shown in Figure 12.

The evaluation results indicate that the patients expressed high levels of satisfaction with the quality and convenience of the proposed adaptive clothing. Specifically, 89% of the surveyed individuals deemed the clothing to possess a high or satisfactory level of convenience, textile quality, and textile fasteners. Furthermore, all respondents, accounting for 66.7%, recognized the high production quality of adaptive clothing.

In addition, the respondents highly evaluated the quality of the textiles (44.4%) and the quality of the Velcro (77.8%), confirming the choice of high-quality materials for the production of adaptive clothing.

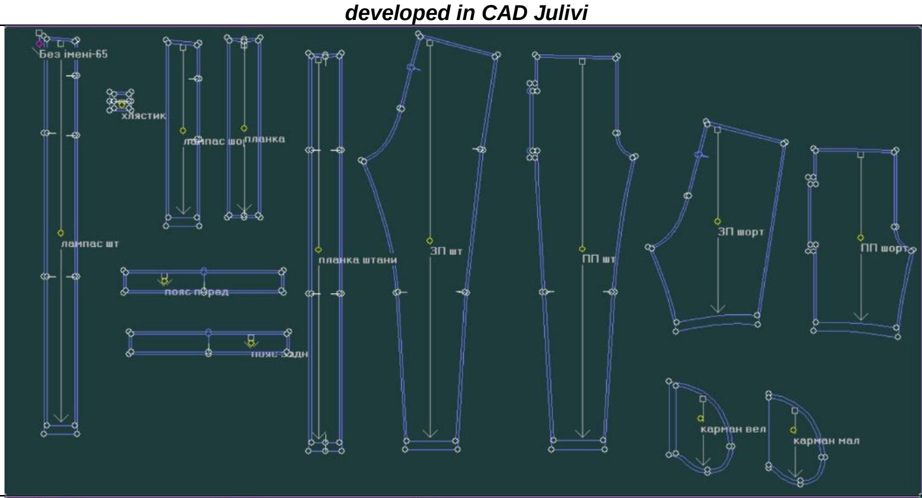
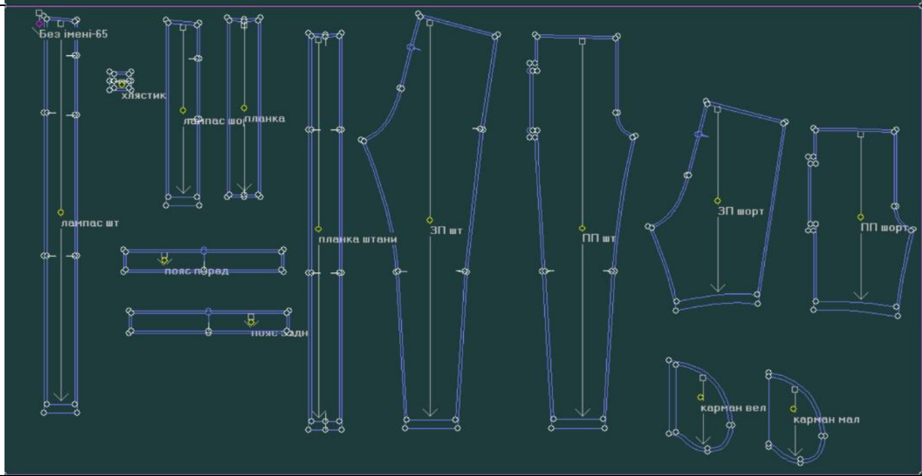
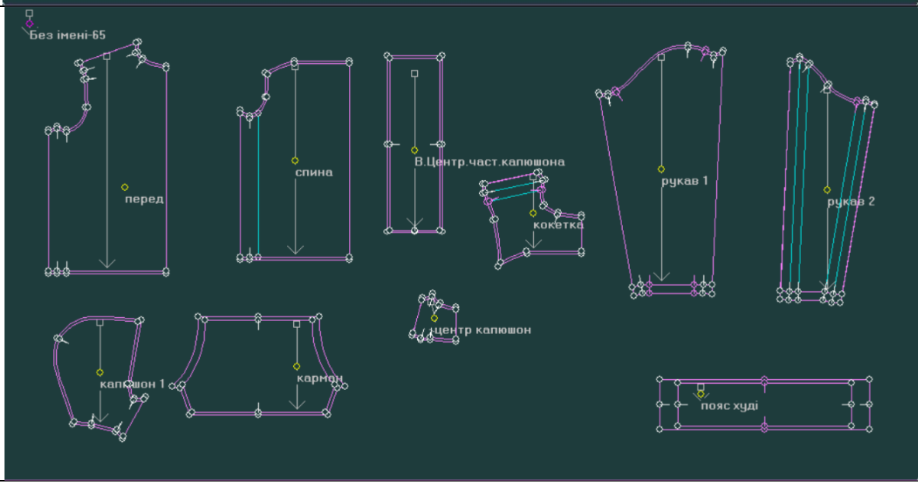
Among the various recommendations for enhancing adaptive clothing quality, the surveyed individuals emphasized the importance of using thinner and lighter textiles for manufacturing shorts. This suggestion was mainly motivated by high ambient temperatures above 30°C during summer.

In conclusion, the alterations made to the design of adaptive clothing have notably improved its overall convenience. Additionally, the meticulous selection of textiles and accessories was identified as crucial to ensuring high-quality adaptive clothing.

(a) (b) (c)

Figure 11. Adaptive clothing 3D models designed in Clo 3D: demi-season set (a), summer set (b), mixed set (demi-season pants and summer T-shirt) (c).

Table 2. Structural features of the developed adaptive clothing.

Product	***Pattern screens of products developed in CAD Julivi***
Shorts, pants	
T-shirt	
Hoodie	

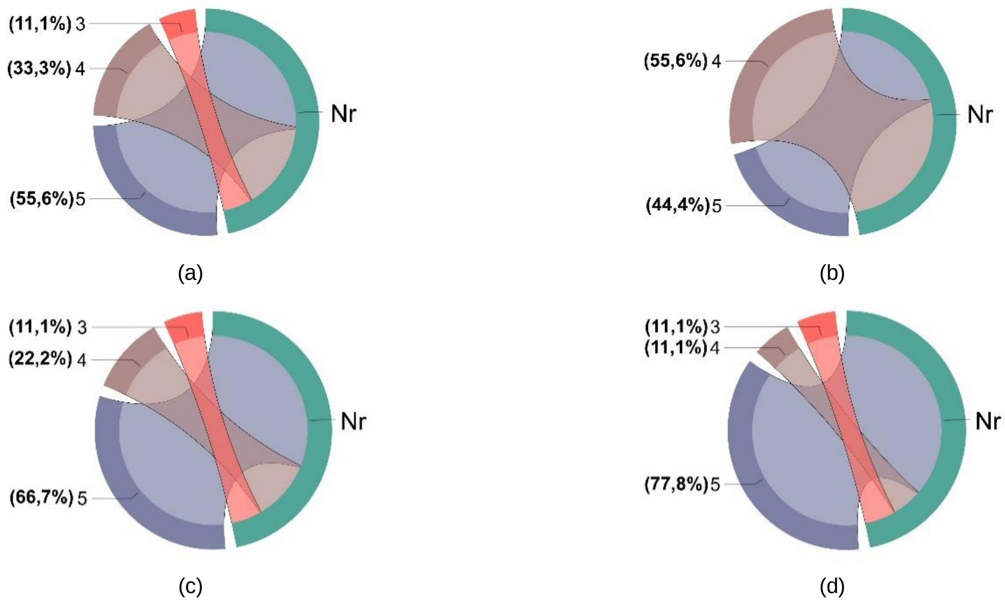


Figure 12. The evaluation of developed adaptive clothing by convenience (a), textile quality (b), production quality (c), and Velcro quality (d): Nr – total number of respondents (Nr=9); 3 – average, 4 – satisfactory, and 5 – high level.

CONCLUSIONS

Based on the literature analysis, it is evident that the field of adaptive clothing design is gaining attention from researchers due to the increasing societal focus on inclusiveness and accessibility. This heightened interest in adaptive clothing is especially important for Ukraine, where now there is a continuous demand for products that cater to the needs of injured individuals.

The research used a comprehensive approach, including engagement with hospital staff and patients with limb injuries to understand their exact requirements during treatment and rehabilitation. This collaboration provided insights into the nature of the patient's injuries, the deficiencies of their current clothing, and their preferences for functional solutions in adaptive clothing.

The information obtained was the foundation for creating sets of men's adaptive clothing, including sweatshirts, pants, T-shirts, and shorts. Considerations were made regarding the placement of cuts in the products, the type of fastenings, transformability, and the sizes and locations of individual parts. A post-wear survey conducted after two weeks confirmed the effectiveness of the developed adaptive clothing sets, with patients expressing high levels of satisfaction with their comfort and quality. The results of this study offer valuable guidance for adaptive clothing designers to address the specific needs of consumers with limb injuries effectively.

This research promotes accessibility and inclusivity by providing comfort and fostering opportunities for personal development among individuals with various limb injuries. The insights gained from this study will be utilized in future research on designing virtual adaptive clothing for individuals with limb amputations. Moreover, we aim to focus on future studies incorporating principles of circular economy and multifunctionality into the design and production of adaptive clothing, further advancing the field in a sustainable and impactful manner.

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THE EFFECT OF GARMENT CUTTING ON FIBER LENGTH RETENTION IN WOOL-BLEND OFFCUTS WITH RESPECT TO THEIR FUTURE USE IN RECYCLED YARN PRODUCTION

BASHO, MEGI*; CHAVOSHI, AVA AND CEBULLA, HOLGER

TU Chemnitz, Faculty of Mechanical Engineering, Professorship of Textile Technology, Reichenhainer Str. 70, 09126, Chemnitz, Germany

ABSTRACT

The growing demand for sustainable textile production highlights the importance for effective recycling of pre-consumer textile waste, particularly wool and wool blends. Production highlights the importance of recycling pre-consumer textile waste to minimize the environmental impact. While many studies focus on fiber recycling, few investigate the root cause of the fiber shortening during the cutting and shredding process. This study investigates how cutting fabric impacts fiber retention in recycled yarn production, focusing on three common knit patterns—Rib 1x1, Double Jersey, and Interlock. Using a 70% wool and 30% silk blend, the study identifies optimal cutting dimensions to minimize fiber loss during recycling. Experimental analyses of fabric samples (1–10 cm lengths) revealed that cuts of approximately 7 cm effectively preserved fiber lengths across all patterns, with confidence intervals demonstrating consistent retention. Image processing techniques further categorized leftover materials, enabling their allocation to specific spinning processes (short-staple, medium-staple, and long-staple). The findings contribute to optimizing recycling processes, improving fiber retention, advancing circular economy practices in textile production, and hold potential for practical implementation in automated recycling systems and enhanced yarn production workflows.

KEYWORDS

Textile Recycling, Pre-Consumer Waste, Wool, Wool Blends, Fiber Length Optimization, Rib, Interlock, Double Jersey.

INTRODUCTION

Fabrics, garments, and fibers are upcycled and recycled in a circular economy to maintain their high-quality value while reducing waste production; yet, around 53 million tons of fibers are generated globally each year in garment manufacturing via linear value chains. Raw materials such as crude oil and cellulose are used to create synthetic and cellulosic fabrics. 73% of global garment production is incinerated or discarded in landfills at the end of its life [1]. On a daily basis, a garbage truck full of textile waste is thrown around the world, consuming land, water, and fossil fuels and polluting the air, water, and soil [2]. When textiles are burned, chemicals and CO2 are produced [3]. The textile industry is one of the world's most important economic sectors, and it is growing in tandem with the worldwide population. Textile recycling reduces the necessity of new fibers in textile production, as well as the use of water and chemicals. Textile waste management is essential for lowering the environmental impact of the textile and garment industries [4]. Increasing textile waste clothing recycling aids in the transition to a circular economy by enabling a closed-loop circular textiles and fashion sector [1]. For this transition to be effective, parties in the (circular) value and supply chains have to engage and take act [1]. A system reform is necessary, with all players in the value chain contributing and cooperating [5]. The rate of change is determined by the quantity and quality of recycled textile waste fibers used in new fashion and interior textile production processes (Figure 1).

LITERATURE REVIEW

The current linear (take-make-dispose) economic model is increasingly unsustainable. Fortunately, circular economy concepts, which entail the continuous restoration and regeneration of value throughout a product's life cycle, are gaining traction in Europe. The circular economy model is defined by the three R's: reduce, reuse, and recycle, which are applied throughout the product's life cycle [6]. The circular economy is based on maximizing the use of available resources and generating renewable flows of materials and products [7]. Recent years have

* **Corresponding author:** Basho M., e-mail: megi.basho@s2024.tu-chemnitz.de

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Figure 1. Mechanical recycling of textile waste (authors own illustration).

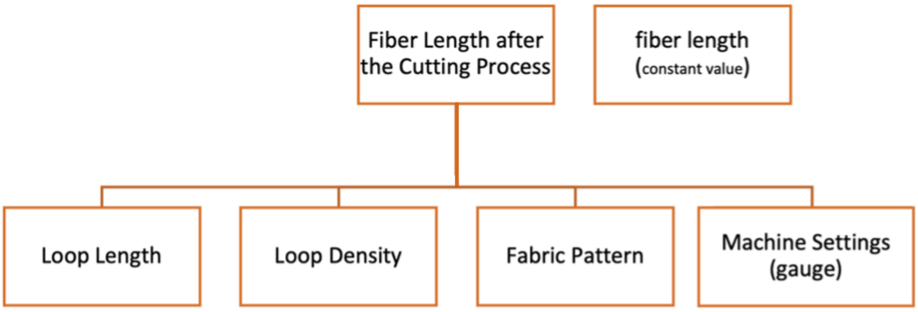

Figure 2. Illustration of the parameters that influence the fiber length after the cutting process (authors own illustration).

seen a surge in attempts to improve recycling efficiency in the textile industry. However, much of the focus has been on post-consumer waste, leaving a gap in understanding and addressing the difficulties of recycling pre-consumer waste, particularly wool and wool blends.

Fiber length is an important parameter in the recycling of wool and wool blends since it influences the quality and performance of the recovered yarn. Previous study has shown that longer fiber lengths result in stronger, more durable yarns that are more suited for recycling. Wiedemann et al. [8] and Wanassi et al. [9] discovered that precise cutting lengths can optimize fiber length during the shredding process, hence improving the quality of recovered yarn. Despite these findings, additional research is needed to improve fiber length and other key factors in recycling pre-consumer wool waste. This study seeks to close this gap by investigating factors influencing fiber length, such as sorting methods, textile orientation prior to cutting, surface design, and binding techniques, in order to establish new standards for closed-loop recycling of wool and wool blends via optimal cutting lengths and key elements in the cutting and shredding processes, as shown in Figure 2.

MATERIALS AND METHODS

Yarn and fabric production

The yarn used in this study consisted from a 70 % wool and 30 % silk fiber blend, with a linear density of Nm 44/1, 543 twists per meter, and an original fiber length of 76.2 mm, according to the producer, where the wool and silk fibers were cut in order to have the same length. Wool fibers had a diameter of 19.5 µm (merino wool), whilst silk fibers had a diameter of 12.3 µm (mulberry silk), ensuring blend-ability. The yarn went to a microscope examination, for distinguishing the wool and silk fibers within yarn, where a Leica Digital Stereomicroscope model M205 was used to acquire digital images from fiber and fabric samples (Figures 3 and 4). Furthermore, three knit patterns were produced from the same yarn blend with the same parameters: rib 1x1, double jersey, and interlock. The primary aim was to determine which knitting pattern, in combination with specific cutting lengths, would yield the highest fiber retention during the recycling process.

End use characteristics and testing

Several fabric properties were examined to assess recycling suitability, several parameters were examined, such as: loop density, loop length, square mass (weight) [g/m^2], etc. (Table 1). These parameters are important because they determine fabric weight, length, and dimensional stability, which all have an impact on the fabric's performance in various applications. To ensure consistency in the experiments, the fabrics were knit on a machine with the same gauge, loop length, yarn type, and yarn count. The mechanical qualities and performance of knitted textiles are heavily influenced by loop density, which is assessed on both the front and back of the fabric. In addition, fiber length was also investigated as it is a significant aspect in the recycling process. Ten samples of raw yarn, each measuring 50 cm, were obtained to assess fiber length distribution using ISO 6989:1981 Method A [12], in which an investigation of 100 fibers per yarn was made. Yarn was untwisted and the fibers were carefully removed from the yarns to determine their respective length using a WIRA Instrumentation machine, specifically designed for precise single fiber length measurements. Furthermore, to assess the fiber length within the fabrics, samples from 1 cm to 10 cm per each fabric were collected, with every fabric sample unraveled back into yarn. For every fabric pattern—Rib 1x1, Double Jersey, and Interlock—10 samples of yarn were collected for each fabric length for loop length examination. This means that for each fabric length (from 1 cm to 10 cm), 10 separate yarn

Table 1. Knitted fabric parameters.

Samples	**S1**	**S2**	**S3**
Garment	T-Shirt	T-Shirt	T-Shirt
Fiber Content	70% merino wool/ 30 % mulberry silk	70% merino wool/ 30 % mulberry silk	70% merino wool/ 30 % mulberry silk
Fabric Type	Weft knit, Rib1x1	Weft knit, Double Jersey	Weft knit, Interlock
Areal Density [g/m^2]	218	214	221
Yarn Fineness [tex]	22.7	22.7	22.7
Loop Length [mm] (per 10 cm)	61.25	65.87	76.51

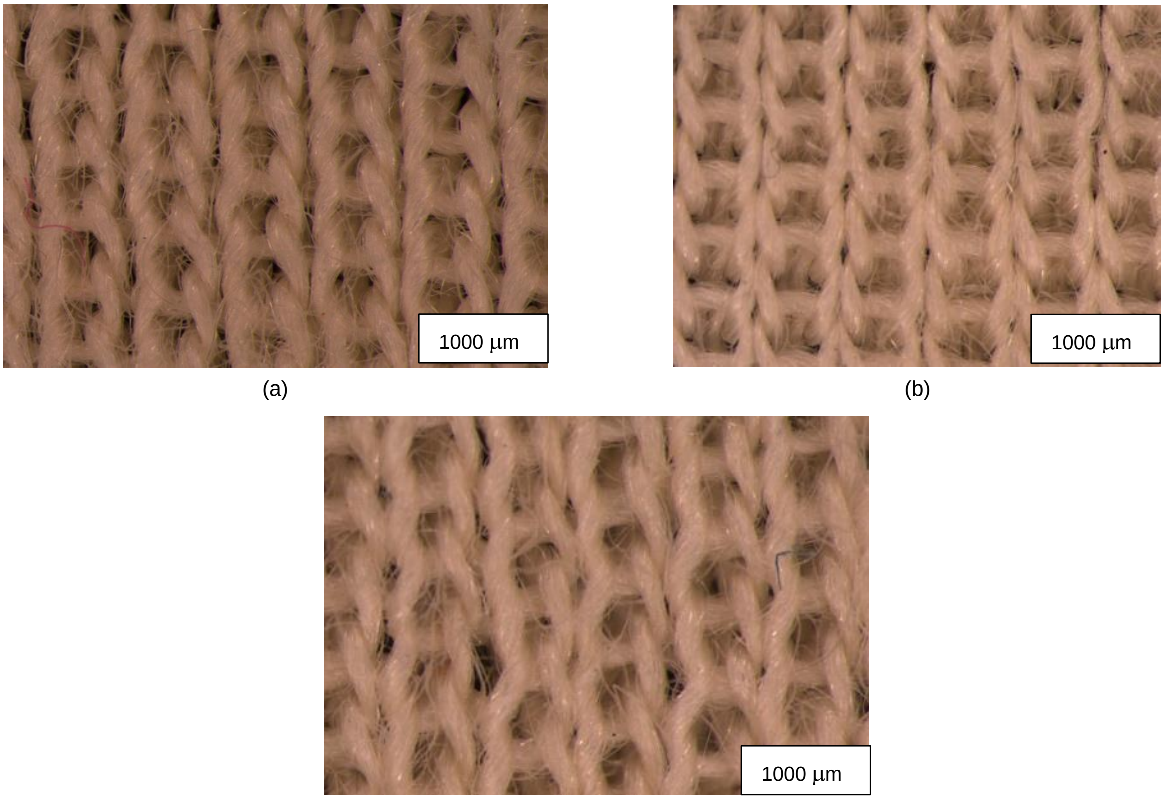

Figure 3. Microscopic images of three knitted patterns: (a) rib1x1, (b) double jersey, (c) interlock with a scale of 1000 μm.

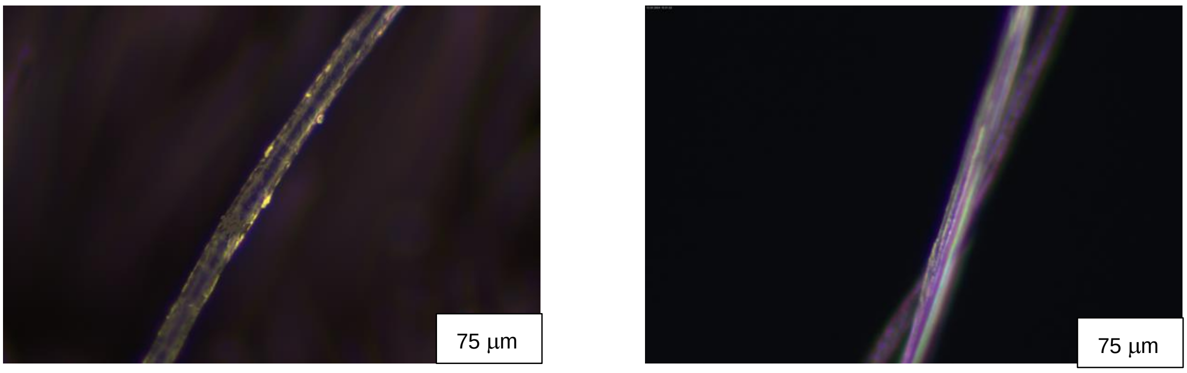

Figure 4. Fiber identifying on microscope with a scale of 75 μm: (a) wool fiber, (b) silk fiber.

Table 2. Loop density of 3 types of knitted fabrics [cm^{-1}].

	Wale			Course		
	MEAN [mm]	**STD [mm]**	**CV [%]**	**MEAN [mm]**	**STD [mm]**	**CV [%]**
Rib 1x1	10.7	0.67	5.1	9.8	0.42	4.3
Double Jersey	13.2	0.63	4.8	10.2	0.42	4.1
Interlock	13.6	0.52	3.8	13	0.67	5.1

samples were carefully unraveled and tested for fiber length with the same ISO 6989:1981 method [12]. This detailed process allowed for a precise evaluation of how cutting affects the fibers within the fabric structure.

Knitting machine

The knitted fabric samples were produced in a circular double bed knitting machine, namely a Terrot type RH 216-1. This machine features an E20 gauge, allowing it to make efficient and high-quality fabrics. The machine was set up to knit three fabrics (Rib1x1, Double Jersey, and Interlock) with the same yarn blend. This continuous yarn specification ensures that the three fabric samples are comparable, allowing for precise study and comparison of their end-of-use qualities. The main factor that influences the rows and the columns of the fabric is the machine gauge, that played a key role in determining the structure and density of the rows and columns in each knitted fabric, influencing the overall fabric characteristics, with the yarn evenly distributed in the whole fabric (length, width etc.).

Fiber length measurement

Fiber lengths were measured using a WIRA Instrumentation machine (manufactured in Italy), specifically designed for precise single fiber length measurements. The assessment began by measuring fiber lengths from ten raw yarn samples, each 50 cm long, to establish a baseline for fiber length distribution prior to recycling. Fibers were subsequently extracted from the leftover fabric, which had been precisely cut into samples of varying lengths, ranging from 1 cm to 10 cm. This step aimed to thoroughly assess how the cutting process affected fiber length. For each fabric sample, 100 individual fibers were carefully analyzed [12].

RESULTS AND DISCUSSION

Loop density

The loop density data (Table 2) provide valuable insight on the structural properties of the knitted fabrics investigated in this pre-consumer waste recycling research.

Analysis found that the Rib 1x1 sample designation had a wale density of 10.7 loops per centimeter and a course density of 9.8 loops per centimeter, implying a balanced and consistent distribution of loops throughout the fabric. The loop density for the Double Jersey pattern was determined to be 13.2 loops per centimeter in the wale direction and 10.2 loops per centimeter in the course direction. When compared to Rib 1x1 and Interlock, Double Jersey's loop density resides between the two, providing a good combination of density and flexibility. The tension used in Double Jersey is higher than in Rib 1x1, leading to a denser wale structure, but the course direction remains relatively less dense due to the fabric's inherent elasticity and double-layered construction. In comparison, the Interlock sample designation had a higher loop density, with 13.6 loops per centimeter in the wale direction and 13 loops per centimeter in the course direction, indicating a denser and tighter knit fabric construction.

Fiber length distribution in raw yarn length

The yarn producer's data sheet reported an initial fiber length of 76.2 mm for both wool and silk fibers. To assess the actual fiber length distribution, ten raw yarn samples, each 50 cm in length, were analyzed using the aforementioned ISO method, which involves examining 100 fibers per sample. The yarn was carefully untwisted, and individual fibers were extracted for precise measurement. Cross-verification of the results revealed a minimum fiber length of 72.8 mm, a maximum of 74.2 mm, and an average of 73.4 mm, with a standard deviation of 0.47 mm and a coefficient of variation of 0.64 %. These findings, illustrated in Figure 5, provide a more accurate understanding of the actual fiber length, which is a critical parameter for evaluating recycling efficiency.

Distribution of fiber length and yarn length (loop length) in cut fabrics

To determine the influence of different cutting lengths on the fiber length, the fabrics were cut in samples from 1 cm till 10 cm in course direction. Afterwards the loops of the fabric pieces are unraveled. The loop length for 10 cm on each of the knitted fabrics is shown in Table 1. The analysis focuses on the course direction (width) because the loops that define the structure of weft knitted fabrics are aligned in this direction (Figure 6).

The loop length (LL) of 10 cm fabric samples for the three knitted patterns shows significant variation in both average loop length and consistency. The Interlock design has the longest mean loop length (76.51 cm), indicating a higher yarn need per unit length than the other patterns.

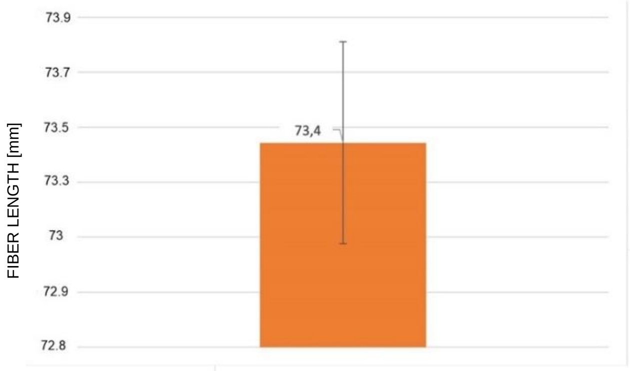

Figure 5. Mean [mm], standard deviation [mm], and coefficient of variation [%] of fiber length in ten raw yarn samples.

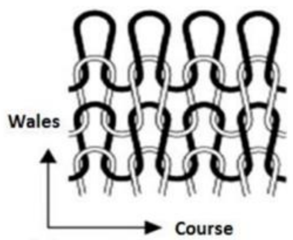

Figure 6. Course and wale direction [13]

Double Jersey, with an average loop length of 65.87 cm, is slightly longer than Rib 1x1, but much shorter than Interlock. The Rib 1x1 pattern has the least mean loop length of 61.25 cm and is the most yarn-efficient for this fabric sample size. For the fiber length distribution in cut fabric length were analyzed three knit patterns: Rib 1x1, Double Jersey, and Interlock. Fiber lengths were measured across fabric sample lengths of 1–10 cm for each pattern, following ISO 6989:1981 Method A. The experimental setup included 100 fiber measurements per sample, with ten yarn samples unraveled per fabric length. The analysis incorporated 95% confidence intervals (CIs) to quantify variability and precision in fiber retention (Figure 7).

The analysis of the Rib 1x1 pattern showed fiber lengths ranging from 44.8 mm to 74 mm within the yarn. It was found that cutting the fabric into lengths greater than 6 cm - ideally between 7 cm and 10 cm -helped retain fiber lengths close to 73.4 mm to 74 mm. This better fiber retention in Rib 1x1 can be attributed to the lower yarn tension during knitting, allowing the fibers to preserve more of their original length. For the Interlock pattern, fiber lengths varied from 46.6 mm to 74 mm, with the optimal cutting length identified between 5 cm and 10 cm. The higher yarn tension used in this pattern resulted in a tighter knit, which caused a slightly greater reduction in fiber length during recycling compared to Rib 1x1. However, despite this reduction, the denser structure of Interlock provided sufficient strength in the recycled fibers. External influences, such as environmental conditions and temperature shifts, may also influence the variability exhibited at the 4 cm length, affecting the fabric's structure. Humidity and temperature changes are known to affect the mechanical properties of textiles, such as fiber tension and elasticity, potentially worsening the effects of loop density and yarn tension when cutting.

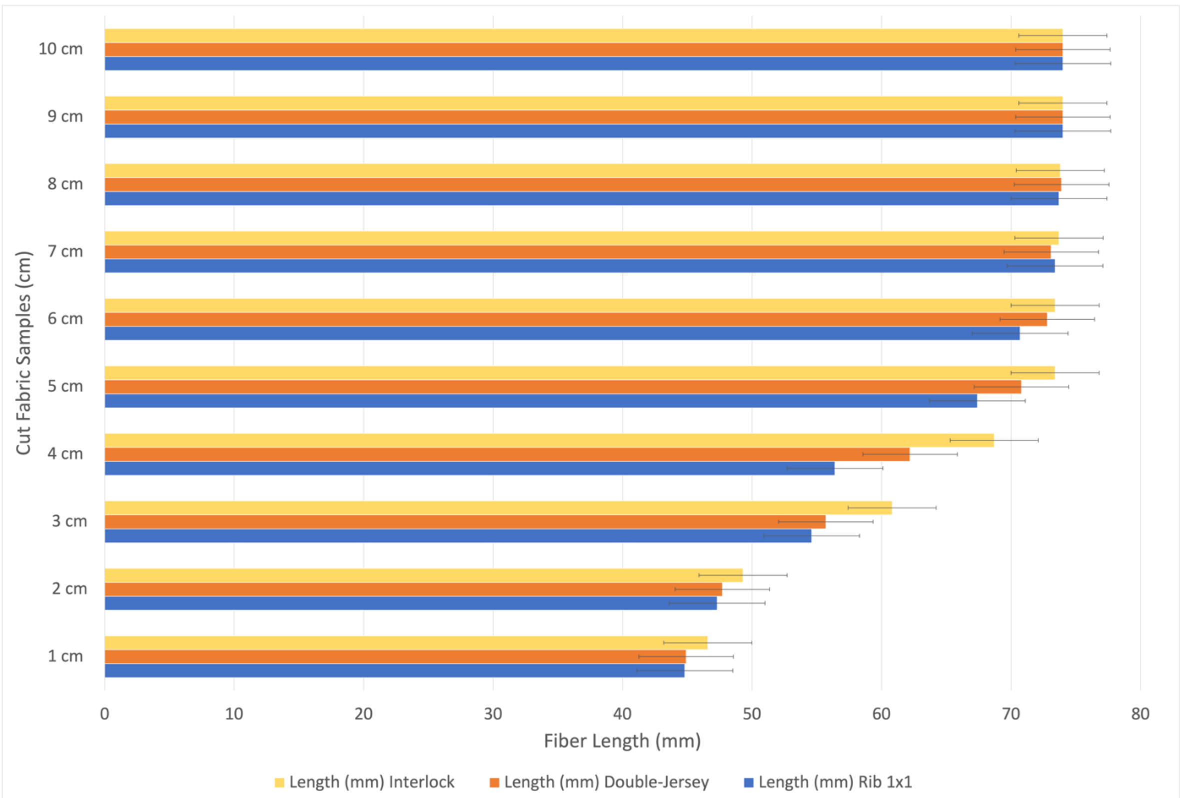

Figure 7. Fiber length of wool-silk blends from cut pre-consumer-waste fabrics (Rib 1x1, Double Jersey, and Interlock).

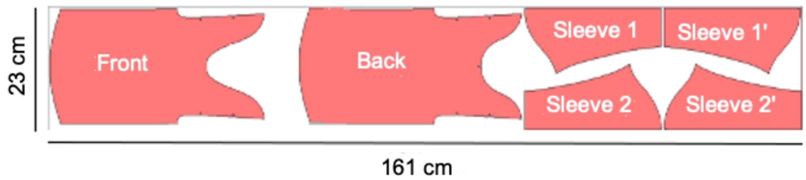

Figure 8. Basic T-Shirt Cutting Pattern (authors own illustration).

Double Jersey pattern offered additional insights into recycling efficiency. Fiber lengths in Double Jersey samples ranged from 44.9 mm to 74 mm, and the best cutting length for recycling was determined to be between 6 cm and 10 cm. While this range is similar to the Rib 1x1 and Interlock patterns, Double Jersey's looser structure resulted in slightly shorter average fiber lengths, which could influence the strength and quality of the recycled yarn. The higher tension applied in the wale direction during Double Jersey knitting created a more compact fiber arrangement, leading to a slight reduction in fiber length. However, by maintaining a cutting length between 6 cm and 10 cm, the resulting fiber lengths remained close to the original 72.8 mm to 74 mm. The diagram displays the fiber lengths for three knit patterns—Rib 1x1, Double-Jersey, and Interlock — across different fabric sample lengths, with 95% confidence intervals (CI) given to show measurement variability. The error bars show the confidence intervals, which provide information on the precision of fiber length retention. Rib 1x1 has the lowest fiber retention, especially in shorter fabric samples, and exhibits greater variability, as indicated by bigger error bars. With a CV of 14.20% and a CI of 5.33 mm, Rib 1x1 has the most variability of the three knit patterns, indicating less consistency in fiber length preservation after recycling. The coefficient of variation (CV) for Interlock is 12.66 %, showing moderate variability, and the CI (5.04 mm) is quite narrow, indicating a consistent and stable fiber retention mechanism. Double-Jersey has similar tendencies but has slightly shorter fibers than Interlock, with more apparent variability. The CV for Double-Jersey is 13.50 %, indicating slightly more variability than Interlock, while its CI (5.20 mm) indicates significantly less precision.

An important observation is that, as shown in Figure 7, after a fabric length of 7 cm, the fiber lengths in the cut samples became identical. This suggests that the cutting dimensions - whether 7x7 cm, 10x10 cm, or even 15x15 cm - have little effect on fiber length retention beyond 7 cm. The fibers in these samples reflect their true length, and this consistency can only be ensured through careful examination of the fabric pattern.

Impact of cutting size and pattern type

In this sub-chapter, fiber lengths within the leftover fabric from pre-consumer wool-silk waste were analyzed. During this investigation, it was found that this waste varies significantly in both shape and size. This prompted the question of how to determine optimal cutting dimensions before recycling to maximize fiber retention. To explore this, a commonly used garment-cutting pattern of a T-Shirt studied, identifying different fabric lengths in the leftover material.

Figure 8 presents a template a T-Shirt cutting pattern, commonly used by garment producers and designers, illustrating the cutting procedure and highlighting areas of leftover fabric. These leftover pieces, whose size and shape are key to fiber retention during recycling, play a crucial role in determining the fiber length outcome. In this case study, the knitted fabric measured 161 cm in length and 23 cm in width, although due to the tubular production on a circular double-bed knitting machine, the actual fabric width would be 46 cm if cut open.

The pink area represents the fabric used for garment production, while the white area shows the leftover pre-consumer waste. The fabric used for two garments is 161 cm, yielding an efficiency of 73 %. The main objective is optimization of the recycling process through the minimization of the fiber length reduction during the process, therefore to reduce the amount of the fiber waste.

Image analysis

Image processing techniques were employed to automate the measurement of fiber lengths in the white area of the fabric pattern depicted in Figure 8, enhancing process efficiency and reducing measurement errors associated with manual methods. The script, developed in Python using OpenCV, Numpy, and scikit-image libraries, first converts the original image to grayscale and then applies the Otsu threshold method to convert it to binary format [14, 15]. To ensure accurate detection, a single-pixel white padding is added around the fabric parts to prevent border interference. Subsequently, two sets of functions are utilized to identify and store the length and location of textile parts in each column of the image. The pixel-based results are then converted to millimeters using metadata from the original image (Figure 8), then the program rounded the lengths to mm. The outcomes ranged from 1 mm to 239 mm. It means each fiber is flagged with red, light blue, blue, and green, based on its detected length. In a further step, to visually represent this division, the fibers are shown with their represented tag-colors in Figure 9(a), 9(b) and 9(c).

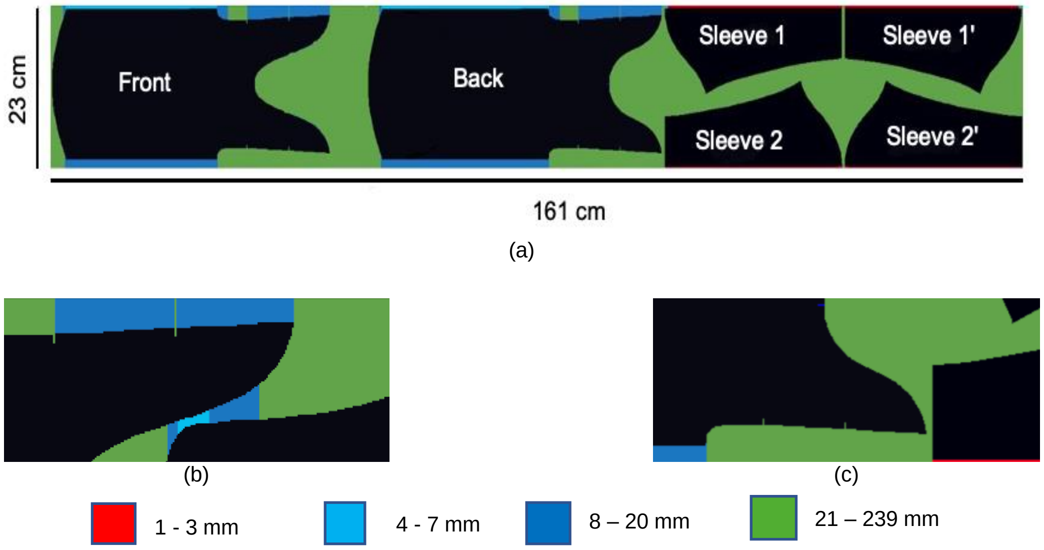

Figure 9. (a) Cutting Pattern colored in accordance with the length of the detected fibers after the cutting process; (b) and (c) magnified view of fiber length distribution in the cutting pattern after the cutting process (authors own illustration).

Table 3. Fabric length [mm] from the leftover material in the cutting pattern; conversion and categorization to fiber length [mm] with programming language.

Categories	Fabric Length [mm]	Fiber Length [mm]
	1	4.5
	3	13.4
	4	17.8
	5	22.4
	6	26.8
	7	31.3
	8	35.8
	9	40.3
	10-15	45.3
	16-20	46.8
	21-25	51.2
	26-30	55.0
	31-35	59.4
	36-40	62.0
	41-45	65.4
	46-50	67.3
	51-55	69.7
	56-60	70.4
	61-65	71.6
	66-70	72.9
	71-239	74.0

The fabric lengths resulted from this analysis, then were multiplied from the program with the average values from the Figure 7. The fiber length for very short fabric pieces, such as a 1 mm leftover, is predicted to be 4.5 mm. This proportionate association persists throughout the dataset, indicating a progressive rise in fiber length as fabric length increases. As fabric lengths increase, this pattern remains visible. For example, fabric leftovers of 10-15 mm equate to a fiber length of 45.3 mm, while those measuring 16-20 mm correspond to a slightly longer fiber length of 46.8 mm. This slow increase implies a direct but non-linear relationship between fabric length and fiber length, implying that as fabric length grows, the converted fiber length reaches a limit. This plateau effect is evident in bigger fabric lengths, as fiber length reaches approximately 74 mm for fabric remnants ranging from 71 to 239 mm, implying that the conversion rate stabilizes after a certain fabric length.

Table 3 indicates that the conversion from fabric to fiber length is not purely linear, with diminishing rewards as length increases. This data is critical for evaluating fiber recovery efficiency in textile recycling, especially when planning for fiber reuse in new yarn manufacturing, where fiber length uniformity can influence yarn quality and textile performance. To visualize the outcome, the different fiber lengths are flagged with different colors (red for 1 mm to 3 mm, light blue for 4 mm to 7 mm, dark blue for 8 mm to 20 mm, and green for 21 mm to 239 mm). This categorization not only helps identify fiber lengths but also aligns each length range with an adequate recycling process, improving sorting accuracy for spinning applications. These insights allow manufacturers to optimize cutting techniques to minimize the generation of less valuable shorter lengths and maximize the retention of high-contributing ranges. This analysis serves as a foundation for directing specific fabric lengths toward appropriate spinning methods (e.g., short-staple, medium-staple, or long-staple), further enhancing the recycling process. By identifying and focusing on the most impactful categories, this approach aids in optimizing textile waste recovery and contributes to sustainable practices in circular textile production.

Categorization of the leftover fabric waste

The classification of residual fabric lengths was meticulously determined by evaluating the remaining fabric fragments, as shown in Figures 9(a), 9(b), and 9(c), and converted to fiber lengths as shown in Table 3. These fragments, often discarded as waste, are further categorized in different spinning processes according to their length and are illustrated in Figure 10.

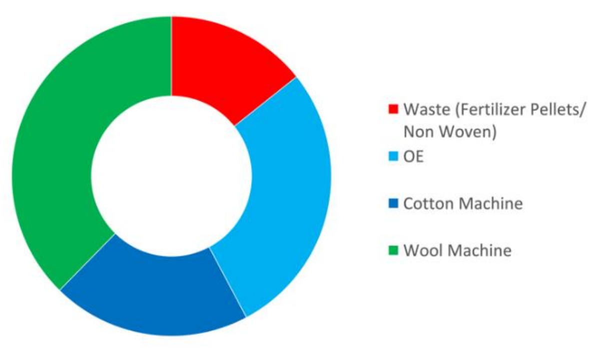

Figure 10. Classification of pre-consumer-waste prior to cutting process [%].

The next step in the recycling process is the spinning process where the fibers are processed by different spinning processes. The long staple fibers can again process in a long staple spinning machinery for wool (green fibers > 50 mm). This is the largest portion with 37.6 % of the fabric.

The fibers with middle fiber length can be processed in the so-called Cotton spinning process (dark blue: from fibers between 35.8 mm to 46.8 mm). Additionally, 20.1 % of the fabric is categorized for processing with cotton spinning machinery. This category requires moderately longer fibers, making it suitable for re-spinning into new yarns. The shorter fibers can be processed in the Open-End spinning process (light blue: from 17.8 mm to 31.3 mm), with a 27.9 % of the fabric is suitable for this spinning process. The OE spinning system is particularly efficient for shorter fibers, making it an ideal choice for this category of residual fabric.

And the rest 14.3 % (from 4.5 mm to 13.4 mm) is too short for dry spinning process. This waste we still can use for non-woven processes or for fertilizer pellets. This classification system optimizes the recycling process by ensuring each type of residual fabric is directed to the most appropriate reprocessing method, maximizing efficiency and sustainability.

Future research

Future research should expand on these findings by looking at a wider range of fabric designs, such as Single Jersey and other core knit structures, in order to gain a more complete understanding of fiber length and retention across diverse patterns. Incorporating these additional patterns would allow for a more comprehensive investigation of the basic knit structures, increasing our understanding of how different knit types effect fiber retention and waste management outcomes.

The following crucial step is to apply these insights directly to cutting machine procedures. This would entail applying the optimal cutting lengths and techniques discovered in this work to actual applications, allowing for the optimization of cutting machine settings for different fabric types and patterns. Researchers can improve the efficiency and precision of fiber recovery by refining the cutting process, ensuring that the maximum feasible fiber length is kept throughout recycling. Furthermore, this study will focus on optimizing the shredding process that occurs after cutting. An efficient shredding process would be designed to manage the various fabric lengths and thicknesses discovered during cutting, ensuring that fibers remain as intact as possible, improving the quality of recovered fibers and lowering waste. Fine-tuning the shredding parameters to meet the individual needs of various knit patterns could considerably increase the production and quality of reusable fibers. By implementing automated technologies, such as advanced fiber measurement and sorting systems, recycling facilities could significantly increase efficiency, reducing labor costs and minimizing resource usage. Exploring automation's potential to streamline the recycling process and decrease material loss would contribute to a more sustainable approach to textile waste management.

CONCLUSIONS

This study emphasizes the importance of fabric designs and cutting lengths in maximizing fiber retention when recycling wool and wool-silk mixes, where these findings suggest that cutting fabric into 7 cm lengths efficiently reduces fiber loss, especially in the Interlock design, which had the maximum fiber retention due to its dense loop structure. This method kept fiber lengths near to the original length, demonstrating that targeted cutting tactics and fabric design are critical in minimizing fiber damage throughout the recycling process. Statistical evaluations, including confidence intervals and coefficients of variation, show that Interlock's compact structure is more consistent in fiber retention than Rib 1x1 and Double Jersey, which have higher variability in fiber length preservation. These findings highlight the importance for employing appropriate fabric structures and cutting procedures to improve the quality of recycled yarn, establishing wool-silk blends as a valuable, sustainable resource in closed-loop textile production systems. The study's classification of fiber lengths for certain spinning processes (e.g., Open-End, Cotton, and Wool) demonstrates how targeted recycling procedures can enhance resource efficiency by diverting waste to appropriate reprocessing technologies. Advancing these developments will help to create more environmentally friendly textile processes and a sustainable approach for managing textile waste.

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CREATIVE APPROACHES TO TEACHING SUSTAINABLE DESIGN

VESELÁ, ZUZANA*; NOSÁLOVÁ, AGÁTA; STŘÍDOVÁ, ANNA; KLOZOVÁ, KATEŘINA AND DITTRT, ŠTĚPÁN

Technical University of Liberec, Faculty of Textile Engineering, Department of Design, Studentská 2, 46117 Liberec, Czech Republic

ABSTRACT

Sustainable design has become a crucial standard of modern design, with its teaching requiring the integration of theory, practice, and innovative pedagogical approaches. This article presents creative teaching methodologies at the Department of Design, Faculty of Textile Engineering, Technical University of Liberec, focusing on Design Thinking combined with Zero-Waste Fashion methods and the integration of artificial intelligence. The instruction blends traditional principles inspired by Bauhaus pedagogy with modern technologies and interdisciplinary projects, thus preparing students for the challenges associated with environmental responsibility. Through specific student projects, the article demonstrates how these innovative approaches can be applied in practice and how they foster the development of empathy, creativity, and critical thinking. Research findings confirm that integrating sustainable methods into education enables students to create aesthetically appealing and functional designs with minimal environmental impact. This approach proves to be pivotal in shaping a new generation of responsible designers.

KEYWORDS

Sustainable Design; Zero-Waste Fashion Design; Design Thinking; Artificial Intelligence; Empathy in Design, Art Pedagogy.

INTRODUCTION

Sustainable design is becoming a key standard for designers across industries, with its importance growing alongside global environmental challenges. Teaching these principles requires a combination of theoretical knowledge, practical experience, and innovative approaches that foster creativity, critical thinking, and the ability of students to address complex problems.

This article focuses on the teaching methodologies of sustainable design at the Department of Design, Faculty of Textile Engineering, Technical University of Liberec (TUL FT KDE). It examines approaches based on the Design Thinking framework, combined with Zero-Waste Fashion methods, the integration of artificial intelligence, and creative techniques inspired by Bauhaus reform pedagogy. This combination enables students to connect environmental responsibility with the aesthetic and functional aspects of design.

The aim of this article is to highlight the core pedagogical methods and demonstrate their practical application through specific student projects. These methods not only support the aesthetic and functional aspects of design but also foster a sense of responsibility and empathy among future designers. Emphasis is placed on interdisciplinarity and the ability to address global environmental challenges.

The integration of sustainability into the creative process of design education has significantly evolved, especially as global awareness of environmental issues has increased. A key moment was the United Nations General Assembly (UNGA) Resolution 57/254, which initiated the UN Decade of Education for Sustainable Development (DESD) for 2005-2014. The resolution highlighted the need for education reform to promote sustainable practices across various fields, including design. This initiative marked a methodological shift from traditional problem-solving approaches to a system-oriented perspective. The proclamation encouraged not only designers but also educational institutions in creative pedagogy for design to consider the broader implications of their work within social and environmental contexts.

As global awareness of environmental challenges has intensified, educational institutions increasingly recognize the importance of equipping students with the skills and knowledge necessary to address complex sustainability issues through creative learning methods. This shift reflects a broader commitment to fostering ethical awareness, critical

* **Corresponding author:** Veselá Z., e-mail: *zuzana.vesela@tul.cz*

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thinking, and collaborative problem-solving among future designers, thereby enhancing their ability to contribute to a sustainable future.

“Design is a way of thinking. Everything around us has an artificial origin, and someone had to design it.” [2] The term Design Thinking dates back to the 1960s and was first described by Herbert A. Simon in his book *The Sciences of the Artificial* [2], paving the way for the development of the Design Thinking concept as we know it today. The complexity of teaching sustainable design offers the opportunity to incorporate interactive and nonlinear project solutions through Design Thinking into innovative pedagogical processes. This method, as defined today, was developed by Stanford’s design school in collaboration with the innovation studio IDEO and consists of five phases: Empathize, Define, Ideate, Prototype, and Test. It is an innovative problem-solving approach focusing on understanding the user, empathy, and a creative process for designing new solutions. It is used for tackling complex or poorly defined problems and emphasizes customer needs and experience. For educational purposes, it is used to enhance learning and support students’ creative thinking, teamwork, and responsibility for their learning. [2], [3], [4], [5].

A research question [6], [7], [8] explored whether Bauhaus reform movement’s artistic pedagogical approaches could be linked with modern Design Thinking educational methods. Would this connection prepare students for new challenges arising from the need for responsible and sustainable design? The answer is yes. Linking Bauhaus’s pedagogical approach with the interactive and nonlinear thinking of Design Thinking proves effective for practical instruction at universities. It has established a new principle for innovative creative teaching methods at TUL FT KDE, showing itself to be key to transforming creative pedagogy and design education under contemporary conditions for sustainable design.

Like Bauhaus emphasized integrating theoretical knowledge with practical skills (craftsmanship), modern sustainable design education demands a combination of theoretical understanding in environmental and ethical principles with innovative teaching methods, enabling students to apply these insights to practical scenarios. The Bauhaus teaching principle focused on combining theoretical and practical skills, which was an innovative approach at the time. The curriculum was based on specific tasks preparing students for real-world artistic, design, and architectural work. This strong link between teaching and real projects reflected the needs of the era, allowing students to develop their theoretical knowledge while refining their practical skills.

This principle naturally connected art and industrial production, significantly influencing the evolution of modern design. Just as Bauhaus promoted an interdisciplinary approach to education in its time, contemporary design education at universities emphasizes practical projects that address global environmental challenges while connecting creativity with responsibility. As Bauhaus responded to the need for an art-industry nexus of its time, today’s educational trends in design face the necessity of incorporating sustainable practices and technologies. This new pedagogy combines creativity, innovation, ethical, and ecological principles, reflecting not only the legacy of Bauhaus pedagogy but also the methodologies of contemporary design.

CREATIVE AND INNOVATIVE PEDAGOGICAL APPROACHES

Design Thinking provides a methodology for addressing complex challenges, including those related to sustainability. This iterative process, focusing on empathy, idea generation, and prototyping, aligns with the teaching objectives of the Department of Design and allows students to translate abstract sustainability principles into practical solutions. Through its three main phases - empathy, idea generation, and prototyping - Design Thinking bridges theoretical knowledge with practical skills and enables a creative approach to solving complex challenges.

In the first phase, emphasis is placed on understanding users’ needs and their environment. Students employ methods such as interviews and observational studies to identify key problems and areas for improvement. During the idea-generation phase, they use brainstorming techniques and visualization tools (sketching through drawing, painting—both traditional hand-crafted and digital art techniques) to create original designs. This process allows students to iteratively test and refine their ideas, facilitating the practical implementation of sustainability principles. The Design Thinking approach serves as a fundamental pedagogical framework utilized in all the examples presented (see the following subchapters). These examples illustrate the practical outcomes derived from applying Design Thinking in combination with other approaches and concepts, such as Zero-Waste Fashion, the integration of artificial intelligence, and interdisciplinary collaboration.

Empathy in design

Empathy is key to understanding users’ needs and creating new products that resonate on a deeper level. Agáta Nosálová applied the Design Thinking method in her bachelor’s thesis, where she designed a unisex clothing collection inspired by stop-motion animation. This approach not only enhanced the creativity of the design but also addressed specific challenges such as garment variability and sustainability, which were the core principles of the project. The creative process employed the draping technique on mannequins to create designs with a minimal number of pattern pieces, emphasizing functionality and emotional connection with the user. The following description outlines how the various phases of Design Thinking were implemented in the practical development of the collection. [9]

a) The first phase of Design Thinking, empathy, was utilized to understand users' needs and their requirements for clothing. The author focused on analyzing a selected range of user needs and exploring ways to adapt garments for different body shapes and the possibility of multiple ways to wear them. The goal was to design clothing that was functional yet easily adaptable for both men and women. Inspiration for the variability of garments was drawn from the concept of stop-motion animation, where shapes and forms change with each new frame. This approach provided a clear understanding of the necessary considerations for universal design and the adaptability of garment silhouettes.

b) **Ideation.** In this phase, the author generated ideas and clothing designs based on the concept of universal, variable garments that can be adjusted, see Fig. 1. The process involved exploring various textile materials and draping techniques, which helped create garments with the desired versatility in form. The variability of garment silhouettes was adapted to the human body through diverse styling approaches. Examples included openings for the head and arms that could be combined in various ways. For this creative process, the author drew inspiration from shaping clay, experimenting with different colors and shapes. The garments were complemented with a series of large-scale patterns printed on textiles using direct digital printing. This process merged artistic creativity with modern textile technology, which was essential for achieving the desired artistic intent, variability, and sustainability. [10]

c) **Prototyping.** The prototyping phase was a critical step in bringing the ideas to life in the form of tangible garments. The author chose to experiment with textile materials, including recycled materials, which contributed to the sustainability of the entire design. She created specific garment models that could be adjusted in terms of size, shape, color, and functionality to meet individual needs. By using various combinations of unused textile materials (e.g., from old sweatshirts and sweaters), prototypes were developed, then tested and refined based on feedback and sustainability requirements. Modeling on wooden mannequins also helped mimic the stop-motion technique, where each step and movement forms a new whole, see Fig. 2.

d) Testing. Testing the garments during the various stages of product design was an integral part of the collection development process. Based on the created prototypes, the garments were tested in real-world use on a 1:1 scale. The testing evaluated not only practicality but also sustainability and functionality of the garments. The garments were assessed for comfort, versatility, and functionality, which helped determine whether the designs met the actual needs of users. The insights gained were implemented by the author into the final design of all three garments, see Fig. 3.

The entire interactive Design Thinking process enabled the student to flexibly respond to challenges that arose during the creation of the collection and to continuously improve the designs based on feedback and the verification of actual user needs. This approach combined the creative and practical aspects of design with the requirements for sustainability, innovation, and flexibility - essential factors for modern unisex clothing design.

Figure 1. Clothing silhouette variability – design drawing.

Figure 2. The process of draping on a mannequin – finding the silhouette of a garment.

Figure 3. Clothing collection – result.

Zero-waste fashion

Within the art education at the Department of Design, students are provided opportunities to creatively utilize upcycling and recycling techniques. Zero-Waste Fashion is an approach that promotes circular economy principles and the efficient use of materials, aiming to eliminate any waste. In pedagogical practice, this approach involves teaching students to plan their designs in a way that minimizes waste during the creation of garments and clothing patterns. The principles of sustainable fashion design and a shift in the approach to fashion design education were articulated by Timo Rissanen in the text *Possibility in Fashion Design Education – A Manifesto* [11]. The core theses of Zero-Waste Fashion principles defined by him are implemented in creative teaching at TUL FT KDE. During the creative process of fashion design education at the Department of Design, students first work with mock-up (auxiliary) materials and then apply their designs in practice, which helps them enhance their problem-solving skills and view design not only from an aesthetic but also from a functional and sustainable perspective.

An example of the application of the Design Thinking approach in this area is Anna Střídová's master's studio project focused on transforming old denim into a modern unisex clothing collection. This project demonstrates how environmental principles can be combined with an attractive and innovative aesthetic result. Emphasizing Zero-Waste Fashion, the project focuses on creating garments with minimal to zero material waste during production, effectively linking sustainability with the aesthetic and functional aspects of modern fashion. The project not only exemplifies creativity in design but also offers a practical demonstration of addressing waste issues in the fashion industry.

Anna Střídová aimed to create an eco-friendly garment design process utilizing upcycling and textile collage techniques. The used old denim (jeans and denim jackets) was effectively deconstructed into flat parts, which were subsequently composed using an artistic authorial collage technique to create new flat material for crafting unique garment models, see Fig. 4 and 5. This method supports the sustainability of the

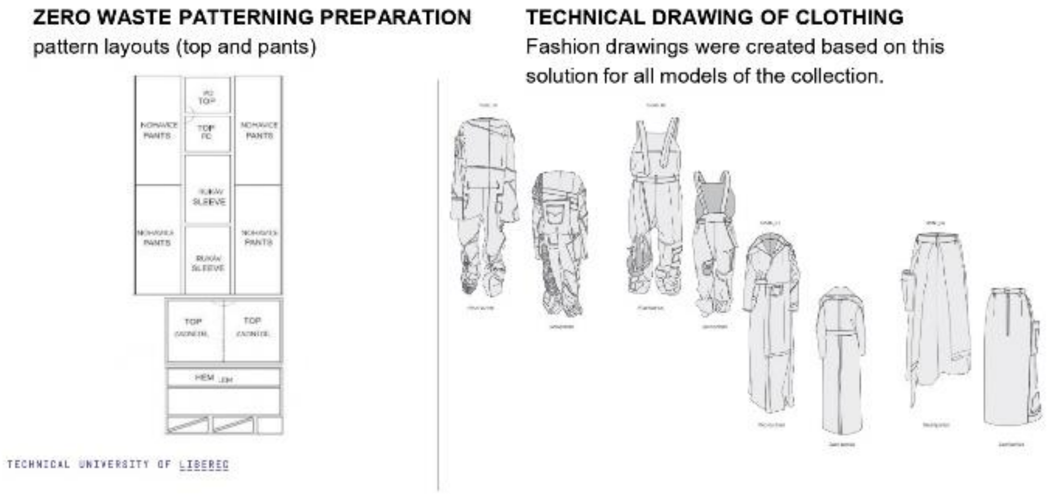

Figure 4. The process of creating a cutting solution and design drawing.

Figure 5. The creation process – authorial textile composition and positioning of the cutting solution.

Figure 6. Clothing prototypes in calico – verification of cutting solutions.

design process and demonstrates how recycled materials can be effectively used while maintaining the quality and originality of individual garments. A significant aspect of this approach is preserving the value of the original material and creatively transforming it into a new form, thus promoting sustainability in fashion design. [12]

The interactive process of design thinking includes verifying pattern solutions through prototyping in calico, which allows finalizing designs into functional and sustainable garments, see Fig. 6. In this way, the project demonstrates how fashion design can be approached creatively and effectively while being both sustainable and innovative. The resulting

Figure 7. Clothing collection – result.

Figure 8. Clothing designs – drawing – IA generated drawing.

clothing collection was tested for aesthetics, comfort, and functionality, which helped determine whether the designs met the actual needs of users. The insights gained were incorporated into the final design of the garments. Anna Střídová's clothing collection project was created as part of the Erasmus+ project: Sustainable Design and Process in Textiles for Higher Education (GreenTEX) [13], see Fig. 7.

Integration of AI and advanced technologies

The implementation of Design Thinking in education at TUL FT KDE also includes interdisciplinary projects. An example is the unisex clothing collection – the master's thesis of Kateřina Klozová, inspired by modern uniformity, which showcases the potential of combining fine arts, generative artificial intelligence, sustainable design practices, and the application of modern textile technology. Integrating AI into the design process allows students to explore new creative possibilities within art practices. The thesis demonstrated how AI can be used to innovate garment silhouettes and pattern variations. In her unisex collection, the author creatively processed and combined waste camouflage materials with thermochromic pigments (pigments that change color depending on temperature). This interdisciplinary approach – merging new technologies with traditional textile techniques – expands the possibilities of sustainable design, making it both innovative and feasible.

One of the key aspects of the author's work was the interaction with AI in developing original patterns for textile printing. By combining digital direct printing and hand screen printing – used mainly for applying thermochromic pigments – unique pattern designs were created, see Fig. 8 and 9. This approach shows how the connection between technology and artistic research can enrich creative solutions in fashion design.

Figure 9. Implementation of textile printing with thermochromic pigments.

Figure 10. Clothing collection – result.

The work also emphasizes interdisciplinary collaboration, particularly in textile printing and the application of new technologies. Experiments with waste camouflage material and thermochromic pigments in the patterns combine elements of art and science, pushing the boundaries of contemporary textile design. The collection, with its color aesthetics, aims to fit seamlessly into both natural and urban environments, see Fig. 10.

A significant part of this thesis project was the issue of sustainability and its relationship to aesthetics. The author focused on how AI can be integrated into the sustainable design process without compromising the aesthetic qualities of the garments. Her work emphasizes that innovative approaches can offer not only functional but also visually appealing solutions that address the needs of the contemporary fashion industry. This project represents a step forward in connecting technology, sustainability, and creative expression, setting the direction for further research and practice in the field of fashion design. The process of developing each garment collection involves experimenting with shapes, proportions, and material tests to ensure that the silhouette smoothly aligns with the overall vision of the project. This careful attention to silhouette design strengthens the integration of abstract ideas into tangible outcomes, supporting the project's goal of merging aesthetics with usability. The garments were evaluated in terms of comfort, variability, and functionality, which allowed for verification of whether the designs truly meet the needs of the users. The findings were incorporated into the final designs of all four outfits and the final garment forms. [14]

Ideas as the basis of creativity

The work presented in this subsection demonstrates the connection between the Design Thinking method and an innovative approach to fashion design, focusing on experimentation with form, materials, and function of garments, while emphasizing sustainability and aesthetics. The foundation of a good design process is a strong conceptual idea that sets the path toward the established goals. The project by Štěpán Dittrt emphasizes the importance of pushing the creative boundaries of garment silhouettes while meeting sustainability criteria. This approach responds to the principles of "good design" according to Dieter Rams – creating products that are useful, aesthetic, and environmentally friendly. However, Štěpán Dittrt's playful design pushes the boundaries of product usefulness and confronts them with new aesthetics and functions.

Štěpán Dittrt’s work expresses a vision that aims to expand the boundaries of traditional fashion design, especially within the academic environment. His approach promotes the value of exploration and experimentation, prioritizing the discovery of new solutions. Throughout the design process, the author repeatedly asked the question, “Is my design good?” The garment silhouettes designed by Dittrt are intended to showcase and encourage other students to go beyond the limits of conventional methodologies in fashion design practice. The new approach to garment silhouettes, combined with a strong conceptual vision, fosters a culture of creativity and ingenuity. In this context, the author's thinking, using the Design Thinking method, becomes a laboratory for innovation, where the connection between conceptual thinking and practical execution can lead to groundbreaking results, see Fig. 11.

One of the defining characteristics of the methodology in artistic work is the emphasis on capturing the central concept or idea, which serves as the foundation for the subsequent development of designs. This idea is not static but cyclical, allowing concepts to evolve through continuous refinement. By repeatedly drawing inspiration, the author gains new ideas for forms, silhouettes, and functions. This project is an example of a dynamic approach to problem-solving in design. In addition to the idea, this project emphasizes the crucial role of developing the silhouette. Silhouettes serve as the primary visual language in fashion design, offering the first impression of a garment’s shape and structure. Artistic techniques used to explore form, such as sketching, draping, and digital simulation, serve to deepen the understanding of material and silhouette. Such a holistic process ensures that the final result aligns with the goals of sustainable design while remaining visually striking and user focused [16], see Fig. 12 and 13.

CAPTURE AN IDEA AND LET IT INSPIRE YOU TO A NEW SOLUTION

Figure 11. Artistic inspiration for the clothing collection concept.

ELABORATE SILHOUETTES

Figure 12. Design drawing.

Figure 13. Clothing collection – result.

RESULTS AND DISCUSSION

The text summarizes the results of innovative approaches in teaching sustainable design at the Department of Design, Faculty of Textile Engineering, Technical University of Liberec. The research confirms that sustainability is a key aspect of modern fashion design, and its teaching must combine theory with practice. The implementation of methods such as Design Thinking, Zero-Waste Fashion, or the integration of artificial intelligence (AI) has demonstrably contributed to the development of creative and responsible thinking among future designers. These creative approaches emphasize the importance of integrating sustainability into all aspects of design education.

Student projects show that, when appropriate methods are applied, it is possible to create innovative, functional, and aesthetically appealing fashion designs without compromising environmental values. The interactive process of Design Thinking allows students to address complex sustainability challenges in an empathetic, creative, and practical way. Practical implementation of creative approaches for sustainable design is presented through selected student projects. The Design Thinking method was used to create a unisex fashion collection inspired by stop-motion animation, emphasizing variability and minimal waste. Similarly, the Zero-Waste Fashion method, supporting circular economy principles and eliminating material waste during garment creation, demonstrates its suitability for use in higher education in creative projects. AI allows students to push the boundaries of creativity in the product design process. The integration of AI enables students to explore new creative possibilities within product design. Combining original design with generative AI and advanced textile technologies represents a significant shift in experimental pedagogy, opening new opportunities for sustainability and innovation.

During work on creative projects, students realized the fundamental connection between theory and practice in the design process. Sustainable design is not just a concept but a mindset and an approach to design that influences every step of their work. The involvement of methods like Design Thinking and Zero-Waste Fashion taught them to approach problems in entirely new ways. The creative process also showed them the importance of understanding the complexity of design challenges. Creating aesthetically attractive garments that meet sustainability criteria was not easy. They had to deal with various limitations, material availability, and still maintain the practical and visual quality of the designs. This process gave them a deeper sense of connection with the overall philosophy of sustainable design, as they realized that every choice they make as designers has an impact.

As part of their artistic research, the team of educators at TUL FT KDE concluded that Bauhaus-inspired education and interdisciplinary collaboration at the university foster a diversity of creative processes, increasing the aesthetic value and functionality of the proposed garments. Bauhaus pedagogical methods, focusing on the connection between theory and practice, were transferred into a modern framework that combines interdisciplinarity and non-linear processes. Contemporary trends in art pedagogy at TUL FT KDE reflect interdisciplinary learning, where the creative process is linked with technologies, crafts, and environmental principles. These principles prepare students to responsibly address challenges such as global environmental issues.

The main results of the research include:

- Increased teaching effectiveness through the integration of sustainable methods and creative techniques.
- The opportunity for deeper student involvement in problem-solving and its practical application with a focus on circular economy.
- The use of new technologies as tools to enhance both the aesthetics and sustainability of designs.
- The support of empathy and critical thinking in student projects, leading to the creation of responsible design solutions.

Innovative pedagogical approaches at the Department of Design, FT TUL, demonstrated that creative education focused on sustainability is not only feasible but also essential for meeting the current needs of the fashion and textile industry. By combining Bauhaus philosophies, advanced technologies, and creative frameworks, a new generation of designers is being shaped, one capable of addressing contemporary environmental and social challenges. The results emphasize the importance of integrating art, technology, and ethics in modern pedagogy.

CONCLUSION

Sustainable design education requires a dynamic and creative curriculum that reflects the complexities of environmental challenges. The use of frameworks such as Design Thinking and the introduction of innovative methods enables educators to prepare students for responsible design practice in the modern environment. The work of the Department of Design, FT TUL, serves as an exemplary model that combines tradition with innovation and shapes a new generation of sustainable designers.

The results of the conducted research highlight the key role of innovative approaches in teaching sustainable design. Pedagogical methods inspired by the Bauhaus philosophy have been adapted to the needs of the contemporary world, with the use of interdisciplinarity, advanced technologies, and the practical application of theory representing an effective way to form a new generation of responsible designers. Moreover, it strengthens interdisciplinary thinking and opens new paths for collaboration across scientific and creative fields.

The research clearly demonstrates that the integration of sustainable techniques and technologies into teaching not only facilitates understanding of their significance in practice but also contributes to creating a framework for responsible innovation in the design profession. This symbiosis of creative and environmentally sensitive approaches represents a model that could be replicated in other educational institutions focused on artistic and craft disciplines.

In summary, the innovative pedagogical strategies implemented in the teaching at the Department of Design, FT TUL, represent a powerful tool for achieving sustainable goals in design, connecting the creative process with technological advancement, and shaping ethically responsible designers for the future. This educational model provides inspiring insights that can be applied internationally and helps address current challenges in both educational and industrial practices.

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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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