BOOK OF PROCEEDINGS

17th Scientific – Professional Symposium and 7th International Scientific – Professional Symposium

TEXTILE SCIENCE & ECONOMY

28th January 2025, Zagreb, Croatia

University of Zagreb Faculty of Textile Technology

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17th Scientific – Professional Symposium and
7th International Scientific-Professional Symposium

SINERGY OF TECHNOLOGY, SCIENCE & ART – THE CONCEPT OF SUSTAINABILITY AND DEVELOPMENT OF TEXTILE PRINTING

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Editor's word

The 17th International Scientific-Professional Symposium "Textile science and economy" - TZG 2025, was organised by the University of Zagreb, Faculty of Textile Technology on January 28th, 2025. In an atmosphere of new technologies and an ever-increasing focus of the market and production on the personalisation of textiles, advanced digital technologies and a growing awareness of the ecological sustainability of production processes. This year's symposium is thematically dedicated to digital textile printing, especially in the context of the paradigm of the synergetic relationship between technology, science and art, hence the title of the main theme: "Synergy of technology, science & art - the concept of sustainability and development of textile printing".

As envisaged in the original idea of the meeting, this year's Textile Science and Economy symposium was also an opportunity for meetings, the exchange of opinions and experiences and the establishment of co-operation between participants from universities, institutes and companies. The planned theme of the conference "Synergy of technology, science & art - the concept of sustainability and development of textile printing" opened up a wide range of possibilities for the submission of papers from various fields of science and art.
The programme of the TZG 2025 conference included invited lectures by renowned experts from universities, research institutions and industry as well as poster presentations of scientific, research-related, artistic and professional work. The presentations were followed by a round table on the conference theme. The event was accompanied by an exhibition of creative and artistic works by students from the Faculty of Textile Technology. Two workshops on digital printing were also held and exhibitors presented their printing technologies and products in the presentation section.

The conference comprised six invited lectures by renowned speakers. Prof. Željko Penava, PhD (University of Zagreb, Faculty of Textile Technology) gave a lecture on “From Paper to Digital Form – Digitisation of Tekstil Journal (1987 – 2024)”. This was followed by Prof. Igor Majnarić, PhD (University of Zagreb, Faculty of Graphic Arts) with a presentation on “The state of production of high-productivity inkjet textile printers after the DRUPA 2024 trade fair”. Branka Falatko (3-Print Group company) gave a lecture on “How digital textile printing influences the modernisation of the textile industry” and Danijel Galinec (Nanodiy d.o.o. company), “DTG's position in relation to the DTF trend”. In addition, independent scientific researcher Alicia Mihalić gave a lecture on “Patterns and life paths of hand-printed fabrics: Creativity and Community in the Work of Twentieth-Century Women Designers”. To conclude the invited lectures, Ana Maria Ricov, a graduate fashion designer (University of Zagreb, Faculty of Textile Technology), presented her creative work, showed fashion collections and emphasised the importance of printing technology for her creative expression.

Two projects were also presented at this year's symposium: Prof. Sanja Ercegović Ražić, PhD presented the Erasmus project *AEQUALIS4TCLF*, and Ebonita Ćurković presented the project *Moving forward with circularity in textile and fashion value chains TEX-DAN*.
A round table was held in which the following people participated: Damir Bistrović (Graphic Center d.o.o.), Dag Knepr (Fespa Croatia), Danijel Galinec (Tvrtka Nanodiy d.o.o.), Branka Falatko (Tvrtka 3-Print Group) and Prof. Martina Glogar, PhD, and the moderator was: Željka Livaić (Print magazin d.o.o.).

At the conference, 34 papers were presented in the categories scientific, professional papers and reviews papers. The papers were presented as poster presentations. The abstracts of all papers presented at the TZG 2025 conference in the categories scientific papers, professional papers and reviews are available in digital form in the TZG 2025 Book of Abstracts. Greater visibility of the TZG 2025 symposium was ensured through the collaboration and publication of selected papers in the journals *Textile* and *Leather and Footwear*. Further full papers are available in digital form in the TZG 2025 Book of Papers.

The symposium also included the organisation of the exhibition "ONVERS RAPORT" at the TTF Gallery, an exhibition by students of the University of Zagreb, Faculty of Textile Technology. The students/authors of the above mentioned exhibition are: Alma Hasanović, Dorotea Belajec, Dora Bužić, Nora Pehar and Tea Šoštarić; mentors are: Prof. art Koraljka Kovač Dugandžić, Assist. Prof. art Lea Popinjač.

The following companies presented their products and activities: Moira (a manufacturer of modern knitted women's clothing), Graphic Center d.o.o., Šimić & Co d.o.o. and the designer Matilda Sporiš with her brand M.A.T.I.A. (Make Any Textile Interesting Again).

We would like to take this opportunity to thank the faculty management for their trust, support and help, as well as all presenters, patrons, sponsors, authors, reviewers, to the exhibitors and especially the scientific and organizational committee and all other staff members whose work and dedication contributed to the realization of the TZG 2025 symposium.

Proceedings editor:

Assist. Prof. **Iva Brlek** Ph. D.
Member of the Organizing Committee

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Original scientific paper

THE WORK OF HUSSEIN CHALAYAN AS A STARTING POINT FOR AN INNOVATIVE APPROACH TO CLOTHING DESIGN

Kimi BIČANIĆ[1]; Irena ŠABARIĆ ŠKUGOR[1,*] & Blaženka BRLOBAŠIĆ ŠAJATOVIĆ[1]

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Abstract: The aim of the paper is to give a new interpretation of the collection based on the inspiration of the selected fashion collections of the designer Hussein Chalayan. In the theoretical part of the thesis, the innovative and avant-garde approach of Hussein Chalayan's selected collections is examined and described. In the experimental part of the thesis, a clothing collection is presented, which was created by examining selected collections by Hussein Chalayan, with a focus on ready-to-wear collections. The result of the work is a collection of dresses shown with project drawings. One model was selected for production and is shown in fashion photographs.

Keywords: *innovative approach; fashion design; hussein chalayan; clothing collection*

1. Introduction

Fashion designers strive to develop their own style in fashion during their work, often exploring the boundaries of design and realization. One designer who is known for his research and innovation in fashion is Hussein Chalayan. He emphasizes multifunctionality, sculpturalism, uniqueness and experimentation. Some of his creations have become reference points in design history, explored and inspired by new generations of designers. A key feature of Chalayan's work is his ability to push established boundaries and conventional ideas in fashion. His creations contain elements of surprise, transformation and technology. In this way, he creates garments that are not only visually appealing but also conceptually rich. All this was an incentive for the young designer to experiment in the footsteps of Hussein Chalayan's selected collections.

2. Hussein Chalayan and his work

The British-Turkish designer Hussein Chalayan was born on August 12, 1970 in Nicosia, the capital of Cyprus. He moved to England in 1978, where he completed his studies at Central Saint Martins University of Art and Design in London. In 1994, he opened his own company, Cartesia Ltd. In London, he designed collections for department stores Marks & Spencer and Topshop, and his garments were available in British department stores such as Harrods, Browns and Harvey Nichols. in 1997, London's Victoria and Albert Museum included Chalayan's designs in an exhibition entitled The Cutting Edge: 50 Years of British Fashion. In the same year, the Costume Museum in Bath awarded his aubergine-coloured silk dress as Dress of the Year. He was a design consultant for the New York knitwear brand TSE (1998–2001). In several interviews, Hussein Chalayan has expressed his disappointment that his work is not understood by many people [1, 2]. The creative director of Gucci and YSL, Tom Ford, considered Hussein Chalayan a new addition to the Gucci group in 2001. However, Tom Ford described Chalayan's work as "too avant-garde" and opted for a collaboration with Stella McCartney and Alexander McQueen [3]. Chalayan's work has also been worn by famous singers such as Bjork and Lady Gaga. He was creative director of PUMA (2008). The company's CEO, Jochen Zeitz, said that the collaboration with Hussein Chalayan has expanded the brand's reach and made PUMA the most sought-after sportswear company in the world. [Hussein Chalayan was awarded the title "Member of the Order of the British Empire" in 2006 and was made an honorary member of the London University of Fashion in 2011. In July 2011, he announced that he would be launching a line called Grey Label to appeal to younger generations. In the same year, he changed the name of the brand from Hussein Chalayan to Chalayan. An exhibition of Chalayan's work was shown at the Design Museum in London in 2009. From 2014 to 2019, he was head of the fashion department at the University of Applied Arts Vienna. Throughout his career, he has collaborated with many fashion brands, such as the German hosiery brand

FALKE (2008) and the fashion house Vionnet (2014) [5]. Today, Hussein Chalayan is Professor of Fashion Design at the Berlin University of Applied Sciences (Hochschule für Technik und Wirtschaft/HTW Berlin) [6].

2.1. A selection of the most important collections by Hussein Chalayan

In this section of the text, selected collections by Hussein Chalayan from 1993 to 2003 are briefly analyzed in order to provide inspiration for my own research and development of a clothing collection. The selected prêt-à-porter collections by Hussein Chalayan, including his last collection, share a common characteristic: sculpturalism, innovation and experimentation.

2.2. The Tangent Flows, fashion collection from 1993.

The Tangent Flows fashion collection is Hussein Chalayan's graduation project from Central Saint Martins School of Art in 1993. The main feature of the collection is the experimentation with unconventional manufacturing processes and materials [7]. It consists of a series of very simply cut silk garments that have undergone an oxidation process in which they take on new patterns and textures and the appearance of the fabric surface changes. Hussein Chalayan buried the finished garments underground together with iron filings and dug them up again six weeks later, shortly before the show [7]. Oxidation is the reaction of molecules, atoms or ions in which electrons are lost. In this process, oxygen combines with another element and changes its appearance and properties. In this case, it is the oxidation of iron filings that came into contact with the silk and turned into rust. The silk garments looked rotten and spoiled and turned a rusty red color. The models presenting the garments looked as if they had emerged from the earth along with the creations, which added to the overall impression [7]. The production method described above underlines the importance of experimentation in designing successful collections. The message he wanted to convey with this collection is that fashion goes fast and is very easy to recycle. However, he also emphasizes the importance and beauty of the process of decomposing and recycling fashion itself [7].

2.3. Along False Equator, fashion collection from 1995.

The relationship between man and technology and the possibilities that arise from their coexistence are the theme of the 1995 fall collection entitled Along False Equator. Hussein Chalayan examines man in the world and questions the concept of human identity and the possibility of its loss in the exploration of the unknown. The creations are simply cut, as the focus is on the unconventional materials from which the garments are made. Elements such as torn, perforated fabrics, antenna-like patterns and unusual shoulder pads were used. The most unconventional are the women's jackets made of Tyvek paper, a wooden corset with metal buckles and garments with a bright pattern [8]. Tyvek paper is a non-woven type of textile. Its fibers are not woven, but are bonded together by pressure and heat. Due to the processing method mentioned above, Tyvek combines some of the best properties of paper, fabric and film. By using nonwovens in the production of women's jackets, Chalayan has presented a classic garment in a new light. The garments appear crumpled and have a texture reminiscent of the rippled surface of water [8]. The surprising element of this collection is a corset made entirely of lacquered wood and closed with metal clasps. This corset later became part of the costume collection of the Metropolitan Museum of Art in New York [9]. In 2005, British historian Caroline Evans described the fashion collection in the fashion magazine 032c as “paper suits with embedded optical fibers that blinked at night like airplane lights”. His interest in airplanes and similar themes can also be seen in later collections, such as the spring 2000 collection, when he designed an airplane-inspired dress that moved with a remote control [8].

2.4. Before Minus Now, fashion collection from 2000.

With his fashion collection Before Minus Now, Hussein Chalayan explored the power of volume, magnetism and erosion and the application of these processes to fashion. [9] He demonstrated the power of volume in a red dress with a fitted top and an A-line skirt reminiscent of a 1950s dress. During the fashion show, the dress changed shape due to the heat - the skirt opened up and increased in volume. The most famous creation from this collection is the Airplane Dress - a dress made of molded plastic that moves and opens at the touch of a button on a console, revealing the pink tulle underneath. [9] Hussein Chalayan experimented with shapes and production methods and designed a dress made of tightly sewn ruffles of pink tulle, which were then cut and shaped by hand. The last five models formed their own entity. The models wore creations of deconstructed monochrome corsets with matching skirts. For the finale, all five models stood motionless on stage and the floor opened up so that the models sank deep under the catwalk along with the models [9].

2.5. After Words, fashion collection from 2000.

The collection After Words is a continuation of the collection Before Minus Now. The two collections from the same year are linked by the way the collection opens and closes. Right at the beginning of the show, five models emerged from the floor on a pedestal. The stage was set up like a living room, with four armchairs, a coffee table, a television and a shelf with several vases. [10] The models wore simple, flowing dresses with a few ruffles and a different colored hem. Models in jackets and coats took vases from the shelf as they left the stage. Tulle also made a reappearance, in the form of dresses and as the lining of pleated skirts. [10] The highlight of the show was the final five models. Four models took to the stage in simple, gray, knee-length, fitted dresses. They took the covers off the armchairs that were part of the stage set and put them on. The dresses were like an improved version of the simple dresses they were already wearing. [10] After the covers were removed from the armchairs, the wooden chairs remained, which the models folded into suitcases and left the stage with. [10] The final creation was a skirt made from a wooden coffee table. The model entered the catwalk wearing a light blue asymmetrical blouse and a tight brown skirt with a belt with two hooks. The model stepped into the center of the table, unfolded it and attached it to the belt so that the table became a skirt. [10] Finally, all the models left the catwalk, the television faded into the background and the living room-like stage remained empty.

2.6. Kingship Journeys, fashion collection 2003.

In his fall collection entitled Kinship Journeys, Hussein Chalayan once again experimented with seemingly incompatible elements. The catwalk featured a trampoline, a closet, a wooden boat and a digital watch, and the models wore creations that combined traditional patterns and embroidery with modern materials and cuts. [11] The first part of the show consisted of black creations with embroidery in different colors. The necklines and sleeves were asymmetrical and the silhouettes of the garments were not clear and distinct. A black helium balloon was attached to the creations with the help of ropes, metal rings or halter tops. [11] The last four creations were the highlight of the show for the same collection. Short skirts with matching tops and dresses in olive green and white and blue check fabric had oversized pockets that were the center of attention. [11] At the very end, all four models lined up and unbuttoned their pockets. As they unbuttoned, gray, air-filled sections of the skirt unfolded. Their appearance and concept was reminiscent of a life jacket. [11]

3. Experimental part

The clothing collection is inspired by the prêt-à-porter collections by Hussein Chalayan, which were described in the previous part of the text. The aim of the collection is to present modern reinterpretations of traditional garments such as corsets and tutus, using innovative and unusual materials for the production of clothing. Materials such as plaster, tulle, rubber and metal were used in the production, while natural dyes such as coffee, cocoa, tea, charcoal and various spices were used instead of paint.

When making the upper part - the corset - it was necessary to make several versions of the prototype. During the production of the prototypes, the shape, the fit on the body, the texture, the colors and the wearing options were researched.

The prototypes were made by laminating the torso to a live model and then discarded. The other two prototypes were made by laminating the torso of a sewing dummy wrapped in foil. The time required to produce each prototype, laminate and mold the desired shape, was approximately half an hour and more than 12 hours for the prototype to dry completely. Subsequently, certain parts of the prototypes were sanded with sandpaper to remove unwanted plaster deposits and to obtain a satisfactory surface for the corset. Finally, each prototype was colored with natural dyes.

a. b. c.

Figure 1: Three corset prototypes created during the research for the collection.

First prototype, Fig. 1 a) The shape of the prototype was obtained by laminating the torso of a living model. It was made from plaster strips dipped in an aqueous coffee solution to obtain the desired color. The prototype was discarded due to the effects of the coffee on the strength of the plaster strips. The prototype did not retain the predetermined shape of the torso, but was elastic.

Second prototype, Fig. 1 b) The shape of the prototype was also obtained by laminating the torso of a living model. It was made from plaster strips immersed in an aqueous solution of green tea, cinnamon and activated charcoal. The prototype was discarded because the above solution did not produce a satisfactory color and the shape of the corset was also unsatisfactory.

Third prototype, Fig. 1 c) The shape of the third prototype was made by laminating a sewing dummy. The corset was made from plaster strips dipped in an aqueous solution of coffee, green tea, activated charcoal, turmeric and cinnamon. This prototype was also unsatisfactory and was discarded because the color and shape were not satisfactory.

Figure 2: Making the final corset

The fourth prototype was made from plaster strips and painted with an aqueous solution of coffee, green tea, chocolate powder, soy sauce, activated charcoal, cinnamon, charcoal and plaster. After a drying time of several hours, the corset was covered with several layers of acrylic paint to prevent the dried plaster from crumbling. The corset was attached to the back with metal clasps, chains and pendants to decorate it and hold it to the body.

Figure 3: Back side of the corset

Figure 4: Sketches and layers of tulle of the lower part of the selected model, tulle skirt

The tulle skirt is inspired by the classic ballet skirt. This skirt consists of several layers of tulle in different lengths, from short to long. The construction of this skirt is similar to a deconstructed ballet skirt, where the order of the layers of tulle is reversed and pleated pieces of tulle have been added in certain places to give the skirt more volume. The skirt is meant to resemble a ballet tutu, but in a more modern version.

4. Results

After the corset and skirt were made, a fashion collection was developed and fashion photos were taken of the finished model.

a. b. c.

Figure 5: The first three models from the collection

The model in figure 5 b. is a long dress made of leather and cotton fabric. There are metal hooks and fasteners on the sides of the pleated skirt, with which the skirt can be lifted, fastened and brought into a completely new shape. In this way, the wearer can change the appearance of the lower part. Figure 5 c. shows a model consisting of a leather skirt and a strapless top. The front of the top is made of vinyl divided into chambers reminiscent of a corset and is doubled at the front. It is assumed that the front part can be inflated or deflated with air and thus takes on a different shape than the vacuumed form with inflated chambers in the front part. The model in Figure 6 a. is a leather dress that can be reshaped by adding and removing parts of the dress. The sleeves, a piece of fabric covering the shoulders and the side parts of the skirt can be removed with zippers. The person wearing this garment can add and remove these parts themselves to create their own version of this dress model.

Figure 6 b. shows a long, oversized tulle dress with a hood, a leather corset and a belt made of chains of different thicknesses and lengths. The last model in this collection, Figure 6 c., consists of an aluminum corset covering the upper body and oversized nylon pants with metal rings on the lower legs.

a. b. c.

Figure 6: The rest of the collection

Figure 7: Fashion photos on the female body

Figure 8: Fashion photos on the male body

5. Conclusion

The great fashion designers who have shaped and continue to shape the history of fashion can be an inexhaustible source of inspiration for young designers who want to push boundaries and challenge the traditional understanding of fashion. Hussein Chalayan's innovative design techniques, conceptual approach and unique use of materials and technology have made him a visionary in the field. With his thought-provoking collections, Chalayan has not only influenced other designers, but has also left a lasting impact on the cultural and social aspects of fashion. The aim of this work was to explore the designer's work and offer our own solutions that emerge from this trail. The influence of Hussein Chalayan has inspired us to think beyond aesthetics and create a collection that is not only visually stunning, but also rich in meaning and innovation. In this collection, the relationship between the designer, the garment and the person wearing the garment is revisited. By combining traditional dress forms such as the corset and tutu with unconventional materials such as plaster and metal, it attempts to combine tradition and modernity. Inspired by Chalayan's boundary-pushing, the model was also presented on a male model who challenges social norms of dress.

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Original scientific paper

THE INFLUENCE OF THE AFRICAN FABRIC PATTERN AND ITS TRANSFORMATION IN THE BATIK TECHNIQUE

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Abstract: *The clothing culture in Africa varies from country to country, but all are characterized by bright colors, embroidery and vibrant jewelry. The fabrics of African culture are decorated with stamp printing, dyeing, painting and embroidery, and the colors are obtained from spices, leaves, fruits, vegetables or grass. Depending on which metal salt they are mixed with (zinc, sulfur or iron), they take on a certain intensity and shade. The peculiarities of the decorations and cuts of clothing in African culture are explored, as are the African ways of combining traditional culture with contemporary design. Traditional costumes were usually not cut and sewn, but wrapped around the body in different ways. The experimental part will show the production of a fabric pattern using the traditional batik technique, which was used in Africa to produce patterned fabrics. By digitizing and editing the resulting pattern, geometric shapes are added to give the pattern a more modern motif. The resulting ornament will be used to make fabrics and a collection of dresses, the construction and modeling of a selected model will be shown.*

Keywords: *Afrika; batik; ornament; clothing construction*

1. Introduction

Clothing culture in Africa varies from country to country, but all are characterized by bright colors, embroidery and colorful jewelry. The weaving, dyeing and printing of textiles is largely based on traditional ornamentation, but is also heavily influenced by the different cultures of the Middle East, Far East and West, which arrived on this continent through the development of trade routes and colonization. Traditional garments made from local materials have adopted new Western tailoring styles. In north-eastern Africa (Egypt, Sudan, Ethiopia, Eritrea) we find the "Jelabiya" (Figure 1a), which goes back to the Arab tribes, i.e. the so-called Thwab of a garment. But unlike the thawb, the jelabiya is wider, has no collar and longer and wider sleeves. In other parts of Africa, we find similar forms in "boubou, dashiki and kaftan". In East Africa, men wear the so-called "kanzu", Fig. 1c, traditional dresses, and women wear "kanga or gomesi" Fig. 1b. In southern Africa, special shirts are worn, known as "madiba shirts" and "safari shirts". In Ethiopia, men wear traditional formal dress Ethiopian suit made of chiffon, while Ethiopian women wear habesha kenis made of cotton cloth in combination with a shawl called Netela [1].

a.

b.

c.

Figure 1. Traditional clothes of Africa a. jaleiyu b. kanga c. kenzu [1]

2. Characteristic African textiles and patterns

Fibers and weaving techniques are different in certain parts of the African continent. Weaving with a narrow stripe is characteristic of West Africa, while people in the Congo weave "raffia" from palm leaves into such a fabric and produce the so-called "Kuba" fabric. Handlooms are still used and passed down from generation to generation. The fabrics are decorated with stamp printing, dyeing, painting and embroidery, and the dyes are made from spices, leaves, fruits, vegetables or even grass. Depending on which chemical they are mixed with (zinc, sulfur or iron), they take on a certain intensity. The color is very important to African culture, as they believe it can even have supernatural properties [2]. The traditional costume was usually not cut and sewn, but wrapped around the body in various ways. African textiles appear under different names depending on how they are made and decorated: Asoke textiles from Nigeria, Adinkra fabrics, Adire fabrics from Nigeria, Batik fabrics, Ewe fabrics, Khasa fabrics, Kente fabrics, Korhogo fabrics from the Ivory Coast, Kuba fabrics from the Congo, African dye fabrics and African print fibers, figure 2.

a. b. c. d.

Figure 2. African textiles a. Asoke, b. Adindra c. Adire c. Batik [2]

3. An overview of the work of contemporary designers inspired by African textiles

There is a certain difference between African designers who live and work in Africa or who are of African origin but create in Europe or America. The latter have a much more pronounced western style in tailoring clothes made from fabrics with African print ornaments. The reason for this probably lies in the market that is looking for a little exoticism but is still a little conventional when it comes to the shape of the clothes. A clear example of this is the Zuri brand, whose T-shirt collections are sewn almost entirely from cotton fabrics from Kenya, thus supporting the local textile industry in Kenya [3]. The fashion company Afriek works in a similar way, collaborating with local tailors in Rwanda (Figure 3a). What is interesting is their policy of sewing on a stamp with the exact first and last name of the tailor who made the garment. This gives her collections a very special touch. [4] In contrast to the designers who design in the West, however, the designers working in Africa clearly deviate from the traditional Western cut of clothing, although they also copy it. In the collection of Mzukisi Mbane from Cape Town, a much greater creativity in approach can be seen, for example in the design of the jacket, Figure 3b. The Christie Brown brand produces luxury clothing for women that is inspired by the patterns and shapes of African dresses and tries to reflect the strong personality of the African woman in a very interesting, almost sculptural way, Figure 3c. [5] The Maxhosa Africa brand is known for its knitwear based on the culture of the Xhosa people, who have a fascinating tradition of knitting in different colors. They mainly use mohair and wool and use traditional weaving methods. It is a very feminine collection by Lisa Folawiyo, who pays great attention to redesigning African ornaments, which is clearly visible in her collections [6].

Figure 3: The work of African designers: Afriek, Mzukisi and Cristie Brown [6]

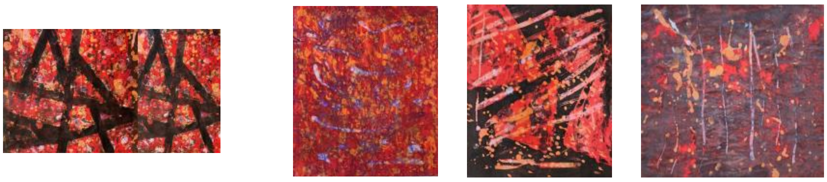
4. Experimental part

The experimental part of the work is divided into two parts. The first part describes the process of making a pattern in the batik technique, and the second part describes the application of the pattern to the collection of women's dresses and shows the construction and modeling according to the pattern.

4. 1. Transformation of an African pattern in the batik technique

The fabric sample for this work was made using the batik technique, a traditional technique used in Africa to produce patterned fabrics. Four 20x40 cm fabrics were prepared, on which the same colors were used in the first three layers, except for the last one, on which a second tone of the darkest color (brown, purple, black and blue) was applied to each layer. Batik as a textile decoration technique is used in all parts of Africa, but the most important is that of Nigeria, with which the Yoruba people produce the Adira fabric. They use cassava paste to obtain a specific color, but in this study the classic method of applying wax was used.

Warm colors - pink, orange and red - were chosen to make the collection reflect a kind of atmospheric conditions in Africa, i.e. heat, as Africa is the continent with the hottest climate in the world. The first layer of wax protected the natural white color of the canvas, after which a light pink was applied to the entire format. After the pink was covered with wax, the yellow-orange was applied. Without removing the layers of wax first, parts of the yellow-orange were protected and the red color was applied. All four fabrics were treated in the manner of expressive painting, but with slightly different brushstrokes to obtain different textures. One sample was covered with black paint after the red paint had been preserved with wax. The second sample was coated with purple paint and the third with brown paint. Only after all the layers of paint had been applied was the wax removed with an iron over the paper. After we had obtained pink, orange and red textures, which were further emphasized with a dark layer of paint, as is usual in batik, the need arose for an additional intervention that would result in a slightly more precise ornament. In view of the fact that in Africa the pattern, the ornament, is usually based on geometric shapes, this esthetic was adopted. A self-adhesive protective tape was used to mark the pattern, which was glued over the entire texture in different directions, creating a geometric mesh. It is also a stylization of the ornament, like the "fiery" texture, a stylization of the characteristic African color. In this way, we have prepared a basic pattern for the fabric, which is used for digital processing. The wax is applied to the entire pattern, but does not adhere to the areas covered by the self-adhesive protective tape. Once the wax has been applied, the strip is removed. A layer of purple paint is first applied to the pattern, which is completely covered with wax except for the areas where the adhesive tape was located, so that it gets into the cracks created by kneading the fabric. Black paint is then applied to the areas that were not protected by wax. After the excess wax was removed with an iron over paper towels, a clear black mesh remained. Three patterns were not treated with black geometric shapes, but left in a soft texture of four colors, figure 4. [7].



a. b. c. d.

Figure 4. Batik fabric patterns

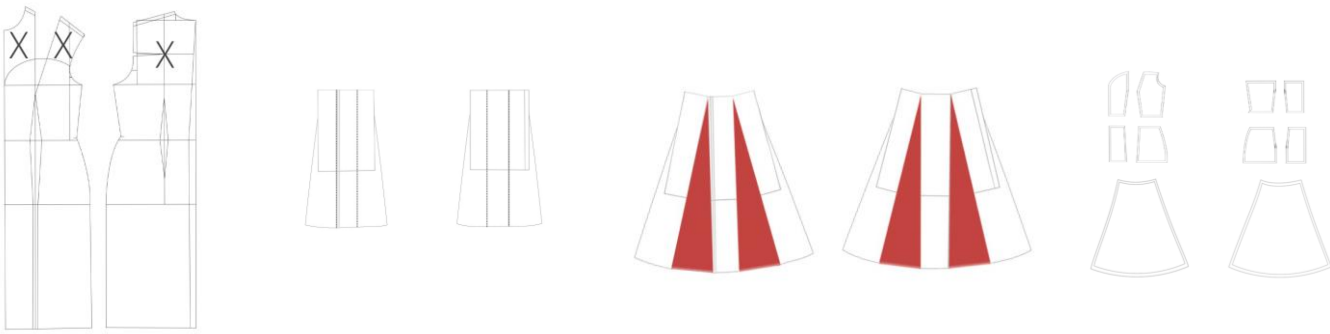
4.2. Collection

The collection of dresses is made in a way more by implementing different textures and combining cold and warm color tones, which give the collection an additional African touch, considering that climate traditionally uses such combinations, figure 5.

a. b. c.

Figure 5. Application of batik patterns on the dress collection

The construction and modeling of the dress was performed for the first model a., figure 6.



a. b. c. d.

Figure 6. Construction of the dress front, back top and bottom part of the dress, and separate cut parts with seam allowances

5. Conclusion

The study deals with the peculiarities of the ornaments and cuts of garments of African culture and their application in modern times. Contemporary designers are increasingly simplifying the ornaments while making the cuts more complex.

The experimental part of the work shows the process of stylization of the selected African ornament and its digital transformation through the batik technique. The resulting ornament is used to create fabrics that are used for the construction and modeling of garments inspired by African culture. The importance of African culture in the context of fashion and its influence on contemporary designers can be emphasized. This work gives an insight into the specifics of African ornaments and cuts and their reinterpretation in a contemporary context. Furthermore, the experimental part of the thesis offers a practical application of the research through the process of stylization and digital transformation.

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Original scientific paper

THE FLUORESCENT COTTON YARNS FOR INTERIOR TEXTILE DESIGN

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Abstract: *The fluorescence of mercerized cotton yarns was investigated in this paper in the context of artistic textile design for interior. For this purpose, cotton yarn chemically bleached and mercerized under industrial conditions (Runolist, Unitas, Croatia) was optically brightened with two commercially available fluorescent whitening agents (FWA) in three concentration. The influence of the FWA concentration to spectral remission, whiteness and its changes with coloristic meaning was investigated. The possible artistic textile design with selected yarns in knitted and woven fabric to be used in interior is given.*

Keywords: *cotton yarns; fluorescence; optical brightener; textile design*

1. Introduction

Today's definition of textiles for interiors often focuses on technological aspects such as their functionality (fire resistance, electrical shielding, heat equalisation or light emission) as well as decorative and design elements [1,2]. Textile walls and soft floor coverings are becoming increasingly interesting for designers, as artistic textile design can complement interior design. Textiles are lightweight, easy to transport and provide sound and light absorption in the interior of public spaces or homes. The use of luminescent textiles with added value for interior design will lead to the development of innovative textiles in architecture in the future [2-6].

Fluorescence is a physical-chemical phenomenon caused by the irradiation of the body with visible light after it has been exposed to high-energy UV radiation (UV-R). It occurs immediately after UV-R absorption and lasts only as long as the primary radiation is present, after which it disappears almost immediately (in about 10^{-8} s). The presence of conjugated double bonds in optical brighteners causes the absorption of UV light, resulting in fluorescence [7]. When applied to textiles, optical brighteners increase the degree of whiteness when used in optimal concentrations. This is why optical brighteners are often referred to as fluorescent whitening agents (FWA). If the concentration of FWA is too high, "quenching" can occur. Regardless of the FWA concentration used, they improve the UV protection properties of textiles, as FWA absorb UV-R and convert it into visible light [8-11].

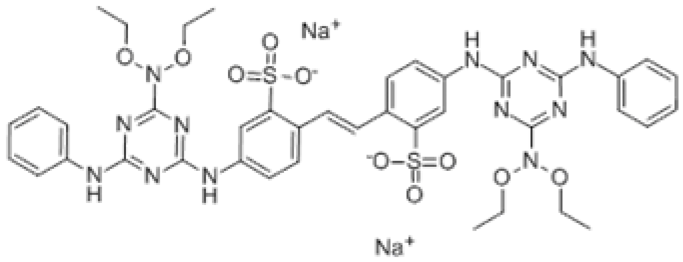
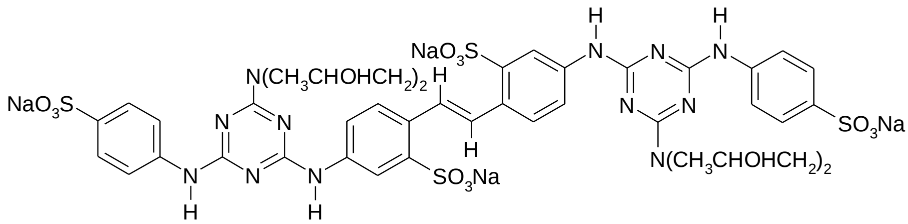
Therefore, the influence of the FWA concentration and the pre-treatment of the cotton yarn on the design effect was investigated, and the possible artistic textile design for these yarns is given.

2. Material and Methods

The cotton yarn chemically bleached and mercerized under industrial conditions (Runolist, Unitas, Croatia) of T_t=16/2 Nm was used in this research. It was optically brightened with two commercially available FWAs from Huntsman, brand Uvitex® by Ciba-Geigy AG (Table 1) – stilbene disulphonic acid triazine derivative (Uvitex RSB) and diamino stilbene disulhonic acid derivative (Uvitex BHT).

Optical brightening was performed in the dyeing machine Ahiba with bath ratio 1:20 at T=80°C for 60 min using three concentrations of FWA: 0.1, 1 and 10 % owf. According to the manufacturer's recommendation, the 2 g/l Na_2SO_4 was added as electrolyte. After the treatment yarns were air-dried.

Table 1: Labels, names, structural formulas and properties of optical brighteners [11]

Label	Name, structural formula and properties
BHT	 Uvitex BHT CI Fluorescent Brightener 113 Derivative of diaminostilbendisulfonic acid λ_{max} = 440 nm High affinity for cellulose fibers, PA, wool, silk and its blends
RSB	 Uvitex RSB Triazine derivative of stilbene disulfonic acid λ_{max} = 435-440 nm Medium affinity to cellulose fibers and its blends with polyester

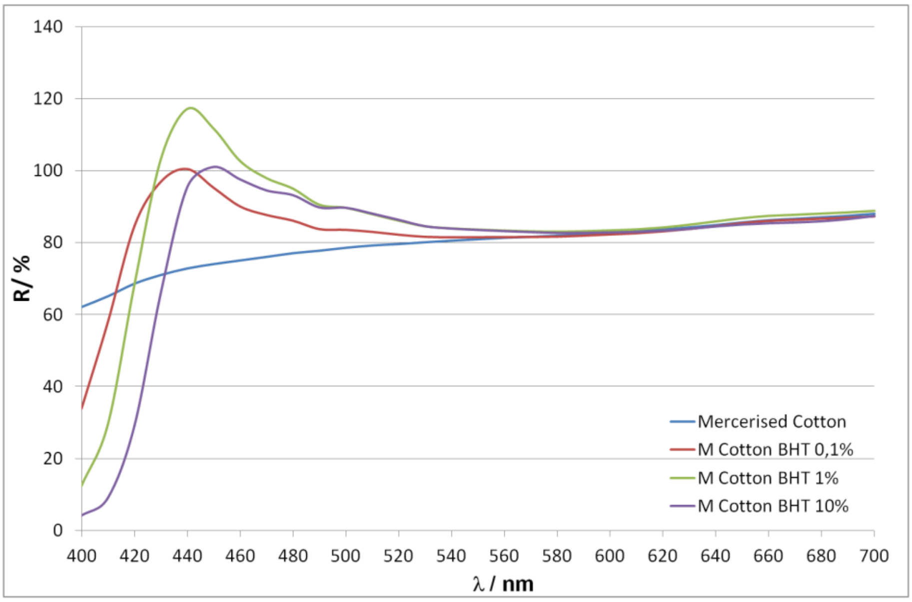
The spectral remission, R [%] was measured on a spectrophotometer Spectraflash SF 300, Datacolor at illuminant D65/8°. The degree of whiteness according to CIE (W_{CIE}) in accordance with ISO 105-J02:1997 *Textiles - Tests for color fastness - Part J02: Instrumental assessment of relative whiteness* as well as the tint deviation from neutral white standard and its coloristic meanings according to [12] were automatically calculated.

3. Results and Discussion

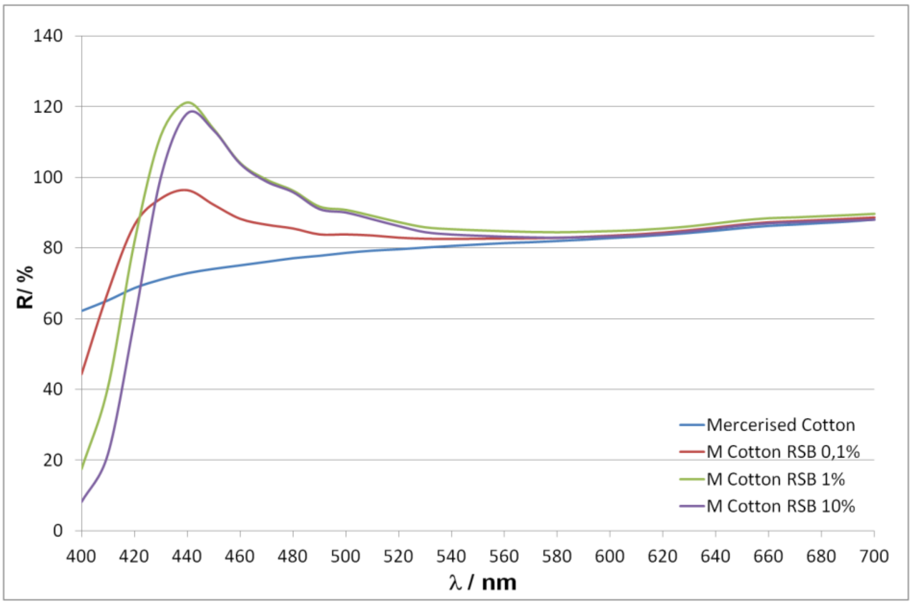
The results of spectral remission (R [%]) of mercerized cotton yarns before and after FWA treatment are shown in Figure 1. Calculated degree of whiteness (W_{CIE}) and the tint deviation from neutral white standard and its coloristic meanings according to [12] are listed in Table 2. Photographs of yarns before and after FWA treatment taken without and with UV excitation are presented in Figure 2.

Table 2: Degree of whiteness according to CIE (W_{CIE}) and tint deviation from the white standard of bleached mercerized (M) and optically brightened cotton yarns with Uvitex BHT and Uvitex RSB in three concentrations

SAMPLE	W_{CIE}	TV	TD	COLORISTIC MEANING
[M] MERCERIZED COTTON	55.0	-2.17	R2	Slightly redder than the white standard
M COTTON BHT 0,1%	109.8	-2.00	R2	Slightly redder than the white standard
M COTTON BHT 1%	129.4	0.40	G3	Appreciably greener than the white standard
M COTTON BHT 10%	84.9	5.39	G5	Very markedly greener than the white standard
M COTTON RSB 0,1%	102.7	-2.13	R2	Slightly redder than the white standard
M COTTON RSB 1%	137.3	-0.46		No appreciable deviation in tint from the white standard
M COTTON RSB 10%	128.2	1.03	G1	Trace greener than the white standard



a.



b.

Figure 1: Remission spectra of mercerized cotton yarn before and after optical brightening with: a. diamino stilbene disulhonic acid derivative (Uvitex BHT), b. stilbene disulphonic acid triazine derivative (Uvitex RSB)

From the results shown in Figure 1 and Table 2, it can be seen that mercerized cotton yarn without FWA treatment has the highest remission at 700 nm and the whiteness is W_{CIE}=55.0. Regardless of the chemical composition of the FWA used, the treatment with the lowest FWA concentration of 0.1 % owf leads to a significantly higher degree of whiteness (W_{CIE} ~100) due to the fluorescence emission at 430-440 nm.

The highest degree of whiteness is achieved with 1 % Uvitex RSB (137.3), while it is also high for Uvitex BHT (129.4). The reason for these high degrees of whiteness at 1 % FWA is the change in the crystal lattice of the cellulose during cotton mercerization, which leads to a very high absorption. It can be seen that mercerized cotton is slightly redder than the white standard, and with the FWA treatment, it becomes greener. This can also be observed as a bathochromic shift of remission curves. It should be noted that when using 1 % Uvitex RSB, a pure white is achieved without any colour deviation from the white standard. When the concentration is increased to 10 %, the remission and whiteness remain almost the same (128.2), and it is a trace greener than the white standard.

Figure 2: Photographs of mercerized cotton yarns (M) before and after optical brightening with diamino stilbene disulhonic acid derivative (BHT) and stilbene disulphonic acid triazine derivative (RSB) taken without and with UV excitation

At 1 % Uvitex BHT, however, it can be seen that this concentration is already above the optimum, as the sample is appreciably greener than the white standard, and when the concentration is increased to 10 %, it becomes very markedly greener than the white standard. This finding as well as the bathochromic shift and the lower remission indicate a quenching of the fluorescence so that the whiteness is significantly lower (84.9).

From the photographs of the mercerized cotton yarns before and after optical brightening, taken without and with UV excitation, it can be seen that in the presence of FWA there is no effect under the UV light. It can also be seen that a low concentration of 0.1 % leads to a reddish tint under UV light, while at higher concentrations it tends to turn white.

Therefore, the highest applied concentration of 1% FWA is considered the best for both applied FWAs. Therefore, these yarns were included in prototypes of design.

4. Design for Interior Spaces

Figures 3-6 show the possible artistic textile design with selected yarns in knitted and woven fabrics for interiors. Figures 4 and 6 are intended to visualize the applications of these textile patterns in architectural environments. The visualization was created by artificial intelligence (Leonardo.Ai) based on sketches and photos by the author design (T. Frasonski).

The designs and visualizations explore the use of knitted fabrics (Figures 4 and 5) and utilise their natural stretch properties to create structural forms reminiscent of curtain walls and roofing. The inherent stretchability of knitted fabrics enables the development of lightweight, versatile textile forms that offer extensive design possibilities.

Conversely, woven fabrics (Figures 6 and 7) with a stable structure can effectively serve as wall panels and movable partitions in interior spaces. The proposed textiles not only contribute to aesthetics, but also improve the functionality of interior spaces by providing thermal insulation and acoustic benefits. Textiles made from optically brightened yarns can enhance the aesthetics of products designed for interior spaces.

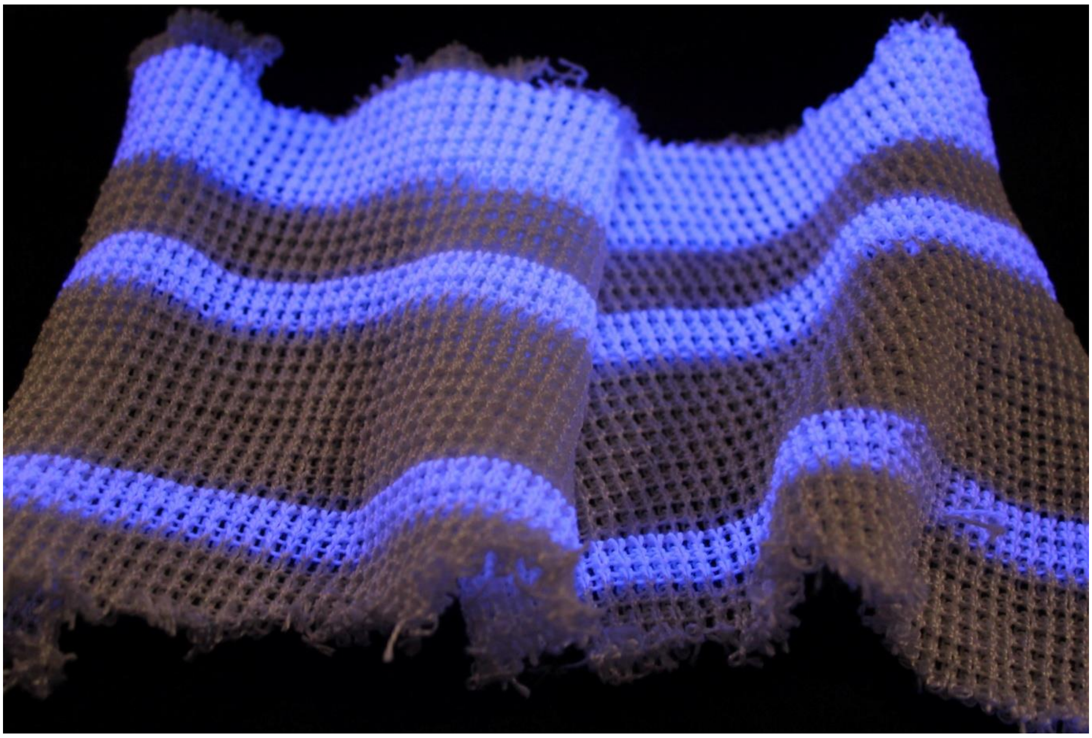


Figure 3: Knitted fabric made of mercerized cotton yarns without and with treatment with 1 % owf Uvitex RSB – design.

Figure 4: Visualization of designed knitted fabrics for use as tensile forms in interior design. The visualization was created with the artificial intelligence Leonardo.Ai

Figure 5: Woven fabric made of mercerized cotton yarns without and with treatment with 1 % owf Uvitex BHT – design.

Figure 6: Visualization of designed woven fabrics with fluorescent yarn. The visualization was created with the artificial intelligence Leonardo.Ai

5. Conclusions

Fluorescence contributes to high whiteness and beauty in the optimal range of FWA concentration. The blue fluorescence of a low FWA concentration neutralises the yellowness of chemically bleached yarns and ensures high luminosity and “most beautiful” whiteness. The quenching of fluorescence is a phenomenon that is negatively noticeable through reduced fluorescence and yellowing. It is important to select the correct fluorescent whitening agents according to their chemical composition and concentration, depending on the composition of the yarn to be treated. Otherwise a high degree of whiteness will not be achieved. Uvitex BHT and Uvitex RSB ensure a high degree of whiteness of mercerized cotton yarns with different tint and can be successfully used as a design element in the textile design of interiors.
The designs can be adapted to the production conditions of the textiles. The use of fluorescent yarns increases the attractiveness when using UV light, as textiles made of optically brightened yarns can enhance the aesthetics of interiors. This study can serve as a suggestion for further experiments in the field of textile finishing for broad application in architecture.

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Original scientific paper

DEEP BLUE – CYANOTYPES AND TEXTILE ART

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Abstract: *This paper, titled "Deep Blue - Cyanotypes and Textile Art" examines the significance of cyanotype in textile art as a sustainable, non-toxic printing method that bridges historical depth with contemporary eco-consciousness. Invented in 1842 by Sir John Herschel, cyanotype has long served as a unique medium for creating illustrations, specifically photograms, establishing a distinctive aesthetic that endures today. Known as the blueprint process, cyanotype is considered a precursor to modern photography, relying on basic chemical components, ferric ammonium citrate and potassium ferricyanide and UV light to produce images.*

In this scientific and artistic research, we explore the historical roots of Prussian blue and the symbolic meanings attributed to the color blue in 19th and 20th century art and culture. Additionally, we analyze the effects of varying exposure times and choice of substrates, comparing types of paper and textiles to understand how UV light intensity and chemical concentrations shape the final image or photogram.To produce a cyanotype print, ferric ammonium citrate and potassium ferricyanide are combined with water in precise ratios to create a photosensitive solution. This solution is applied to a substrate, such as paper or fabric, and dried in a dark environment to prevent premature exposure. Once dried, the coated substrate is exposed to sunlight or UV light, initiating a photochemical reaction that results in the intense blue color characteristic of cyanotypes. The image is then developed and fixed by rinsing the substrate in water, completing the process.

While cyanotype is one of the more eco-friendly printmaking methods, its sustainability depends on responsible chemical handling and disposal practices. Cyanotype can be applied to various natural fibers and fabrics, such as cotton, linen, or recycled paper, making it adaptable to sustainable materials that can decompose or be recycled at the end of their lifecycle. Ultimately, this paper will explore the practical applications and artistic impact of cyanotype techniques on textiles, underscoring its significance in advancing sustainable practices within textile art. This paper aims to highlight both the practical and aesthetic impacts of cyanotype in textile art, advocating for its role in sustainable art practices.

Keywords: *cyanotype, photogram, Prussian blue colour, textile, textile art*

1. Introduction – *Deep blue* and the historical aspects of cyanotypes

The cyanotype process, renowned for its extrodinary deep blue tones, is among the oldest photographic printing methods. Its origins date back to the 19th century, when scientific curiosity about light-sensitive materials intersected with artistic exploration. This rich history of cyanotypes, spanning scientific discovery, practical application, and artistic expression, underscores the enduring appeal of this specific photographic process. Cyanotypes, while often viewed through the lens of art, also have a fascinating scientific and historical legacy, as they were initially employed for practical documentation rather than artistic expression. The early British pioneers sir John Herschel and Henry Fox Talbot referred to it as "photogenic drawing", a technique involving chemically treated writing paper that enabled them to capture and preserve images [1]. As the author James Berry states: "Many chemists had noticed the action of light upon various compounds of iron before Herschel, but, in 1840 and 1842, he was the first to use the salts of that metal for the photographic process he named cyanotype" [2]. However, Herschel, a passionate botanist and scientist, first created the anthotype [3]. An anthotype is created by using plant extracts, typically derived from petals, berries, or other plant parts traditionally used for dyeing fabrics. These extracts are mixed with alcohol and applied to paper as a light-sensitive coating. Semi-transparent flat objects are then arranged on top of the coated paper and exposed to UV light, similar to the cyanotype process which we will explore in detail later on in this paper. The areas exposed to the light gradually brighten, forming a positive image or photogram and the exposure time varies depending on the sensitivity of the plant dyes, ranging from several hours to days or even months [3].

As an extension of the anthotype, Herschel discovered that ferric ammonium citrate combined with potassium ferricyanide could create a photosensitive emulsion capable of producing blue images in 1842. He named this process cyanotypes and the compounds which make it so extrodinary are the same to this day. The cyanotype process harnesses the sensitivity of ferric compounds to ultraviolet light. Upon exposure, a chemical reaction occurs, leaving behind a rich blue image, a hue so iconic that it has become synonymous with the process itself. This research thus focuses on the importance of historical, scientific and artistic expression of the colour blue in art history and cyanotypes in textile art. Moreover, this paper highlights the significance of cyanotypes as a simple, non-toxic, sustainable printing method and showcases various experiments, both on paper and textiles, with different exposure times.

Cyanotypes found one of their first prominent uses in the field of botany, thanks to the pioneering work of English botanist and photographer Anna Atkins. Often regarded as the first female photographer, Atkins used cyanotypes to document plant specimens, creating detailed and visually captivating impressions known as photograms. What Atkins clearly noticed is how plants produce pictures [4]. Her seminal work, *Photographs of British Algae: Cyanotype Impressions*, published in 1843, stands as a testament to the scientific utility and aesthetic potential of the medium. Atkins's innovative work demonstrated the potential of cyanotypes for capturing intricate botanical details, offering an affordable and accurate method for documenting plant species [4]. By using cyanotypes, Atkins was able to capture intricate details of plant structures in a way that was both accurate and visually engaging, blending the realms of art and science and thus she is widely recognized as a pioneer in both photography and botanical documentation. Despite the objections of other botanists, who were frustrated by the photogram's inability to capture crucial details like colour, roots, or seeds, Atkins had always viewed photograms as a valuable tool for illustration [4]. Atkins' work bridged the gap between art and science, showing that photography could serve as a precise and objective medium for scientific documentation. Her cyanotypes offered unparalleled detail and accuracy in the study of algae, making them valuable for botanists and scientists. Her contributions highlighted the importance of cyanotypes in botany, as they provided a practical tool for scientific illustration and preservation, long before modern photographic techniques were accessible. Atkins' meticulous documentation of British algae provided a comprehensive visual catalogue of various plant specimens and her book was an invaluable resource for researchers in the mid-19th century and contributed to the growing field of natural science and taxonomy.

Beyond botany, cyanotypes became a practical tool for engineers and architects, serving as the precursor to modern blueprints. This type of printing was affordable alternative to hand drawing copies of architectural blueprints. This process has had a significant impact on architecture, particularly in the context of blueprinting and design visualization [5]. Cyanotypes transformed architecture by enabling efficient and precise reproduction of plans, marking a critical step in the modernization of architectural workflows. They simplified the sharing of plans between architects, engineers, contractors, and builders streamlining communication in construction projects [5]. While no longer in widespread use, their historical and aesthetic value continues to inspire architects and artists, bridging the past and present in the visualization of built environments.Their simplicity and affordability made them an essential part of industrial and architectural documentation throughout the late 19th and early 20th centuries and despite being overshadowed by advancements in photographic technology, the cyanotype's accessibility and unique visual qualities have sustained its appeal.

In recent times, the cyanotype process has experienced a renaissance among textile artists, designers, and photographers who appreciate its handcrafted quality and historical significance and is being used frequently as a safe printing technique, offering a sustainable and creative approach to producing unique, nature-inspired designs on both fabric and paper.

1.1. The symbolic meanings of the colour blue in art history and textiles

The colour blue has held profound symbolic significance in both art history and textiles, embodying a spectrum of meanings that span spirituality, tranquillity and status. In medieval and Renaissance art, blue was synonymous with divinity and purity, particularly in its use of ultramarine, a rare and costly pigment derived from lapis lazuli. The stone itself, forms in contact metamorphic environments, often in limestone deposits subjected to high heat and pressure. The blue colour comes primarily from lazurite, a mineral in the sodalite group, while calcite, pyrite, and other minerals are present as secondary components [6]. Beyond its spiritual connotations, blue also conveyed power and wealth, as its rarity made it a luxury reserved for the elite. Similarly, in the realm of textiles, indigo dye, extracted from plants and traded extensively across continents, became a cornerstone of cultural identity and prestige. From Japanese kimonos to West African *adire* cloth; the traditional textile art form originating from Nigeria, indigo blues signified social standing, tradition, and artistry, often reserved for ceremonial attire or symbolic expressions of status.

The emotional and philosophical aspects of blue further deepen its significance. Associated with the natural elements of sky and sea, blue is often linked to serenity, vastness, and introspection, a theme that emerges in artistic movements like Romanticism, where artists used shades of blue to evoke solitude and reflection. This same calm quality influenced textile patterns, with many cultures using blue dyes to create motifs inspired by nature and water. Johann Wolfgang von Goethe, in his influential work *Theory of Colours* (1810), explores the psychological and emotional effects of colours, including blue, which he views as a colour of depth, introspection, and paradox. According to Goethe, blue has a unique quality of creating both attraction and detachment. He describes blue as a "contradictory colour" because, while it has a calming and soothing effect, it also evokes a sense of melancholy and yearning [7]. Goethe associates blue with the infinite and the intangible, noting that it is often perceived as receding in space, as seen in the sky and distant mountains [7]. This quality gives it a sense of vastness and mystery. He writes that blue "has a peculiar and almost indescribable effect on the eye", as it combines the excitement of colour with a sense of coolness and restraint [7]. For Goethe, this duality makes blue a colour of profound emotional resonance, capable of inspiring calm reflection or deep nostalgia. His observations influenced later artists and thinkers, especially within Romanticism, who embraced blue as a symbol of both the sublime and the introspective human spirit [7].

Moreover, blue is also imbued with the "melancholic", as reflected in phrases like "the blues" and works of art that use deep, moody sounds to express longing, loss, or contemplation. For example, the term blues in music is not only associated with musical genre but also represents sadness. In this context, Miles Davis's seminal jazz album *Kind of Blue* (1959) reflects the works emotional depth and introspective tone, often evoking a sense of melancholy and reflection [8]. Whether in the bold azure of medieval illuminations, the soft indigo of traditional fabrics, or the layered tones of a painting, blue remains a complex symbol that connects the spiritual, emotional, and material worlds, bridging human experience with the infinite and the divine.

1.2. Prussian blue in 20th century art

Prussian Blue's role in 20th-century art underscores its enduring appeal and versatility. From Picasso's emotive explorations to Kandinsky's spiritual abstractions, Rothko's meditative canvases, and Kiefer's historical narratives, the pigment has transcended its material origins to become a symbol of emotional depth, innovation, and cultural reflection. Its impact on art history serves as a testament to the power of colour in shaping artistic expression thus this chapter briefly explains how Prussian blue became a significant colour in 20th century art, primarily painting. Prussian Blue, a deep, rich blue pigment, has had a profound impact on art history since its discovery in the early 18th century. In the early 18th century, Prussian Blue (ferric hexacyanoferrate (II)) was discovered as the first purely synthetic pigment. This innovative blue pigment was more affordable, readily available, and easier to produce compared to ultramarine and other blue pigments commonly used in paintings at the time [9]. The pigment, renowned for its vibrancy, stability, and affordability, gained significant prominence in the 20th century as artists sought to expand their colour palette and explore new artistic approaches, directions and representations. Its unique properties made it a symbol of both tradition and innovation, contributing to its enduring legacy in modern and contemporary art and has had an essential influence on cyanotypes. In this chapter we shall present some of the most prominent uses of the Prussian blue, as it has significance for both art and textiles.

One of the most iconic uses of Prussian Blue in the 20th century is found in the work of Pablo Picasso during his *Blue Period* (1901-1904). While this phase slightly predates the century, its influence resonated throughout and is still considered one of the most important periods in art history. The *Blue Period* spanning roughly from 1901 to 1904, is one of the most poignant and celebrated phases of his artistic career. Characterized by the dominance of blue and blue-green tones, this period was marked by deeply emotional and melancholic themes, reflecting both personal struggles and a broader social commentary on human suffering and isolation [10]. Prussian Blue dominated Picasso's palette as he created deeply emotive works like *The Old Guitarist* (1903). The colour's intensity and melancholic undertones mirrored the themes of poverty, isolation, and despair in his art. Picasso's use of the pigment demonstrated its power to evoke profound emotional responses [10].

Similarly, Prussian Blue played a crucial role in the rise of abstract art, particularly with the work of Wassily Kandinsky. As one of the pioneers of abstraction, Kandinsky often employed blue hues to convey spiritual and emotional depth. In pieces like *Composition VII* (1913), the colour's presence is both dynamic and grounding, reflecting his belief in the transcendental qualities of blue. Kandinsky's use of blue colour was not merely decorative; it aligned with his theoretical writings, where he associated blue with spirituality and introspection [11].

In the realm of printmaking, Prussian Blue also emerged as a popular choice. Japanese woodblock prints, which had influenced European Impressionists and Post-Impressionists, utilized this pigment extensively. During the 20th century, artists like Henri Rivière incorporated techniques reminiscent of Japanese prints, employing Prussian Blue to create atmospheric depth and tonal contrast in their work [12]. Moreover, the mid-20th century saw Prussian Blue's adaptation in modernist and minimalist contexts. Mark Rothko, though known for his vibrant red and orange fields, occasionally employed blue tones to explore themes of the sublime and the infinite. For Rothko, darker blues, including shades reminiscent of Prussian Blue, served to envelop viewers in an experience of quiet reflection [13]. Furthermore, Yves Klein's *International Klein Blue*, while chemically distinct, owes conceptual debts to Prussian Blue's historical role. Klein's obsession with monochrome blue as a vehicle for the immaterial and infinite echoed the symbolic weight carried by Prussian Blue in earlier periods [14]. One of his essential works, such as *IKB 79* (1959), redefined the use of blue as a medium for both physical and metaphysical exploration. In summary, Prussian Blue has played a pivotal role in shaping the artistic narrative across diverse movements and mediums. Its adoption in woodblock prints and its influence on European Impressionists and Post-Impressionists highlight its global impact. Prussian Blue remains a timeless pigment, reflecting art's capacity to transcend boundaries and connect deeply with the human experience.

2. Cyanotypes

2.1. Cyanotypes on paper: photograms and negatives

The cyanotype process is a simple and non-toxic method, especially for creating photograms, as previously mentioned and explained. For photograms, we use an object, usually a plant, because it is the easiest to achieve a contact print. When creating cyanotypes on paper, it is important to use a flat, dry object to ensure the contact print can be easily attached (Figure 1.). In the cyanotype process, light-sensitive iron salts: potassium ferricyanide and ammonium ferric citrate are used instead of light-sensitive silver salts. These salts are sensitive to ultraviolet (UV) light, which can come from the Sun or darkroom UV light sources. The next step involves preparing the light-sensitive solution. This is made by combining potassium ferricyanide and ammonium ferric citrate in equal parts. The solution should be mixed in a dimly lit or low-UV environment to avoid premature exposure. Once mixed, the solution is applied evenly on paper using a brush or applicator. To ensure even coverage, the application must be done quickly and efficiently and we have to keep in mind about the strokes we apply onto the paper since they will be visible once the print is dry.

The image is produced through contact printing, by placing a negative or an object directly onto the prepared surface. If using a negative, the process becomes more complex with lots of various variables. Working with negatives requires basic photography knowledge, including how to create negatives and manipulate the black, grey and white tones. In this process, the toning process is crucial and involves a more advanced understanding of developing negatives and exposing them to UV light. Creating negatives for cyanotypes can be approached using traditional analogue techniques or modern digital tools, depending on the desired outcome and resources available. Both methods allow for precise control over tonal ranges, contrast, and image size, which directly influence the quality of the final cyanotype print. Traditional film photography provides a tactile and analogue method for creating negatives. Photographers can capture images on black-and-white film, which is well-suited for cyanotypes due to its tonal range and contrast [15]. After shooting, the film must be processed in a darkroom to create a physical negative. If the original film negative is smaller than the desired cyanotype, an enlarger can be used to create a larger contact-sized negative on transparent photographic paper or film. This traditional approach maintains the authenticity of historical photographic processes while offering rich tonal detail [16]. Digital methods for creating negatives have gained popularity due to their accessibility and flexibility. A digital negative is created by inverting a scanned or digital image's tones using photo editing software, such as Adobe Photoshop [17]. Adjusting the image's contrast ensures a full tonal range, from deep blacks to clear whites, which is essential for capturing details in the cyanotype print. Once edited, the negative is printed onto a transparent medium, such as inkjet transparency film, using a high-quality printer with pigment-based inks for durability [18]. This method allows artists to produce negatives at any desired size and refine details for precise control over the final print. In addition to photographic negatives, handmade or experimental negatives can be created for unique effects. Artists may use opaque markers, India ink, or cut-out materials to design negatives on transparency film. Objects like leaves, lace, or textured materials can also be directly placed on the sensitized surface, acting as negatives to create intricate, abstract patterns [15]. This approach merges artistic expression with the cyanotype's inherently experimental nature. The choice between traditional and digital methods, or a combination of both, depends on the artistic intent and technical preferences. Each method offers distinct advantages, from the tactile engagement of analogue processes to the precision and adaptability of digital tools.

The exposure time depends on the amount of UV radiation, which triggers a chemical reaction on the photosensitive surface that is not covered by the object. On that part of the surface, the iron salts altered by ultraviolet light react with potassium ferricyanide, creating an insoluble blue colour. Washing the substrate with water concludes the exposure and stops the chemical reaction, washing away the excess unexposed iron salts, while the areas exposed to light turn blue. This step is crucial as it can take longer for the salts to be rinsed. When drying a cyanotype on paper, it is vital to do it in a shaded room, because any further exposure will change the outcome of the cyanotype print. When working with cyanotypes on paper, it is crucial to consider the paper's qualities as well. The best option is a 300 to 400 g/m² cotton blend or pure cotton paper, as it absorbs the chemicals effectively. However, pure cotton papers are costly but give the best results, making them the preferred choice for professional and high-quality cyanotype prints, where durability and vibrancy are essential.

2.2. Cyanotypes on textiles

Cyanotype printing on textiles is a creative and artistic method that produces permanent, striking blue designs on fabric (Figure 2). Unlike paper-based cyanotypes, which are commonly used for scientific or photographic purposes, working with textiles offers greater versatility, allowing for applications in textile art, home décor, and fashion design. For example, cyanotype prints can be found in contemporary clothing, tote bags, scarves, cushion covers, and even upholstery, showcasing the technique's adaptability and appeal in modern design contexts [17]. The process begins with selecting the fabric, as the material greatly influences the quality of the final print. Natural fibres like cotton, linen, or silk are ideal because they absorb the photosensitive chemicals effectively and yield vibrant, often deep blue results. In contrast, synthetic fabrics or blends may resist the coating or result in uneven prints due to poor absorption. Pre-washing the fabric is essential to remove any manufacturing residues or sizing agents that might interfere with the chemical coating [18]. After washing, the fabric should be ironed to create a smooth surface, which is critical for achieving even coverage and clear designs. The fabric is coated with a solution of ferric ammonium citrate and potassium ferricyanide, which forms the light-sensitive layer. This solution can be brushed, sprayed, or immersed onto the fabric, depending on the desired effect but this process has to be carefully done. Brushing allows for controlled application, while immersion ensures uniform coating across the entire piece. For artistic effects, uneven brushing or deliberate streaking can add texture to the final design [16]. Furthermore, there are two primary methods for creating cyanotype prints on textiles: the wet and the dry process and both are straightforward and simple but require precise timing and controlled lighting conditions.

In the dry process, the coated fabric is left to dry in a darkroom or a light-proof space to prevent accidental exposure. Once the fabric is completely dry, the design is arranged. Objects like leaves, flowers or stencils are commonly used to block light and create striking silhouettes. For more detailed imagery, photographic negatives printed on transparent film can be used, as they transfer intricate patterns onto the fabric. These objects or negatives are pressed flat against the fabric using a glass sheet to ensure clear, sharp edges in the final print [15]. For example, artists like Atkins, who pioneered cyanotypes on paper, inspired textile designers to use botanical motifs. Modern creators often replicate this by arranging pressed leaves and flowers on fabric to produce organic, nature-inspired patterns. Furthermore, the wet process involves arranging the design directly onto the coated fabric while it is still wet. This technique can create softer, more diffused edges in the final print, as the moisture allows light to scatter slightly under the objects. The wet process is particularly effective for achieving dreamy or abstract effects. For example, stencils with intricate patterns can be used to overlay multiple textures, resulting in layered and visually complex designs [17]. Both methods are equally effective, but they yield different artistic outcomes. The choice of method often depends on the desired aesthetic and the precision required for the project.

After arranging the design, the fabric is exposed to UV light, either from direct sunlight or a UV lamp. Exposure times vary depending on the intensity of the light, but generally range from 5 to 20 minutes in summer time. As the exposure progresses, the fabric turns a faint grey-green colour, indicating that the chemical reaction is occurring (Figure 3.). Once exposure is complete, the fabric is rinsed thoroughly in water to wash away unexposed chemicals, revealing the final blue print. Adding a vinegar rinse can enhance the depth of the blue tones [16]. Cyanotype textiles have been used in various artistic and practical applications. In home décor, cyanotype-printed fabrics are popular for creating unique cushion covers, curtains, or wall hangings. In fashion, designers have incorporated cyanotype patterns into garments, blending traditional techniques with contemporary aesthetics. For example, British fashion brand *By Walid* has utilized cyanotype prints on vintage fabrics to create eco-friendly and artistic clothing pieces. Similarly, textile artist Melanie Bowles has explored cyanotypes in combination with digital printing, demonstrating the fusion of historical and modern techniques in textile design [19]. British textile artists and designers Zoë Burt and Allan Brown often incorporate cyanotype prints with plant-based dyed fabrics. Cyanotype printing has become a cherished technique among contemporary textile artists, blending historical photographic methods with innovative design practices. By incorporating sustainable materials and natural dyes, artists like Burt and Brown demonstrate how traditional processes can be reimagined to address modern concerns, such as environmental consciousness and individuality in design. Today, cyanotype on textiles not only celebrates the intersection of art and science but also serves as a versatile medium for storytelling, personal expression, and sustainable creative practices.

2.3. The toning process and preserving cyanotypes

Toning in the cyanotype process refers to the alteration of the traditional blue tone of cyanotype prints through chemical and non-chemical treatments, which produce various colours and enhance the aesthetic qualities of the print. This process is commonly used to expand the creative possibilities of cyanotypes, moving beyond the distinctive blue tone that characterizes the method as we previously elaborated. The use of toning is widespread in art and design, where it allows for the creation of unique and expressive cyanotypes. It is also employed to mimic the look of antique photographs in preservation efforts or for educational demonstrations that showcase the principles of photography and chemistry. By transforming the monochromatic blue prints into multi-coloured artworks, toning enhances the versatility and expressive potential of cyanotype photography, bridging the gap between scientific documentation and artistic expression.

Toning is primarily employed to introduce alternative colour tones, such as browns, purples, greens, or blacks, which provide a vintage or nuanced appearance to the prints. Artists and photographers use this technique to achieve personalized effects that reflect their artistic vision. Additionally, in some cases, toning can improve the longevity and stability of cyanotype prints by altering the chemical composition of the dye [16]. Different substances interact with cyanotypes to produce a range of colours. Tea and coffee are frequently used to create warm sepia or brown tones, offering a soft, antique aesthetic. Tannic acid can result in deep brown or purple hues and is often combined with tea or coffee for enhanced effects [17]. Sodium carbonate may shift the blue to lighter shades or introduce greenish tones. Hydrogen peroxide can intensify the existing blue tones by accelerating oxidation during the development process. Additionally, bleaching and re-toning allow for the partial or complete removal of the blue before applying a toning agent, such as tannic acid, to introduce new colours [15].

However, it is essential to highlight the plant-based toning process as it is not harmful. Moreover, toning with plants is widely used in artistic projects, sustainability education, and personalized cyanotype printing. Artists use locally sourced plants to reflect the flora of specific regions, creating works that emphasize the connection between nature and the medium. Plant based toning works with only natural components such as tannins, anthocyanins, and chlorophyll, which can interact with the iron-based chemistry of cyanotype prints. When exposed to plant extracts, these compounds replace or modify the ferric compounds in the cyanotype, producing a range of colours and tones [17]. Plant-based toning appeals to artists and photographers interested in sustainable and organic methods and it reduces reliance on synthetic chemicals and embraces renewable resources, aligning with environmental concerns [15]. Furthermore, the unpredictability and individuality introduced by plant-based toning make each print unique. Variables such as plant species, growth conditions, and extraction techniques contribute to the distinctive character of the final result.

While toning enhances the visual appeal of cyanotypes, it presents challenges. The process can be unpredictable, with results varying based on paper type, exposure levels, and chemical concentrations but that can also be a positive aspect of this process. Not knowing the final result as each cyanotype is unique. However, when it comes to toning, over-bleaching or inadequate washing may degrade the print, leading to a loss of detail or structural stability of the paper or fabric. Thus, plant-based toning is the way to go as toning cyanotypes with plants is a sustainable, creative method that transforms traditional blue prints into expressive, individualized artworks. This process celebrates the natural world and highlights the interplay of science and art, offering an eco-friendly alternative to chemical-based toning processes. For these reasons, experimentation is often necessary to achieve consistent and desirable outcomes [17].

Figure 1: Cyanotype on a cotton blend 300 g paper, mentor: assistant professor of art Lea Popinjač, exposure time 1 hour. Photo by Petra Krpan, 2024.

Figure 2. Cyanotype on cotton with embroidery, mentor: assistant professor of art Lea Popinjač, design by Sára Komárková, exposure time 2 hours. Photo by Petra Krpan, 2024.

Figure 3. Cyanotype process. Photo by Petra Krpan, 2024.

3. Conclusion

Cyanotype printing has emerged as a sustainable practice within contemporary textile design due to its eco-friendly process and compatibility with natural and plant-based materials. Unlike many modern dyeing techniques, cyanotypes rely on water-based chemicals that are non-toxic and biodegradable, making them an environmentally conscious and safe choice. The process avoids harmful industrial dyes and chemical-intensive procedures, especially if doing the plant-based toning process, reducing its ecological footprint. Moreover, the emphasis on using natural fibres such as cotton, linen, and silk further aligns cyanotype printing with sustainable textile practices today (Figure 4.). These materials not only absorb the chemicals effectively but also decompose naturally, promoting a circular lifecycle for textiles.

Figure 4. Cyanotype on silk, design by Petra Krpan, exposure time 2 hours, 2024. Photo by Petra Krpan, 2024.

Contemporary textile artists and designers have embraced cyanotype printing as a way to integrate sustainability into their work while preserving its artistic and expressive potential. By incorporating upcycled or vintage fabrics, many practitioners reduce waste and give new life to discarded materials. For example, the use of botanical elements in the printing process not only produces visually striking patterns but also fosters a connection with nature, encouraging mindful and sustainable approach to design. The revival of cyanotype printing demonstrates how traditional techniques can be adapted to meet the demands of sustainability goals, offering an inspiring blend of art, tradition, and most important, ecological responsibility. Thus, cyanotype printing's accessibility, low environmental impact, and versatility make it a compelling choice for those committed to sustainable textile and art practices. As the global textile industry increasingly focuses on reducing its environmental impact, the revival of processes like cyanotype printing reflects a broader shift toward eco-conscious innovation in art and textile design.

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Original scientific paper

INVESTIGATION OF SURFACE MODIFICATIONS OF ELECTROSPUN POLYCAPROLACTONE FILAMENTS WITH ALKALINE HYDROLYSIS

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Abstract: *Medical textile materials are an important staple of healthcare, as they encompass a wide variety of devices, from simple bandages and gausses, to complex implants. These devices are often made from various materials, one of which is polycaprolactone (PCL). PCL is a biodegradable and biocompatible polymer that has found a great use in the medical field, which has been expanding due to the advances of the electrospinning process. Unfortunately PCL lacks active groups, such as hydroxyl and carboxyl and is therefore inherently hydrophobic. This in turn can limit the application of PCL in tissue engineering, as well as wound management. To remedy this situation, surface modification methods can be used. Therefore, in this research a conventional method used for surface modification of polymer surfaces, alkaline hydrolysis, has been implemented. With the use of four different concentrations of sodium hydroxide (NaOH) (0.25, 0.5, 0.75 and 1 mol/dm^3) in two time regiments of 60 and 120 minutes, electrospun PCL filaments were modified. Further on, to investigate the level of success alkaline hydrolysis might have had on PCL filaments, changes in lengths/shrinking as well as vertical water migration were investigated. The obtained results show that alkaline hydrolysis influenced the dimensions of the filaments, while the vertical water migration tests have shown that in comparison to the untreated filaments, modified filaments have a clear hydrophilic character.*

Keywords: *PCL; electrospinning; medical textiles; alkaline hydrolysis*

1. Introduction

1.1 Medical textile materials

Medical textile materials are a crucial and a fast growing segment of the technical textile materials. These materials encompass a wide variety of medical devices, raging from the simple ones, such as bandages and wipes, all the way to more complex ones, such as implants and oxygenator membranes. Therefore, medical textile materials can be divided into seven categories:

1. Implantable medical textile materials
2. Non-implantable medical materials
3. Healthcare and hygiene medical textile materials
4. Intelligent medical and healthcare textile materials
5. Medical textile materials in healthcare environments
6. Environmental hygiene control components
7. Medical textile materials for Extracorporeal devices [1].

Due to the growing concern caused by the drug resistant microorganism such as *Staphylococcus aureus* and *Escherichia coli*, research and development of antimicrobial textile materials have seen a great interest [2, 3]. These materials often contain various antimicrobial agents that are either incorporated into the material, or are coated onto the material surface [4]. Some of the most notable antimicrobial agents in use are metal and metal oxide nanoparticles. Due to their specific size, shape and large ratio of surface area in comparison to volume, these materials can effectively inhibit the growth or outright destroy bacterial colonies [5, 6]. Besides their antimicrobial properties medical textile materials for wound management have to effectively remove wound exudate without any spillage and enable an appropriate climate for wound healing [7]. Therefore to achieve this, medical textile materials for wound management have to have a hydrophilic character [8].

Medical implants, especially implants intended for management of ligament and tendon tears are an important aid in the successful treatment as well as restoration of mobility and normal bodily functions. To be eligible for this purpose, materials, textile or otherwise have to be biocompatible with the human body. Moreover, these materials shouldn't cause inflammation through oxidative stress. To achieve this, implants have to have incorporated antioxidants or surface active groups [9]. Furthermore, it has been noted that for the successful treatment and cell proliferation implants should likewise have to have active groups [10]

1.2 Electrospinning

In recent years a great deal of focus and effort has been placed on the research pertaining to the use of electrospinning process, particularly electrospinning of medical textile materials. As the name suggests, electrospinning process is a fabrication method that relies on the use of electrical fields to successfully fabricate textile materials. In this process, a polymer melt or solution is extruded out of the small diameter syringe needle. The syringe needle used in the electrospinning process is electrically charged, this in turn results in the formation of a Taylor cone, a conical formation that forms on the tip of the needle due to the effect of the surrounding high voltage electrical field. As soon as the surface tension of the cone breaks a polymer jet is formed. Due to excessive surface charge at its end, the jet starts to whip, this in turn causes the formation of smaller filaments that are further stretched as they travel towards the collector [11, 12].

Due to their specific porous structure, small diameter and alignment on mats or yarns electrospun medical textile materials can be used for various purposes such as wound management, tissue engineering, biosensing, implant fabrication and personal protective equipment [13].

1.3 Polycaprolactone – Surface modifications

Polycaprolactone (PCL) (Figure 1.) is an aliphatic polyester that is obtained from crude oil through Ring opening polymerization of ε – caprolactone [14, 15]. In comparison to other biodegradable polymers such as polylactic acid, mechanical properties of PCL are middling (Tensile strength – 14 MPa; Young's modulus – 190 MPa). Moreover, PCL has low melting temperature of 65 ^{0}C and exceptionally low glass transition temperature of -65 ^{0}C. Despite the wanting mechanical properties, PCL makes it up in its biocompatibility, and processability. Unlike many other polymers, PCL has been approved by U.S. Food and Drug Administration (FDA), and has ever since then been used in the fabrication of various medical devices [16].

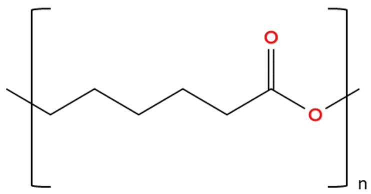


Figure 1: Chemical structure of PCL

As evident form it's chemical structure, PCL lack surface active groups, which makes it intrinsically hydrophobic. This in turn makes it less susceptible for cell proliferation, which may limit its use for tissue engineering, as well as difficult to coat with antimicrobial agents [17, 18]. To successfully overcome this disadvantage surface modification can be used. This involves the use of plasma treatment, aminolysis and alkaline hydrolysis [19, 20]. With the use of strong base, such as sodium hydroxide (NaOH), the ester groups in PCL are cleaved, this in turn leads to the formation of oligomers that contain hydroxyl and carboxyl groups [20]. The reaction of PCL alkaline hydrolysis of PCL is shown in Figure 2. Due to its ease of use, affordable price as well as reliability when it comes to imparting of new active groups, alkaline hydrolysis is a common method in the PCL surface modification [20-22].

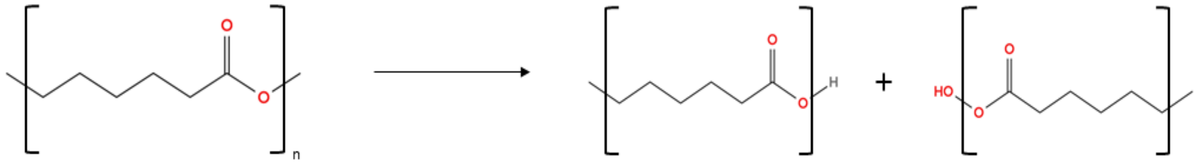


Figure 2: Reaction of PCL alkaline hydrolysis

The main goal of this paper will be focused on the investigation of the influence alkaline hydrolysis with four different concentrations of NaOH (0.25, 0.5, 0.75 and 1 mol/dm^3) in two time regiments of 60 and 120 minutes may have on the dimensions of electrospun PCL filaments as well as their potentially acquired hydrophilicity.

2. Methods and Materials

2.1 PCL electrospinning

For the purposes of PCL electrospinning Hexafluoroisopropanol (Halocarbon, USA) was used as a solvent, while polycaprolactone (Vornia Biomaterials Ltd., Ireland) was used as polymer. The 10% solution of PCL/HFIP was electrospun using a custom made machinery. Electrospinning solution was extruded out of a 21 gauge syringe needle, while a stainless steel wire was used as a collector for the filament. For the electrospinning process, the applied voltage was 6.4 kV.

2.2 Surface modification of electrospun PCL

For the purposes of PCL surface modification NaOH pellets (Merck, USA) were used. Throughout the investigation deionised water was solely used. The prepared concentrations of NaOH were 0.25, 0.5, 0.75 and 1 mol/dm^3. Afterwards, from a single filament, 8 strands of 20 cm length were transferred into eight glass beakers. Each beaker was filled with 10 cm^3 of dissolved NaOH. By doing so, two beakers contained the same concentration of NaOH. Four of the filled beakers were set aside for 60 minutes, while another four were set aside for 120 minutes. Throughout its length, the process was done at room temperature. After the aforementioned time periods had passed, strands were taken out and thoroughly washed with deionised water. After the washing had finished, the samples were placed in the desiccator for 24 hours.

2.3 Investigation of alkaline hydrolysis' effect on the PCL

After the 24 hours had passed, the samples were taken out of the desiccator and their length had been measured using a ruler. Furthermore, to identify the effect alkaline hydrolysis might have had on the change of the hydrophobic nature of the PCL, a vertical water migration test was conducted. For the purposes of this investigation a cationic dye Methylene Blue (Merck, USA) was used as a colorant to track the migration of the water. A 5% aqueous solution (dissolved in deionised water) of the aforementioned dye was used throughout the investigation. The 20 cm modified samples were cut into quadruplicate samples. As a control a quadruplicate of untreated PCL was used. In this investigation the samples were held vertically, with their upper parts clamped to a horizontal rod, while the lower parts were immersed in a Petri dish containing the dye solution. After 5 minutes the lengths the dye had traversed up the samples were measured.

3. Results and discussion

3.1 Results and discussion of the shrinking investigation

With the use of a ruler, modified PCL samples had their lengths measured and compared to the initial 20 cm. The obtained values are shown in Table 1.

Table 1: Measured length of samples after the treatment with NaOH

Samples	Measured lengths [cm]	Samples	Measured lengths [cm]
0 mol/dm³ – 60 minutes	19.9	0 mol/dm³ – 120 minutes	19.8
1 mol/dm³ – 60 minutes	18.5	1 mol/dm³ – 120 minutes	19.0
0.75 mol/dm³ – 60 minutes	18.7	0.75 mol/dm³ – 120 minutes	18.6
0.5 mol/dm³ – 60 minutes	17.0	0.5 mol/dm³ – 120 minutes	18.5
0.25 mol/dm³ – 60 minutes	18.9	0.25 mol/dm³ – 120 minutes	19.0

As shown in Table 2, a change in lengths in comparison to the initial 20 cm was observed. Each of the investigated samples had shrunk, although a linear increase with the increase of the NaOH solution concentration wasn't present. Moreover, it is worth mentioning that based on the obtained results, samples that were treated for 120 minutes hadn't shrunk considerably in relation to the samples that were treated for 60 minutes. By comparing the obtained results it can be observed that except for the samples treated with 0.75 mol/dm^3 with a 120 minute treatment, measured lengths obtained for samples treated with a 60 minute treatment were shorter. In comparison to the treated samples, the untreated samples that were placed in deionised water for aforementioned time intervals had also shrunk, although not as considerably as the samples that were treated with NaOH. This is the result of the PCL's properties, more precisely its low glass transition temperature (-65 ^{0}C), which makes PCL a highly ductile polymer at slight changes of temperature [23]. Therefore, in comparison to the untreated samples, samples treated with NaOH had excessively shrunk due to the effect of alkaline hydrolysis.

3.2 Results and discussion of the vertical water migration test

The results obtained for water migration test are shown in Tables 2 and 3, while the graphical representations of mean values are shown in Figure 3.

Table 2: Values of lengths coloured dye solution had traversed in 5 minutes – 60 minute samples

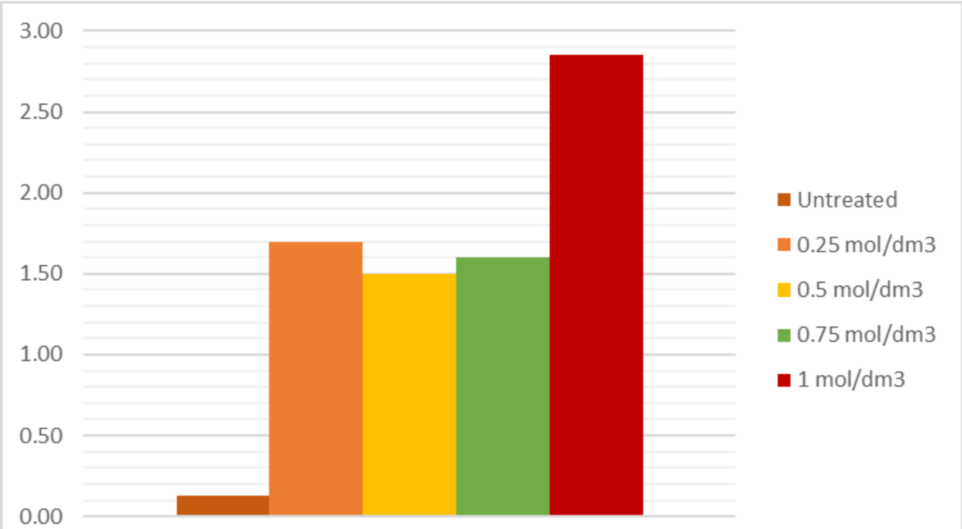
Samples	Untreated	0.25 mol/dm³	0.5 mol/dm³	0.75 mol/dm³	1 mol/dm³
1	0.1	1.5	1.5	2.1	2.7
2	0.2	1.5	0.5	1.2	3.5
3	0.1	1.5	1.7	1.7	2.2
4	0.1	2.3	2.3	1.4	3.0
x̄	0.13	1.7	1.5	1.6	2.85
M	0.1	1.5	1.6	1.55	2.85
σ	0.05	0.4	0.75	0.39	0.54
CV [%]	40.00	23.53	49.89	24.47	19.11

Where: x̄ - Average; M – Median; σ – Standard deviation; CV – coefficient of variation

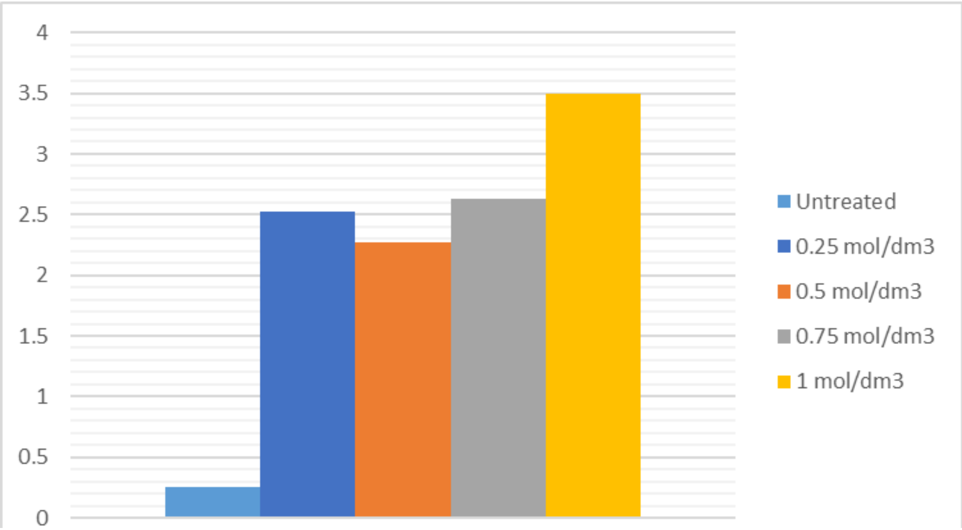
Table 3: Values of lengths coloured dye solution had traversed in 5 minutes – 120 minute samples

Samples	Untreated	0.25 mol/dm³	0.5 mol/dm³	0.75 mol/dm³	1 mol/dm³
1	0.1	2.3	2.7	2.7	3.3
2	0.3	2.0	1.3	2.0	3.8
3	0.4	2.3	2.0	2.3	3.0
4	0.2	3.5	3.1	3.5	3.9
x̄	0.25	2.53	2.28	2.63	3.5
M	0.25	2.3	2.35	2.5	3.55
σ	0.13	067	0.79	0.65	0.42
CV [%]	51.64	26.34	34.87	24.76	12.12

Where: x̄ - Average; M – Median; σ – Standard deviation; CV – coefficient of variation



a.



b.

Figure 3: Mean values of traversed lengths: a – 60 minute samples; b – 120 minute samples

As seen in the tables, as well as the figure, following was observed:

- Untreated samples had negligible measured traversed lengths
- Among the treated samples, the maximum measured traversed lengths were observed on samples treated with 1 mol/dm^3 NaOH solution, for both treatment times
- Among the treated samples, the minimum measured traversed lengths were observed on samples treated with 0.5 mol/dm^3 NaOH solution, for both treatment times
- A linear increase in measured traversed lengths, with a linear increase of NaOH solution concentrations wasn't present.
- Among the treated samples, the samples that were treated for 120 minutes had larger measured traversed lengths than the samples treated for 60 minutes.

In comparison to the untreated PCL samples, the modified PCL samples showcased not only the ability to wick the water, but also as Li, et. al. mention in their research, as a response to present wicking a hydrophilic character [24]. As for the deviations in the measured traversed lengths, a deviation in the surface morphology of the modified filaments might have been a main cause.

4. Conclusion

In this research a surface modification of electrospun PCL filaments was conducted. The main goal of this modification was to impart new, hydrophilic properties to said filament, so that they may potentially be used for further functionalization such as antimicrobial coating. To achieve surface modifications, an inexpensive and easy to use method of alkaline hydrolysis with NaOH was applied. To successfully investigate the level of effect alkaline hydrolysis might have at different concentrations and different treatment times, four concentrations with a 0.25 increment were used, ranging from 0.25 mol/dm^3 to 1 mol/dm^3, with two treatment regiments of 60 minutes and 120 minutes. As a follow-up to the surface modification, dimensional stability and vertical water migration were investigated. Based on the obtained results it was observed that all of the samples had shrunk extensively in comparison to the samples placed in water due to the effect of the alkaline hydrolysis. Furthermore, it was also observed thanks to the vertical water migration testing, that in comparison to the untreated samples, modified samples had an evident wicking ability and as a result a present hydrophilicity. Moreover, based on the observations during the investigation, it was observed that no linearity in the increase of wicking or shrinking with the increase of NaOH concentration was present. This may indicate that that alkaline hydrolysis might have affected the structure of the samples. Finally, it is worth noting that this investigation was a first step in a broader set of investigations, intended to investigate mechanical properties and to functionalize said samples for antimicrobial purposes.

Funding

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Original scientific paper

COFFEE RING EFFECT IN SYNERGY WITH COPPER NANOPARTICLES FOR SUSTAINABLE FUTURE OF INDUSTRIAL PROCESSING

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Abstract: *The coffee ring effect, a natural phenomenon observed when a droplet of liquid containing dispersed particles evaporates, results in the accumulation of particles along the droplet's edges. This effect, often considered a limitation in achieving uniform coatings, has recently been harnessed for innovative applications in materials science. Copper nanoparticles (CuNPs), known for their exceptional antimicrobial, catalytic, and conductive properties, present significant potential when combined with this phenomenon. This study explores the synergistic relationship between the coffee ring effect and CuNPs for the functionalization of textiles. By utilizing the self-assembling nature of the coffee ring effect, CuNPs can be deposited in controlled patterns, enhancing their performance and reducing material waste. This approach offers a sustainable and scalable solution for materials formulation and processing, paving the way for environmentally friendly production of advanced materials with enhanced properties such as antimicrobial activity and durability. The findings demonstrate a promising integration of natural physical phenomena with nanotechnology, contributing to the sustainable future of textile manufacturing. The concept has been validated in our previous studies using several models that included two active substances, pantoprazole and doxycycline, along with two excipients, sodium chloride and (2-hydroxypropyl)-β-cyclodextrin (HP-βCD), studied under various conditions. The results were analysed using microscopy to observe characteristic patterns. Special attention was given to the behaviour of saline solution, with the collected data being categorized into clusters. In the model containing pantoprazole and HP-βCD, interactions between these two components were observed, which were further investigated using differential scanning calorimetry. The such concepted preliminary research validated the hypothesis that the coffee ring effect can be utilized to study the properties of soluble formulations. The aim of this work was to deeper our understanding of the coffee ring effect so that we could gain deeper insights into the interactions between active compounds and other process parameters, which is crucial for creating formulations that improve stability and efficacy in solutions or in colloid phases. This approach not only holds promise for improving processing outcomes but also offers potential advancements in physical and chemical properties of novel formulations or advanced materials. Furthermore, the reduced need for highly potent materials enhances safety and reduces costs associated with working with very active substances. This dual benefit underscores the significant potential of employing the coffee ring effect in the advancement of industrial scale formulation science and technology. Through this innovative approach, we open new avenues for the development of more effective and stable products.*

Keywords: *coffee ring effect; copper nanoparticles; industrial application; sustainable solutions*

1. Introduction

The coffee ring effect is a phenomenon observed when a droplet containing suspended particles or solutes evaporates on a solid surface. As the droplet dries, the particles migrate and accumulate at the edges, leaving behind a ring-like deposit that is darker or more concentrated at the periphery than in the center. This effect occurs due to capillary flow within the droplet: as the liquid at the edges evaporates faster, it draws liquid from the center outward to replenish the evaporating edge. This outward flow carries suspended particles to the droplet's boundary, where they deposit and form the characteristic ring. The coffee ring effect is commonly seen with colloidal suspensions, nanoparticles, or dissolved solutes and has implications in various applications, such as inkjet printing, coating technologies, and biomedical diagnostics, where uniform deposition of materials is often desired. Understanding and controlling this effect is crucial for achieving high-precision patterns and consistent material performance in these fields.

In the context of scientific research, the coffee ring effect represents an intriguing phenomenon of circular deposition on a surface following the evaporation of a droplet containing particles. The analysis of this phenomenon provides crucial insights into the distribution of substances on surfaces, enabling a deeper understanding of interactions between particles, surfaces, and the environment. It also offers opportunities to study crystal growth and crystallization processes. Although the coffee ring effect was observed much earlier, systematic study began with Deegan's seminal paper in 1997 [1], which provided a fundamental explanation of the phenomenon. Deegan and colleagues explored the effect in detail, emphasizing the complexity of the underlying mechanism and highlighting capillary flow as the key factor. They observed that the phenomenon arises due to the uneven evaporation of liquid at the edges and center of the droplet. As the droplet evaporates, the contact line with the surface remains stationary, requiring liquid evaporating from the edges to be replenished from the center. Consequently, particles are transported toward the edges, resulting in particle deposition that forms the characteristic ring.

Studying the formation mechanisms and structure of these rings not only expands the fundamental understanding of colloidal systems but also establishes a framework for developing innovative strategies across a wide range of fields, from materials science to biomedicine [2, 3]. This underscores the breadth and depth of its applicability and significance. Beyond the mechanism itself, the coffee ring effect draws attention to diverse phenomena that are central to scientific inquiry, such as surface hydrophobicity, the Marangoni effect, surface tension, crystallization, and the movement of the contact line, among others. In addition to its fundamental importance, the coffee ring effect is highly relevant in optimizing the composition of inks and printing techniques using inkjet printers. Here, the goal is to minimize particle segregation during drying and achieve a uniform ink deposition. Research into the distribution, shape, and type of particles in microdroplets of pharmaceutical preparations after solvent evaporation is particularly valuable for observing interactions and developing drug formulations. This approach requires minimal material quantities, making it highly efficient for conducting multiple experiments with small amounts—especially beneficial in studies where resources are limited or expensive. Due to its efficiency, the coffee ring effect is ideal for early-stage drug optimization and testing, enabling detailed evaluations and accelerating research progress.

Inkjet printing is a versatile digital printing technique in which tiny droplets of liquid ink are precisely ejected onto a substrate to create patterns, images, or functional layers. This technology operates without physical contact between the printing head and the substrate, making it suitable for a wide range of materials, including paper, plastics, textiles, glass, and even biological tissues. Inkjet printing is widely used in both commercial applications, such as graphic printing and packaging, and in advanced fields like electronics, biomedical engineering, and material science. In these specialized areas, inkjet printing enables the deposition of functional materials, such as conductive inks, biomolecules, or nanoparticles, to create devices like sensors, displays, and photovoltaic cells. Its key advantages include high precision, low material waste, scalability, and the ability to produce complex patterns rapidly and cost-effectively. Inkjet printing recently emerged as a promising technology for creating functional material patterns and advancing optoelectronic devices. This method stands out for its simplicity, cost-effectiveness, versatility, and speed, offering a compelling alternative to traditional techniques such as photolithography, electron beam lithography, nanoimprinting, and microcontact printing. A critical aspect of inkjet printing is the deposition morphology of functional materials, which significantly influences both the resolution of the printed patterns and the overall performance of the resulting devices. One of the key challenges in achieving precise deposition is the beforementioned coffee ring effect, characterized by the accumulation of solutes at the droplet edges during evaporation, which results in a ring-like deposit that is darker at the perimeter than at the center. Commonly observed in systems containing colloidal particles, nanoparticles, and molecular solutions, the coffee ring effect also plays a prominent role in inkjet printing. Effectively managing this phenomenon is essential for high-precision patterns and high-performance devices in inkjet printing.

2. The "Coffee Ring" Effect

2.1 Mechanism of the "Coffee Ring" Effect

In recent decades, extensive research has been devoted to uncovering the mechanisms underlying the "coffee ring" effect, with a particular focus on the capillary forces influencing particles within evaporating droplets. In 1997, Deegan and colleagues from the University of Chicago identified the root cause of this phenomenon as the increased evaporation rate at the droplet's perimeter compared to its center. This disparity drives an outward capillary flow, which transports suspended particles toward the edges, resulting in a distinctive ring-like deposit. An illustration of this process is provided in Figure 1.

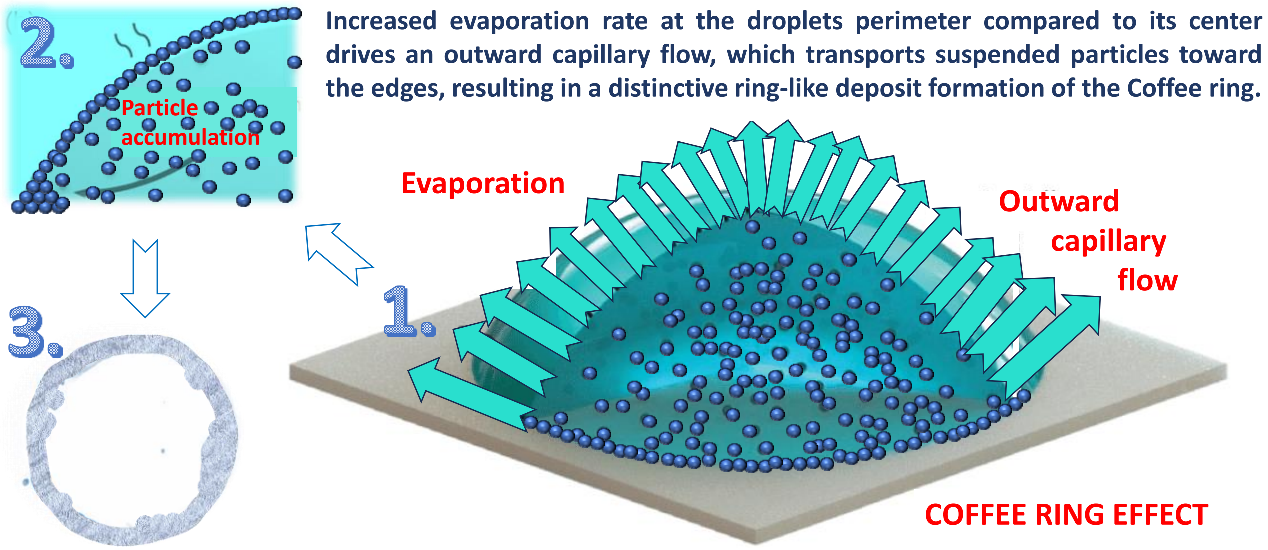

Figure 1: Coffee ring effect presented in a schematic way with drawing out a mechanism of an evaporating droplet containing a suspension of microparticles, from which it can be observed that more stronger evaporation near the contact line leads to the internal ow to the outer edge. [https://arxiv.org/abs/2201.12128]

The mechanism of the coffee ring effect involves the interplay of evaporation dynamics, capillary flow, and particle movement within a drying droplet. Evaporation is typically faster at the edges of the droplet compared to the center because the edges are thinner and more exposed to the surrounding air. This creates an imbalance, with liquid evaporating faster at the periphery than at the interior.

To replenish the evaporating liquid at the edges, a flow is induced from the center of the droplet toward the edges. This outward capillary flow carries suspended particles or solutes from the droplet's interior to its periphery. As the liquid evaporates completely, the particles that have been transported to the edges are left behind, forming a dense, ring-like deposit. This phenomenon results in a characteristic circular stain with a darker periphery and a lighter center. The process involves surface tension, adhesion between particles and the substrate, and fluid dynamics within the droplet. Solvent properties, particle size, and substrate interactions also influence the extent of the effect.

The coffee ring effect is influenced by many different parameters, such are evaporation rate, particle concentration, surface wettability, and solvent properties. Variations in these parameters can enhance, suppress, or even eliminate the effect. Due to this, in order to be able to control or prevent the coffee ring effect, researchers often modify particle-surface interactions, alter solvent evaporation rates, or use additives to change the flow dynamics within the droplet. These methods are especially important in fields like inkjet printing, coatings, and materials science, where uniform deposition is crucial.

2.2 Supressing the "Coffee Ring" Effect

2.2.1 Reducing Outward Capillary Flow

The outward capillary flow in a drying droplet directs particles toward the edges, resulting in the "coffee ring" effect. Suppressing this flow can mitigate the phenomenon. Ellipsoid-shaped particles could inhibit "coffee ring" formation during droplet evaporation as they generate strong interparticle capillary forces when reaching the air-water interface due to outward flow. This interaction forms loosely aggregated structures, raising the droplet's surface viscosity and promoting uniform particle deposition as the liquid evaporates.

Alternative strategies to reduce the outward flow include modifying the suspension composition. For example, adding dodecanethiol to gold nanoparticle suspensions enhances interparticle interactions, forming a stable monolayer at the liquid surface. This immobilizes particles, preventing their migration inward or toward the edges. Another approach involves lowering the substrate temperature, which reduces edge evaporation rates more than those at the center, balancing the overall evaporation process and suppressing outward flow.

2.2.2 Enhancing Inward Marangoni Flow

Differences in temperature between the center and edges of a droplet generate surface tension gradients, driving Marangoni flow from areas of lower to higher surface tension. This inward flow along the droplet's surface counteracts the outward capillary flow, helping to suppress the "coffee ring" effect. Strengthening Marangoni flow can therefore promote uniform particle deposition. One effective approach is to adjust the solvent composition. For example, adding ethylene glycol solvent with a high boiling point and low surface tension to a droplet slows central evaporation, creating a surface tension gradient that enhances inward Marangoni flow. Similarly, incorporating surfactants into the droplet can amplify this effect. During evaporation, surfactants accumulate at the edges, reducing surface tension locally and initiating an inward flow that balances particle distribution across the droplet.

2.2.3 Controlling Three-Phase Line Motion

The "coffee ring" effect depends on the pinning of the three-phase contact line (where the liquid, air, and substrate meet) during the evaporation of a droplet. If this contact line recedes as the droplet shrinks, the particles no longer accumulate at the edges, thereby suppressing the formation of the "coffee ring" effect. On hydrophobic surfaces, the deformation of the liquid at the contact line generates a capillary force strong enough to counteract the adhesive interactions between particles and the substrate, causing the particles to migrate inward instead. [1]

Droplets on low-viscosity substrates lead to a concentrated, point-like deposition pattern, effectively preventing the formation of the "coffee ring" structure. Other approaches to suppress the effect involve external physical interventions, such as applying magnetic fields, utilizing electrowetting, or employing ultra-low-adhesion substrates to encourage the movement or sliding of the three-phase contact line. In inkjet printing, controlling the "coffee ring" effect, either suppressing or enhancing it, enables manipulation of solute deposition patterns, facilitating the creation of high-performance functional patterns. This principle has been utilized for the fabrication of photonic crystals, biosensors, semiconductor thin films, and other advanced technologies. Furthermore, leveraging the "coffee ring" effect has led to innovative applications such as the development of transparent conductive films and short-channel transistors.

2.2.4. Introducing Cu nanoparticles to coffee ring effect

The introduction of copper (Cu) nanoparticles into systems exhibiting the coffee ring effect are important for applications such as conductive inks, sensors, and optoelectronic devices. While Cu nanoparticles offer unique properties like high electrical conductivity, cost-effectiveness, and catalytic activity, their integration into inkjet-printed patterns presents both benefits and drawbacks. Firstly, the Cu nanoparticles, due to their size, surface energy, and interactions with the solvent, can significantly alter the dynamics of droplet evaporation and deposition. Cu nanoparticles tend to aggregate near the droplet edges due to their high density and response to capillary forces. This exacerbates the coffee ring effect, leading to uneven deposition, which is detrimental to applications requiring uniformity. [2]

Secondly, Cu nanoparticles influence the evaporation rate of droplets by altering thermal conductivity: they can either accelerate or decelerate edge deposition, depending on solvent properties and particle concentration. In addition, they interact with substrates which can counteract the outward flow, suppressing the coffee ring effect. However, this suppression is often inconsistent and substrate-dependent, requiring precise control of ink formulations.

Despite those drawbacks, the applications of Cu nanoparticles are numerous: in conductive inks they offer potential for low-cost, high-performance electronics. By this it has to be emphasized that the uniformity in deposition is critical, and mitigating the coffee ring effect ensures reliable circuit performance. Cu nanoparticles can form dense networks when the effect is well-controlled, enabling high electrical conductivity. In addition, Cu nanoparticles are a part of functional films with tunable optical and electrical properties. Suppressing the coffee ring effect can lead to smoother films with better performance metrics.
However, significant drawbacks are related mainly to their potential oxidation and deposition. Overall, Cu nanoparticles are prone to oxidation, particularly under ambient conditions. Oxidation disrupts the conductivity and other functional properties of the deposited patterns, complicating their use in electronic applications. Ink formulations must include reducing agents or protective coatings, adding complexity to the system. Achieving consistent suppression of the coffee ring effect with Cu nanoparticles is challenging. Strategies such as adding surfactants or altering solvent viscosity can lead to unpredictable interactions within the system. Excessive surfactants can also destabilize the nanoparticle dispersion, reducing the quality of patterns. [3]

3. Materials and Methods

3.1. Preparation of solutions for the analysis of coffee ring effect

The experimental procedure to obtain a coffee ring sample was performed as follows: firstly a solution containing the analyte at a specific concentration of the active substance or in-situ synthesized copper nanoparticles using ascorbic acid was prepared. A 0.5 µl droplet of this solution was then carefully dispensed onto a previously cleaned and flat substrate surface (glass slide) using a 10 µl glass syringe, ensuring that the droplet remained in a fixed position. Subsequently, the droplet was allowed to evaporate either at room temperature or under controlled conditions in a chamber. For this study, the deposition process involved applying 30 droplets of 0.5 µl each onto each glass substrate. For the formulations, the first row of 10 droplets consisted of a solution of a single component, the middle row of 10 droplets contained the formulation solution, while the last row of 10 droplets included a solution of the other component (Figure 2).

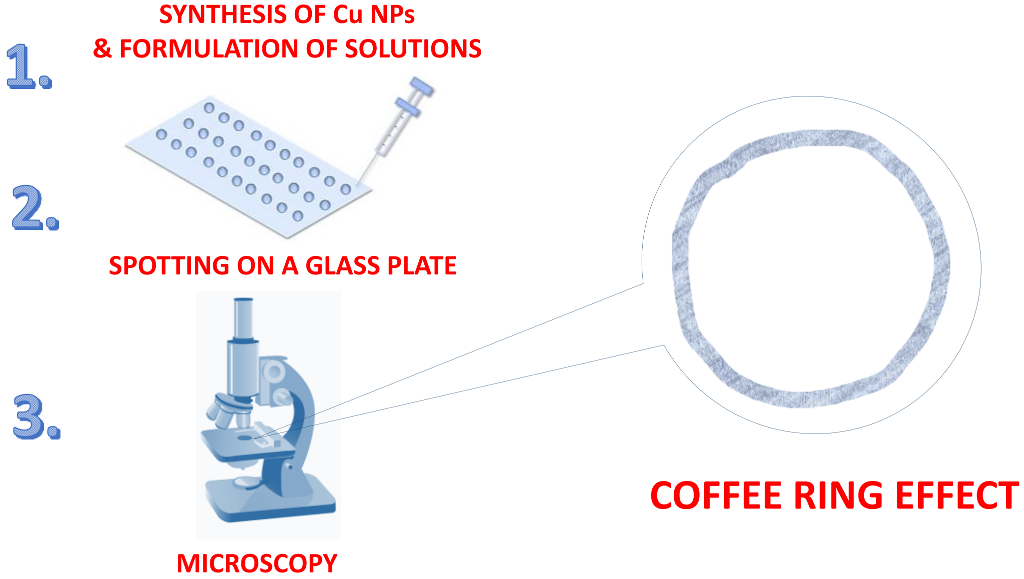

Figure 2: Experimental workflow of sample preparation, sampling and analysis of coffee ring effects

This method offers the most important advantage of beeing fast, reliable and reproducible. The time required for the entire process, from droplet deposition to ring formation, takes a short amount of time. It is also efficient as it requires only a very small volume of solution, reducing material consumption. Furthermore, the method is straightforward, as it does not rely on complex equipment or advanced techniques. Its simplicity and efficiency make it an ideal choice for rapid and precise analyses.

3.2. Sample Analysis Using an Optical Microscope

After the complete evaporation of the droplet, the resulting characteristic rings were analyzed using the KERN OBE 134 digital optical microscope. Morphology, uniformity, and the structure of the formed characteristic rings were examined with the Olympus BX53M optical microscope with polarization. These microscopes were employed to investigate the distribution of crystals and assess the effect of adding another substance on their initial structure. Through image analysis, the study explored how interactions between components influence crystal formation and organization, offering insights into changes in their morphological characteristics and structural properties. Microphotographs were taken for all samples using the built-in digital camera. The data were stored on a hard drive and subsequently processed as required.

4. Results and Discussion

The preliminary results included the investigation of a model system comprising (2-hydroxypropyl)-β-cyclodextrin (HP-βCD) and pantoprazole. In this controlled formulation, HP-βCD remains invisible at the microscopic level due to its amorphous nature. Pantoprazole forms consistent ring-like patterns. The darker inner ring may be a result of the specific structure of HP-βCD, which causes pantoprazole to be pulled toward the interior. The outer region appears more transparent because of the presence of HP-βCD. The formulation observed under atmospheric conditions is very similar to the controlled formulation. As shown in Figure 3, areas of lighter and darker rings are visible, indicating somewhat weaker interactions under normal environmental conditions. The formulation consistently produces uniform rings with 100% reproducibility. This uniformity suggests very strong interactions under controlled conditions, making this formulation highly promising for further research.

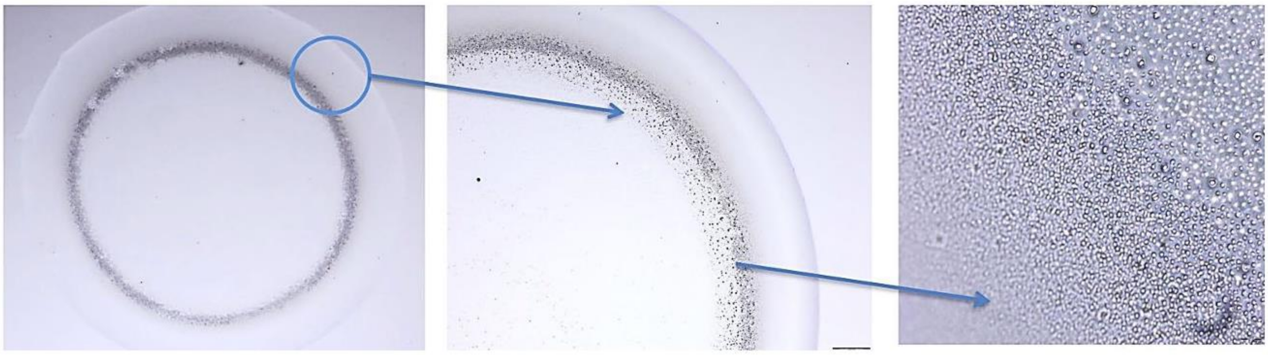

Figure 3: Preliminary results of the first model system and obtained coffee ring effect of high reproducibility

Following the preliminary investigations, the next system was more complex, involving the addition of sodium chloride and pantoprazole under controlled conditions. Similar to the preliminary results, pantoprazole demonstrated consistent reproducibility, regardless of the conditions. Specifically, the characteristic pattern shown in Figure 3 was still observed. Sodium chloride exhibited crystallization in the same manner as previously described, with each droplet corresponding to one of the clusters, demonstrating improved reproducibility of sodium chloride under controlled conditions. The formulation of sodium chloride and pantoprazole differs significantly from that observed under atmospheric conditions. Typical sodium chloride crystallization was observed within the droplet's interior, while the edges differed from those of pure pantoprazole, indicating potential interactions. All droplets of the formulation exhibited full reproducibility (Figure 4).

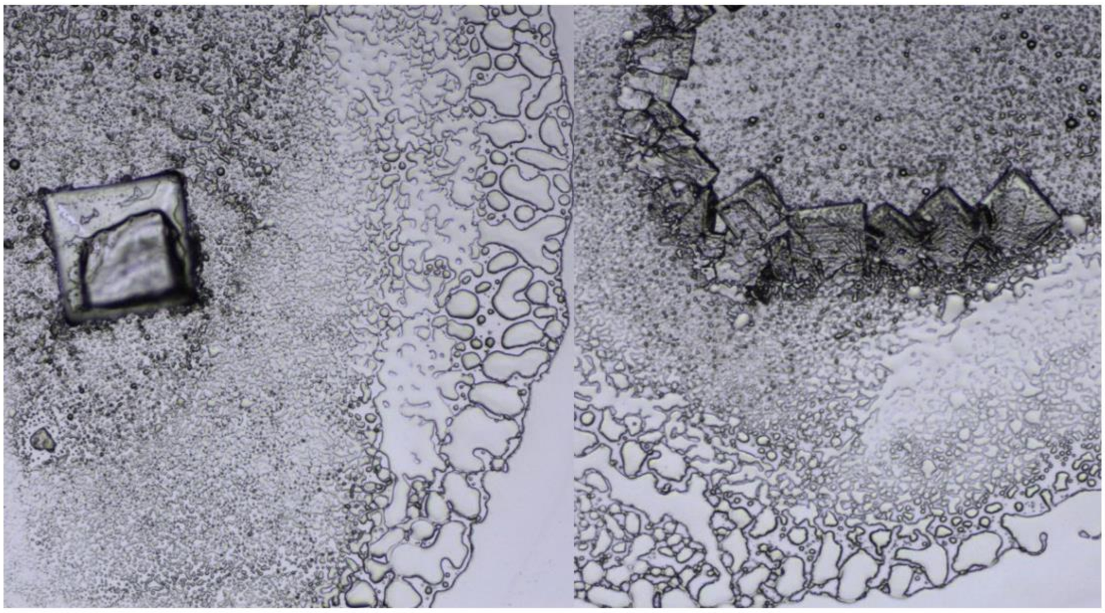

Figure 4: Investigation of the model system: Sodium chloride, HP-βCD, and pantoprazole

After numerous experiments exploring and elucidating potential interactions in various formulations, the next phase focuses on a formulation incorporating the interactions of three components: NaCl, (2-hydroxypropyl)-β-cyclodextrin (HP-βCD), and pantoprazole.

This controlled formulation results in two distinct types of ring patterns, as shown in Figures 3 and 4. The samples differ at the edges and "depressions" are observed, characterized by darker and lighter regions. The darker region may be a result of interactions between pantoprazol and HP-βCD, as illustrated in Figure 4. Additionally, a difference is observed in the internal structure of the droplet, where sample lacks the characteristic dendritic crystal structure.

The formation of coffee rings from the evaporation of analyte-containing droplets is commonly observed in applications such as micropatterning, bioarrays, and trace detection. The coffee-ring effect, driven by contact line pinning, can significantly impact detection uniformity and sensitivity. In this study, we explored a straightforward and practical method to suppress coffee rings by promoting controllable nanoparticle aggregation through superhydrophobicity-enabled dynamic evaporation.

The footprint of copper nanoparticle (CuNP) deposition formed on a superhydrophobic surface after dynamic evaporation was reduced by several orders of magnitude compared to traditional non-interventional evaporation methods. These findings are illustrated in Figure 5. A related investigation on gold nanoparticles (AuNPs) by Han et al. (2024), supported by numerical simulations and theoretical analyses, highlighted that factors such as substrate wettability, temperature, and droplet motion play vital roles in suppressing the coffee-ring effect. [4] More notably, the force mechanisms acting on AuNPs at the liquid interface/contact line were analyzed, leading to the development of universal mathematical models and regime maps. These models utilize a dimensionless parameter G to classify different deposition modes of AuNPs under varying evaporation conditions, thereby unveiling the enrichment mechanisms of nanoparticles under superhydrophobicity-induced dynamic evaporation. The theoretical models and enrichment mechanisms were validated through single-molecule detection experiments using rhodamine 6. This demonstrated remarkable sensitivity (10^{-17} M, with an enhancement factor of approximately 10^{13}) and excellent uniformity (relative standard deviation of about 5.57%). These results underscore the accuracy of the proposed models and offer valuable insights for advancing research and applications related to nanoparticle aggregation. [4]

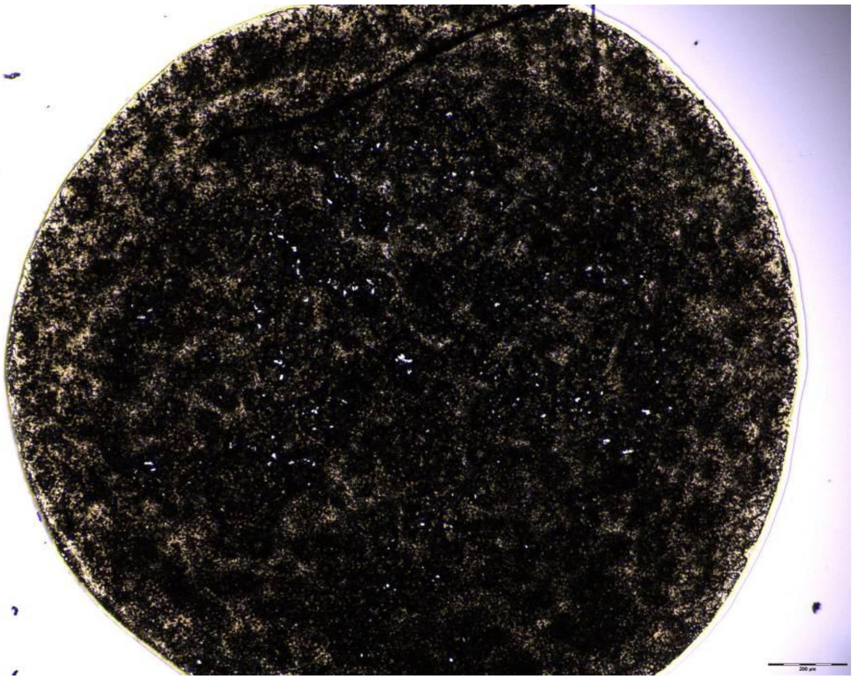

Figure 5: Coffee ring effect obtained with in-situ synthesised Cu nanoparticles by using ascorbic acid

5. Conclusions

Due to the obtained results several conclusions can be established:

1. Development of a Precise Micro-Droplet Deposition Method on Glass
A highly accurate methodology has been established for the deposition of micro-droplets onto glass surfaces. This method incorporates precise control over droplet volume, ensuring experimental reproducibility and accurate results. Measurements of droplet diameters have demonstrated a high degree of precision, with minimal variation between droplets. The average droplet diameter was found to be 2095.65 µm, with a deviation of 51.85 µm. These findings confirm the reliability and accuracy of the applied methodology.

2. Identification of Morphologies Using Microscopic Techniques
Different substances, when dried as micro-droplets on glass surfaces, form distinct and identifiable shapes that can be analyzed microscopically. Microscopic examination of the samples revealed that each substance exhibits a unique deposition pattern, enabling their differentiation and identification. For instance, pantoprazole: Exhibits characteristic edges with uniform, consistent ring patterns without significant agglomeration or variation, indicating stable and uniform crystallization.
Doxycycline: Demonstrates a distinct ring-like pattern with a high concentration of particles at the edges. The central area shows a much lower particle concentration, while the edges are dense and well-defined.
These observations highlight the potential of microscopic techniques for analyzing and identifying different substances based on the morphological patterns formed by their dried droplets. This method offers valuable applications in scientific and industrial fields.

3. Variability in Sodium Chloride and Cu Nanoparticle Samples
For sodium chloride (NaCl) droplets, significant variability was observed in the shapes of dried droplets. This variability was linked to changes in atmospheric conditions. To minimize this variation, a controlled atmospheric environment was introduced, which significantly improved the reproducibility of the results. To evaluate the extent of this variability, clustering analysis was conducted for sodium chloride samples using both subjective observation and computational algorithms. The results indicated that clustering based on researcher observations yielded more rational and accurate results than computational methods alone.

4. Interactions in Model Systems
The observed model systems revealed evidence of interactions between the components under study. A key example is the interaction between pantoprazole and HP-βCD, which led to changes in the characteristic ring patterns formed by deposition. Specifically, the interaction resulted in the formation of a well-defined, darker circular particle structure. This alteration not only provides insight into the interaction between these two substances but also reveals the mechanisms of their interaction at the microscopic level. These interactions can lead to diverse morphological crystal scenarios depending on the interactions between components. For instance, in certain formulations, monocrystals of sodium chloride were formed. In other cases, satellite crystals were observed, depending on the specific interactions between components. These varied morphological structures demonstrate the complexity and diversity of patterns that emerge from component interactions.

5. Supressing the coffee ring effect by copper nanoparticles
Copper nanoparticles have shown strong suppression of the coffee ring effect, which needs to be investigated further. Therefore in our future investigations we will optimize the amounts, concentrations, shape and the size of nanoparticles in order to further investigate this interesting phenomena

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Original scientific paper

COLORFUL TEXTILES FROM COLORFUL NATURE

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Abstract: *The demands of modern life and industry strive for environmentally friendly and sustainable processes in all areas of human activity, including the textile industry. In response to this demand, natural dyes, which had fallen into obscurity at the end of the 19th century, have gained popularity as an acceptable alternative to synthetic dyes. In the past, natural dyes of plant and animal origin for dyeing textiles were mainly used for dyeing protein fibers, while cellulose materials were bleached. However, the revival of the use of natural dyes poses a challenge and puts the emphasis on the use of natural dyes for cotton materials. In addition to the beautiful coloration, the modern use of these dyes also implies the study of their multifunctional properties (antimicrobial, antifungal, protection against UV radiation, etc.). The research presented in this paper provides an overview of the results obtained in the field of the application of natural dyes of plant and animal origin, including through dyeing techniques and textile printing, focusing on the contribution to the study of textile heritage and the modern fashion industry based on the principles of circular economy. Research in the field of historical textiles contributes to the identification of archeological textile finds and in the field of restoration and conservation. In the production of modern textiles, the focus is on the idea of "zero waste", i.e. the use of plant waste, weeds or invasive species. To ensure an "eco" premise, care must be taken to ensure that the choice of plants does not endanger their habitat, that the technological processes do not cause pollution, that the choice of chemicals does not compromise the quality of the textiles and that textile material is produced that is safe for human health.*

Keywords: *natural dyes; textile materials; circular economy; zero waste*

1. Introduction

Natural dyes are dyes and pigments obtained from mineral, animal or plant sources with a minimum of chemical treatment (Fig.1). Natural dyes can be classified according to their coloring properties, their chemical composition, their origin (from plants, animals, minerals), their hue or their areas of application (food industry, pharmaceutical industry, textile industry, etc.) [1-3]. Mineral, i.e. inorganic natural dyes cannot be used for textiles as they cannot bind chemically. Organic natural dyes include natural dyes of plant origin and natural dyes of animal origin, although research today is moving towards the extraction of dyes from algae, fungi and bacteria [1-3]. In terms of their coloring properties, most natural dyes are classified as acid dyes, more rarely in the group of direct dyes (e.g. turmeric), and plants from the indigo family belong to the vat dyes [1-3].

a. b. c. d. e.

Figure 1: Possible sources of natural dyes (a. minerals, b. animal sources, c. plant sources, d. algae, e. fungi) [1-3]

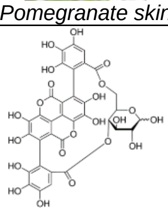
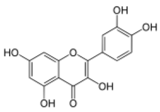
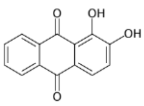
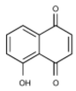
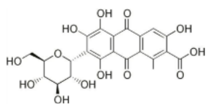
The revival of the use of natural dyes refers primarily to the use of natural plant dyes. Natural plant dyes are easy to use and also fulfil the "zero waste" concept, which refers to the use of plant waste, weeds or invasive species. To ensure the "eco" premise, it is forbidden to use plants that are protected by law [3-4]. In addition, the use of natural dyes creates beautiful colorations in harmonious shades that are as harmonious as the nature from which they originate (Fig. 2). Scientific research in the field of these dyes contributes to the preservation of textile heritage through collaboration with archaeologists, conservators and textile restorers. The textiles processed in this way are used in the manufacture of hobby products, for social benefit by organising workshops for the general public, then in colour and aromatherapy and in tourism. However, the most revolutionary application is in the modern fashion industry, which is based on the principles of the circular economy and the multifunctional properties of textiles (Fig. 2) [3-6].

a. b. c. d. e.

Figure 2: Areas of application of natural dyes (a. coloration, b. textile restoration, c. multifunctional properties, d. textile design, e. clothing design) [3-6]

Natural dyes are rich in chemical compounds that give textiles a natural coloring and multifunctional properties (Tab.1): they have antibacterial and antiallergic effects, prevent the development of unpleasant odors and provide excellent protection against harmful UV radiation, etc. [1,2,7]. In addition, the authors confirmed that the application of oxygen plasma pre-treatment technology improves the dyeing and antimicrobial properties of wool fabrics dyed with natural pomegranate peel extract [7].

Table 1. Examples of active ingredients in natural dye sources that impart multifunctional properties to textiles [1,2,7]

Plant	 *Pomegranate skin*	 Onion skin	 *Madder root*	 *Walnut leaves*	 *Dactylopius coccus*
Active substance	 *punicalin*	 *quercetin*	 *alizarin*	 *juglone*	 cochineal
Multi-functional properties	*The skin of the pomegranate contains a variety of bioactive compounds such as polyphenols, flavonoids, tannins, anthocyanins and organic acids, which have various biological properties, including antioxidant, anti-inflammatory, antimicrobial, anti-cancer and cardioprotective effects.*	*Onion peels are associated with the prevention of cancer, oxidative stress-related dysfunctions, cardiovascular and neurological diseases and the growth of microorganisms, as they contain beneficial biocomponents. The biocomponents of onion skin have a strong antioxidant effect.*	*Madder root is useful in the treatment of urinary gravel, cleansing of the bladder and urethra, dropsy, amenorrhea and jaundice. Madder is good for treating kidney stones the size of a grain or sand.*	*The leaves of the walnut are used in traditional medicine to treat a variety of ailments, including digestive problems, skin problems and respiratory complaints. It is considered anti-inflammatory and can help to reduce fever and relieve pain. The leabrd also contain antioxidants that can protect the body from free radical damage*	*The insects of the genus Dactylopius coccus contain bioactive compounds that can have various bioactive effects, such as antioxidant, antihypertensive, anti-inflammatory, antimicrobial and immunomodulatory effects, which have a positive impact on human health.*

Chemical compounds that are extracted from plants and belong to the group of mordant dyes are mostly flavanoids and tannins [1,2]. Mordant dyes produce different colors through complex formation with metal salts (mordants) - these dyes have polygenetic properties. Aluminum, copper, iron and tin salts are most commonly used as mordants. These dyes are most commonly used for protein fibers with: pre-treatment of the fibers (before dyeing), simultaneous treatment (together with dyeing) or post-treatment (after dyeing). This can be seen in the dyeing of tresses (Fig.3). Cellulose materials (flax, hemp, nettle, cotton) were bleached, and fabrics made of wool and silk protein were dyed with natural mordants of plant origin [8,9].

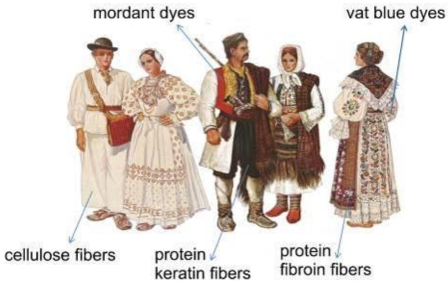


Figure 3: The presence of natural dyes in folk costumes [8,9]

2. Experimental

The experimental part of this thesis presents examples of the application of natural dyes in the field of contribution to textile heritage, the realization of the idea of "zero-waste" dyes of plant origin and the application of natural dyes of animal origin. The focus is on the presentation of the implementation of the dyeing process, the application of optimal process parameters and the analysis of textile dyeing.

2.1 Contribution to textile heritage

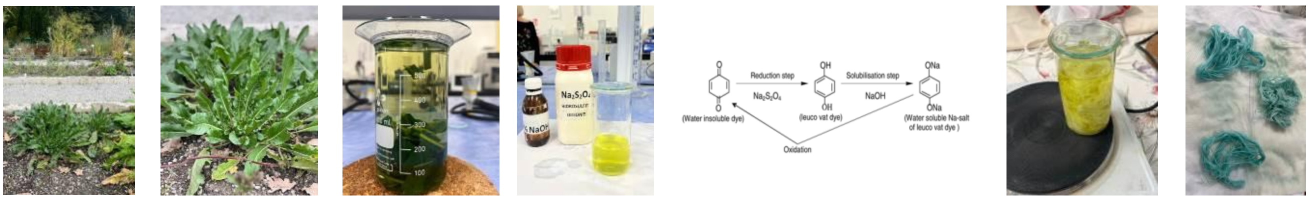
The contribution of modern scientific research on natural dyes has made a major contribution to the identification of archaeological textile finds (Fig. 4) and to the conservation and restoration of historical textiles [8-10]. Natural dyes are present in historical remains and, given the problem of sampling, non-destructive methods of analysis are preferred, especially in the initial stages. Figures 5 and 6 show the analysis of a sample of black yarn from a phelon depicting the Ascension of Christ, owned by the Diocese of Dalmatia in Šibenik and restored at the Croatian Restoration Institute. The analysis was carried out using non-destructive methods: Remission Spectrophotometry, Fourier Transform Infrared Spectrophotometry (FTIR) and Scanning Electron Microscopy (SEM). It was confirmed that the black coloration of the silk yarn was caused by the reaction of a tannin agent and iron(II) sulphate [10].

Figure 4: Natural dyes in archaeology [8,9]

a. b.

Figure 5: Back side of phelonion with a depiction of the Ascension of Christ, a. before conservation (Archives HRZ-a, photos: I. Marinković, S. Lucić Vujičić, 2022.), b. FTIR-ATR analysis of black yarn from povijesnog liturgijskog tekstila (Fig. 5) [10]

Historic blue-tinted textiles were obtained in our region from the willow plant (Isatis tinctoria L.) (Fig. 3). Willow is a plant native to Europe and was used intensively until the arrival of indigo. The cultivation and use of vrbovnik was regulated by guilds that resisted the import of indigo from the East, which threatened their monopoly on the production of the blue dye. At the University of Zagreb, in cooperation with the Faculty of Textile Technology and the Botanical Garden of the Faculty of Natural Sciences, the optimization of dye extraction and reduction as well as the dyeing of textiles with vat dye from Isatis tinctoria is being carried out in order to optimise the identification methods of blue-dyed textiles in historical textiles in the next step. Dyeing with vat dyes is based on the principle of converting a water-insoluble keto-substituted dye by reduction into a water-soluble enolate-leuco compound bound to cellulose. This penetrates the fibre, where it is reoxidized back to its original insoluble form. All these dyes contain two or more keto groups (C=O) separated by a conjugated system of double bonds (Fig. 6a) [1,2].



a. b. c. d. e.

Figure 6: Obtaining natural blue dye a. cultivation of the plant Isatis tinctoria L., b. dye extraction, c. dye reduction, d. dyeing, e. blue cotton yarn

2.2. Zero waste natural dyes plant origin

Nowadays, natural colourants of plant origin are used most frequently. Natural dyes must be obtained from organic waste, from easily renewable sources or from invasive species. It is forbidden to use protected plants or to endanger plant habitats (Fig. 7). From an economic perspective, the use of natural dyes fits into the global economic trend of transitioning from a linear economy to a circular economy, with a circular bioeconomy as the global goal. The use of biowaste to produce natural dyes is in line with one of the key postulates of the circular economy, namely waste minimization [3-5].

Figure 7: Potential sources of natural dyes [4]

2.2 Natural dyes animal origin

Research on natural dyes of animal origin includes the study of dyes from the glands of sea snails (Murex brandaris and Murex trunculus) and scale insects (lat. *Dactylopius coccus*), from which crimson and purple were historically obtained [11-14]. The words purple and crimson usually refer to purple and crimson fabrics or the dye with which the fabrics were dyed to be purple or crimson. However, purple and crimson are two different shades. Due to their position within the color wheel (Fig.8), crimson takes on h* values of about 15° towards red and orange tones, while purple takes on h* values of about 330° red towards blue tones [12]. An analysis of the purple dye extracted from molluscs from the Adriatic Sea [11] was performed and FTIR analysis confirmed the presence of: 6,6'-dibromoindigotine, 6,6'-dibromoindirubine, 6-bromoindigotine and indigo (Fig.9a). The research on the cochineal dye, which is obtained from the louse *Dactylopius coccus* (Fig.9b), included the investigation of the influence of the type and concentration of the mordant on the dyeing of cotton and wool, the color fastness and the improvement of UV protection [13,14]. Particular emphasis was placed on investigating the influence of the pretreatment of cotton by cationization on the improvement of properties [12].

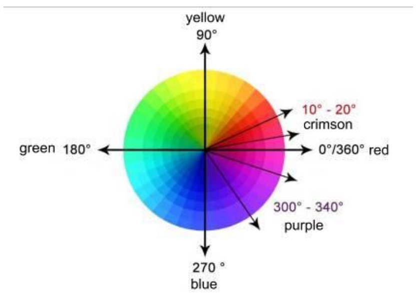
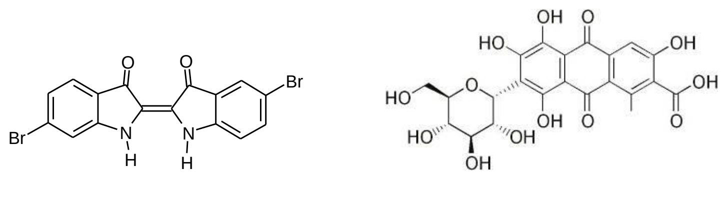


Figure 8. The position of crimson and purple in the color wheel



a. b.

Figure 9. Chemical structure of natural dyes animal origin, a. 6,6'-dibromoindigotin – murex, b. cochineal [11,12]

2.3 Phases of the dyeing process

Dyeing with natural dyes comprises the following phases (Fig.10): Dye extraction, mordanting and dyeing. Dye extraction is traditionally carried out in water at 100 °C for 60 minutes. The bath is then allowed to cool and after at least 6 hours the bath is decanted and filtered. Extraction can also be carried out using modern methods such as microwaves or ultrasound (Fig.11) in order to increase resource utilization and shorten the process time. The textile material is then treated with metal salts (mordants). The mordanting can take place as a pre-treatment, simultaneously during the dyeing process or as a post-treatment. Finally, the third phase is the dyeing process, in which the natural pigment, the metal ions and the textile material are brought together [4].

Figure 10. Phases of the dyeing process

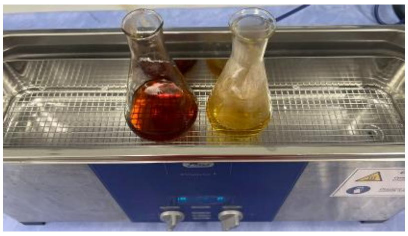
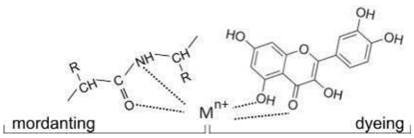


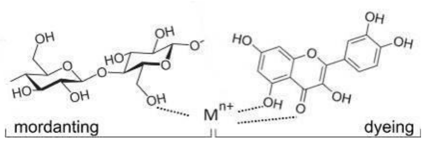
Figure 11. Extraction of natural dyes in an ultrasonic bath

2.4 Natural mordant dyes

Since more than 90% of natural dyes are acid mordant dyes, mordanting is a particularly important step in the dyeing process. Mordanting is usually carried out with metal salts, which is often a disadvantage of natural dyes. This fact is not correct. Do not use salts of heavy metals that are very harmful and prohibited, e.g. cadmium, lead, chromium. It is also important to use the optimum concentration of chemicals. Today, organic agents such as tannins, chitozam, etc. are often preferred. However, the widest range of shades and the best color fastness are achieved by using metal salts in a concentration of 1-5 % of the material weight (owm): Potassium aluminum sulphate dodecahydrate $KAl(SO_4)_2{\cdot}12H_2O$, copper(II) sulphate pentahydrate $CuSO_4{\cdot}5H_2O$ and iron(II) sulfate heptahydrate $FeSO_4{\cdot}7H_2O$. The use of mordants in a concentration of more than 5% can cause allergic skin reactions, water contamination and the destruction of textiles. Figure 12 shows the formation of a metal complex between natural pigment, metal ion and protein (a.) and cellulose textile material (b.).



a.



b.

Figure 12: Schematic representation of ligand formation: fiber - metal ion - natural dye, a. protein textile material, b. cellulose textile material [4]

2.5 Laboratory analysis

The quality results of the application of natural dyes in the processes of dyeing and textile printing are preceded by analytical laboratory analyses of the natural pigments (Fig.13). After the technological processes have been carried out, the dyeing of textile materials is analysed. The analysis of natural pigments usually includes FTIR analysis of dyes, absorption spectroscopy of dye solutions and, in the case of printing, testing of rheological properties, (Fig. 13) For dyed textiles, a remission spectrophotometric analysis is carried out and the colour fastness is determined according to suitable standards, depending on the intended use of the material: washing, artificial light, rubber coating, etc.

Figure 13: Laboratory analysis of natural dyes

3. Results and discussion

The results presented in this paper give an overview of the research carried out *at the* University of Zagreb Faculty of textile technology in the Department of textile chemistry and ecology. The results show the field of application of natural dyes of plant and animal origin, including dyeing techniques and textile printing, with an emphasis on the contribution to the study of textile heritage and the modern fashion industry based on the principles of circular economy. The investigation of the choice of metal salts as mordants is at the forefront. By binding a metal ion to the functional groups of a natural pigment, a chelate is formed whose color depends on the choice of salt. By using different salts, different colors with excellent durability can be obtained from a single natural raw material. The research results presented in Table 2 [4] on dyeing wool, silk, PA and cotton fabrics in aqueous extracts of pomegranate peels, red onion peels and green walnut shells and leaves confirm the possibility of using these sources of natural dyes. The chromophores punicagalin and punicalin contained in the pomegranate extract together with metal ions of aluminum, copper and iron result in a yellow color. Quercetin, which is contained in the skin of red onions, gives an orange-red color, and juglone in walnuts gives a red-brown color. Aluminum as a humectant increases brightness and saturation, which contributes to the perception of a more brilliant tone, while copper decreases brightness and saturation, resulting in duller tones. Iron has a significant effect on all color parameters and results in dark brown, slightly achromatic tones. All dyes exhibit good wash fastness, which depends not only on the dye but also on the amount of dye exhausted, i.e. better stability was achieved even with low exhaustion, which confirms the justification for the use of wetting agents in dyeing processes with natural dyes.

Table 2. Wool, silk, PA and cotton fabric dyed with natural mordant dyes [4]

Mordant	W-pom.	W-onion	W-oak	S-pom.	S-onion	S-oak	PA-pom.	PA-onion	PA-oak	C-pom.	C-onion	C-oak
-												
Al												
Cu												
Fe												

Similar observations can be seen in research on the use of dyed wool fibers in the production of felt images. On the basis of the color chart obtained by the combination of mordant dyes and metal salts, felt pictures were produced, which represent a contribution to applied art. This research was conducted on the island of Cres, where discarded wool is a major ecological problem due to unpleasant odors, environmental esthetics and rodent accumulations (Fig.14).

a. b. c.

Figure 14. Utilization of wool waste, a. discarded wool, b. color map, (Legend: 1 – walnut + Cu; 2 – walnut + Al; 3 – walnut + Fe; 4 – yarrow + Cu; 5 – nettle + Fe; 6 – nettle + Cu; 7 – nettle + Al; 8 – oak + Al; 9 – oak + Fe; 10 – oak + Cu; 11 – chamomile + Al; 12 – chamomile + Fe; 13 – chamomile + Cu; 14 – marigol + Cu; 15 – marigol + Fe; 16 – marigol + Al; 17 – St. John's wort + Cu; 18 – St. John's wort + Fe; 19 – St. John's wort + Al), c. felt picture

Natural dyes can be successfully used in textile screen printing, whereby the stability of the rheological properties of the thickening agent is given with different printing paste compositions and fixing conditions. Table 3 shows the results of studies on screen printing on hand-knitted wool with alpaca and merino wool raw materials using the thickener Prisulon DCA 90. The measurement of the viscosity of the thickener on a Brookfield DV II+ viscometer was decisive for the selection of the printing conditions. The viscosity measurements carried out for the thickener Prisulon DCA 90 with a dry matter content of 9 % show a slight difference in viscosity depending on the change in pH value at the same spindle speed (Fig.15). The deviations in the viscosity values proved to be satisfactory for manual screen printing, and the end product shown in Fig. 16 was realized by optimizing the process parameters [15].

Table 3. Screen printing on hand-knitted wool with alpaca and merino wool

Alpaca			Merino		
Turmeric	Onion	Walnut + Fe	Turmeric	Onion	Walnut + Fe
					

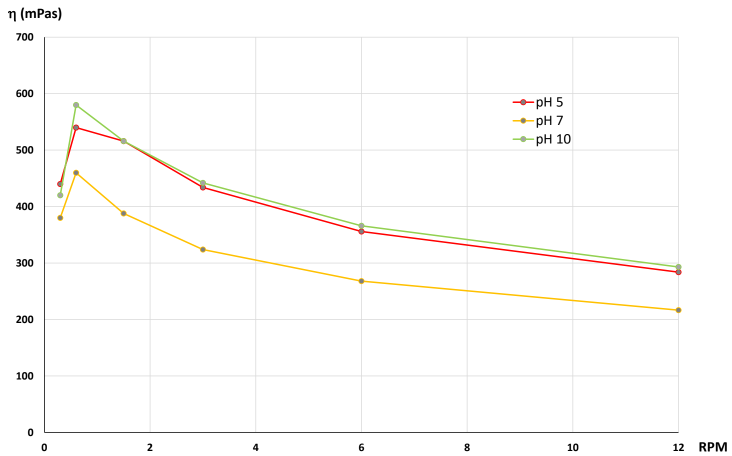
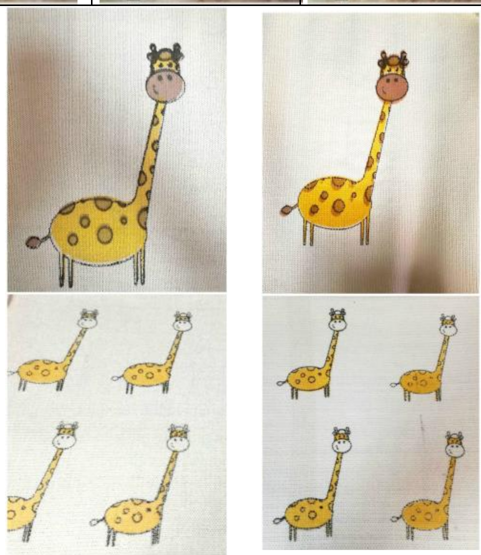


Figure 15. Viscosity of thickener Prisulon DCA 90at different pH



a. b.

Figure 16. Finished product with print, a. alpaca, b. merino

Nowadays, natural dyes are increasingly being used, leading to a new way of decorating textiles, namely plant transfer printing, popularly known as "eco-printing", in which the shape and/or pigment of a plant is transferred to the textile. The fact that the patterns are unique and unpredictable underlines the notion of artistic freedom. The results shown are very different and depend on the process parameters: the pH value (Fig.17), the use of the mordant, the capillarity of the fabric and the properties of the plant material. The adjustment of these parameters is the result of the knowledge and experience of a textile drugstore and has a considerable influence on the intensity and sharpness of the print as well as on the wash fastness. However, the choice of the "best" result certainly depends on the designer's attitude and the market's requirements for the esthetics and purpose of the textile material. The "Hamadryad" clothing collection was realized through the synergy of textile chemistry and sustainable design (Fig.18). Considering the fact that it is inspired by Greek mythology, i.e. Greek nymphs who were born and died together with the tree they were connected to, the contribution to sustainable design was confirmed by the choice of cutting and plant printing technique. Clothing produced in this way can help to raise the market's awareness of its impact on environmental protection. This research is a direct contribution to the need to understand this link, understand and target natural dyes and develop branding techniques to achieve effects with natural dyes in the context of sustainable fashion and textile and apparel production [5,6].

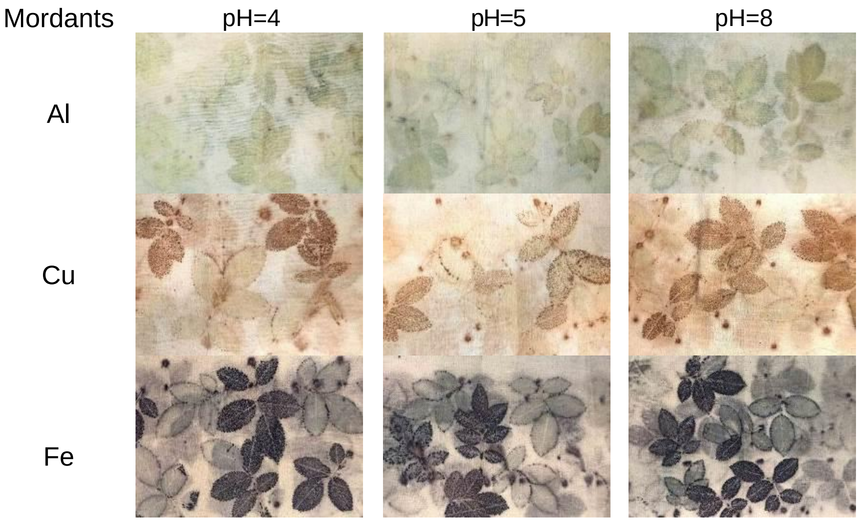


Figure 17. Samples of transfer plant printed cotton in different conditions of pH and mordanting

Figure 18. Selection from the "Hamadryad" clothing collection (fashion illustration and realisation)

The red shades on historical textiles were obtained from the plant *Rubia tinctorum* or from animal sources, as described in section 2.2. For the study of the *Rubia tinctorum* plant, the root was collected in the village of Petrovići in Montenegro at an altitude of about 700 meters above sea level (Fig.19), where it grows as a wild species. *Rubia tinctorum* root (Fig.20) is rich in the chemical compound alicin and can be successfully used to dye wool and silk in an extremely wide range of red shades with h-values from 30° (red part of the spectrum) to 70° (yellow part of the spectrum). In combination with varying brightness and color intensity, textiles made of wool and silk in shades of orange, pink, red and burgundy were produced with satisfactory fastness (Fig.21). This research can make an important contribution to reviving the use of the *Rubia tinctorum* plant for dyeing modern textiles, whether for fashion purposes or for the restoration and preservation of traditional, historical textiles [16].

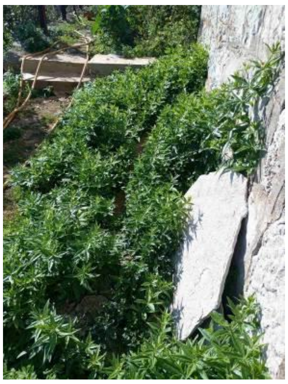


Figure 19. Natural habitat of the plant *Rubia tinctorum*

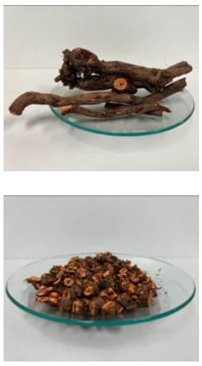


Figure 20. Root of the plant *Rubia tinctorum*

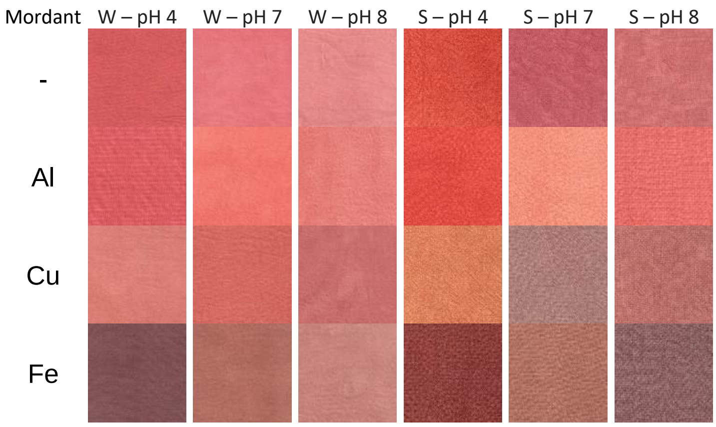


Figure 21. Samples of wool (W) and silk (S) dyed under different conditions

The following is a study of the application of natural cochineal dye for dyeing felted wool (Fig.22). Purple tones were obtained, and on the basis of spectrophotometric analysis (Fig.23) and fastness testing, the dyed wool was used to make hats in combination with a significant lace (Fig.24) [17].

Figure 21. Wool felting and fyeing samples

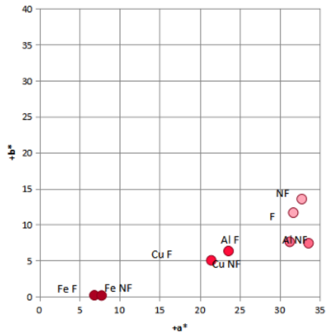


Figure 22. Spectrophotometric analysis

Figure. 23 Felted wool hat

Like most natural dyes, cochineal is used for dyeing protein textile materials. However, due to market demands, a study of the applicability of cochineal for dyeing cotton was conducted. For this purpose, cotton is cationized in the pre-treatment process. Cationized cotton fabrics adsorb more natural cochineal dye than the noncationized fabrics. When cationized, cotton possesses amino groups together with hydroxyl and carboxyl ones, so the adsorption of anionic dye is very rapid due to attraction. The results achieved with and without electrolyte are quite similar, so an electrolyte is not necessary. In the case of noncationized fabrics, an addition of electrolyte is important for exhaustion. Pre-mordanting and cationization showed synergism considering dye exhaustion. The exhaustion is higher when the electrolyte was used, but from the chromacity achieved and visual assessment it is not necessary. If only cationization is performed, the pure purple hue of cochineal is achieved. If violet hue needs to be achieved, mordanting with Fe-salt is necessary. Thus, when the process of cationization is performed before dyeing with natural dye, salt can be reduced or even unnecessary, making it friendlier for the environment (Fig. 24).

Additionally, the fabric UV protection was determined according to AS 4399:2020 Sun protective clothing - Evaluation and classification, by UV-A and UV-B transmission measurement and calculation of Ultraviolet protection factor (UPF). The obtained results prove that textiles dyed with cochineal dye and pre-treated with mordant can significantly affect the protective properties from UV radiation (Fig. 25). Fabrics dyed with cochineal dye have a UPF value ranging from 10 to 15. A significant increase in UPF values is achieved by using mordants: with aluminum salt UPF is 40, with copper salt up to 35 and the highest values are achieved with salt of iron UPF 50+. Research has shown that cochineal colored cotton offers protection against UVB radiation, and therefore it may reduce the risk of subsequent occurrence of skin cancer. This is significant because skin cancer worldwide incidence rates increase in the elderly population [13].

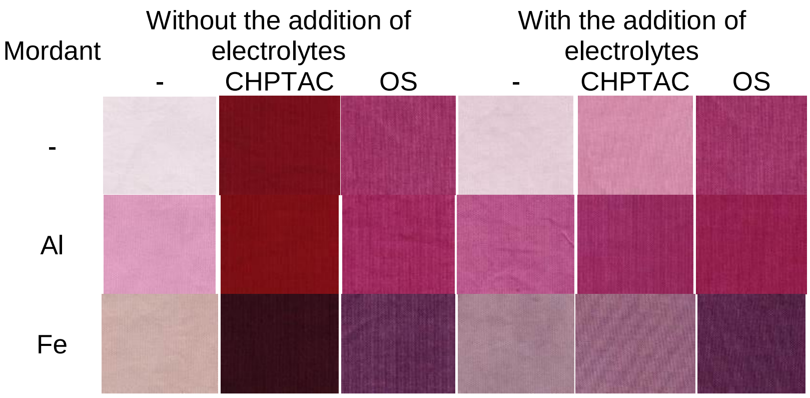


Figure 24. Cotton fabric dyed with cochineal dye [12]

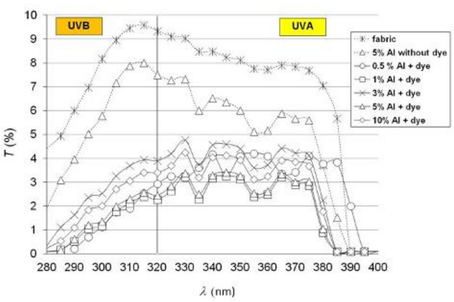


Figure 25. Increased UV protection [13]

4. Conclusion

Previous scientific research in the field of analysis and optimization of the application of natural dyes at the University of Zagreb, Faculty of Textile Technology, Department of Chemical Textile Technology and Ecology, is based on the application of natural plant dyes, the identification of extracted compounds and the analysis of their properties.
The presented research shows that today there is a growing awareness of environmental protection, new findings in the field of sustainable chemistry, the use of biodegradable materials and the increased use of environmentally friendly textile products.
The research mentioned above has led to collaboration in the fields of ethnology, textile restoration, applied arts, etc. and certainly shows the interdisciplinary nature of this field. The research presented in this paper represents an extremely important step in the application of modern analytical methods and the optimization of the possibilities of using dyes of plant and animal origin.

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Review paper

THE OVERVIEW OF CROATIAN SUSTAINABLE TEXTILE AND GARMENT SECTOR POTENTIALS

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Abstract: *The paper deals with the overview of sustainable textile and garment sector potentials mapped for Majur municipality as one of the Danube Region, within the project Green-Tex. The main objective of the DRP0200404 Green-Tex project is to strengthen transnational collaboration and innovation in the Danube area's sustainable textile sector and thus make value chain actors in partner regions more resilient and competitive in adjusting to global shifts from traditional to more regenerative circular economy based green textile practices. One of the projects activities is to create and test new solutions throughout the entire value chain, starting from fashion design to production, usage, textile waste collection and recycling, and verify them in various contexts within the project territory.*

Keywords: *Green-Tex; Danube Region; sustainable value chains; circular economy; recycling*

1. Introduction

The Green-Tex project is addressing circular economy and sustainable production and consumption challenges throughout the entire textile sector value chain, as presented in the figure 1. The overview is starting with product design and sourcing, followed by the production process, marketing and market reach, product use and end of life (reuse, waste collection and recycling).

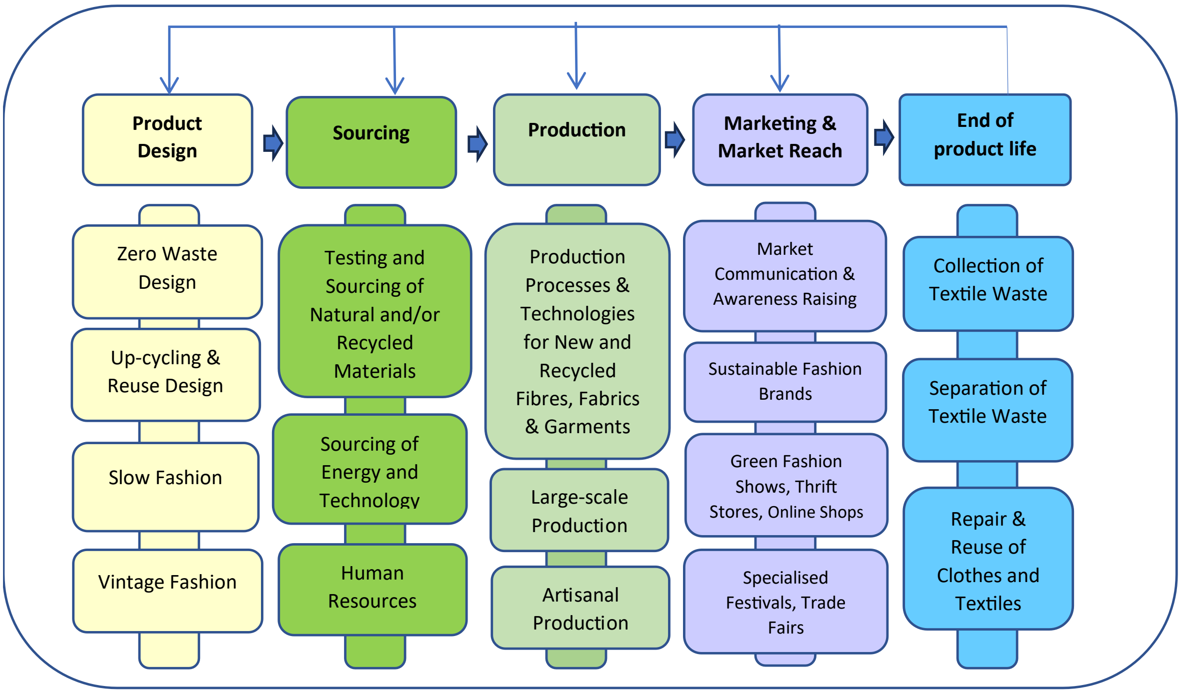

Figure 1: The overview of Circularity in the Textile and Garment Sector [1]

The textile and garment industry in Croatia is an evolving sector with a rich history but faces challenges and opportunities due to global trends and technological advancements. The industry is a key employer, particularly in regions like Varaždin and Međimurje, although there has been a decline in recent years due to competition from lower-cost countries. Croatia's textile and garment production is strongly export-oriented, with 80-90% of production being exported. Croatia specializes in niche markets, including high-quality garments, workwear, and technical textiles.

Croatian companies are adopting advanced technologies such as automation and artificial intelligence (AI)-driven production to streamline manufacturing processes, reduce errors, and improve productivity. This reduces dependency on manual labour and mitigates the impact of a shrinkage of workforce.

Additionally, there is a growing focus on sustainable practices, including the use of eco-friendly materials and product certification by eco-labels, such as the Öko-Tex. Water-saving processes and the upcycling of textile waste with the aim to minimize environmental impact are the most important criteria.

On the other hand, Croatia faces stiff competition from countries with lower labor costs. This challenge has led to downsizing of domestic companies and work labour outsourcing. Additionally, the textile industry in Croatia struggles with an aging workforce, as younger generations are less inclined to enter the sector. This trend is coupled with a general decline in skilled labour. Furthermore, Croatia's textile sector is under pressure from international global giants, which are increasingly dominating the fast-fashion market and supply chains.

Major opportunities which are identified for Croatian textile industry are the following:

1. Niche Markets: Croatian textile companies can capitalize on high-end niche markets by focusing on quality, craftsmanship, and sustainability, which are gaining importance globally.
2. Sustainability and Circularity: The push for a circular economy in fashion provides an opportunity for Croatian producers to lead in the production of sustainable and eco-friendly textiles.
3. Smart Textiles: With smart textiles and biotechnology, Croatia could further expand its role in producing technical textiles for industries such as healthcare and sports, which are seeing increasing demand for multifunctional and interactive fabrics.

2. Mapping of Green Textile and Garment potentials

Since the Croatian region of DRP0200404 Green-Tex project is Majur municipality, main project activities of both Croatian partners, (University of Zagreb Faculty of Textile Technology (TTF) and Majur, are located in Sisak-Moslavina County, presented in figure 2.

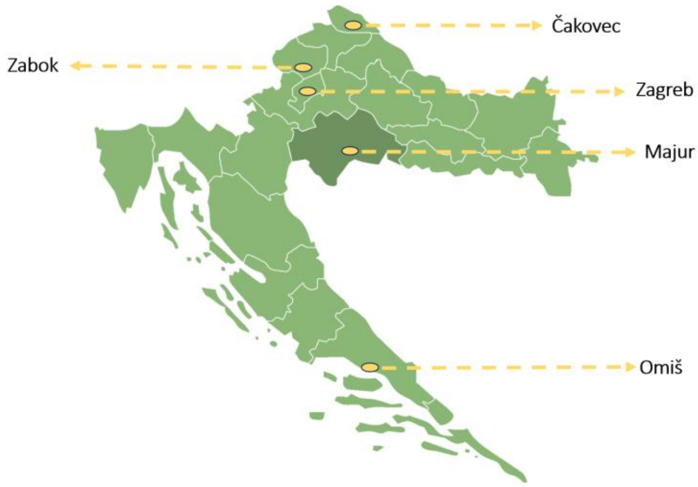

Figure 2: Croatian counties (Majur Region is highlighted) and towns where projects key stakeholders are located

Sisak-Moslavina County has a long-standing history of processing natural textile fibers and textile production within the factory Siscia. However, in recent years, this tradition has been gradually fading, despite the efforts of certain individuals who strive to preserve at least part of the cultural heritage.
Today, there are no factories involved in wool processing or the production of woollen fabrics in the whole Croatia. One of the few textile factories in Croatia that keeps focus solely on naural fibers is Regeneracija Non-wovens (founded in 1954 with focus on the recycling of textile waste) which is producing woollen carpets, made from the 100% wool. When Varteks closed its production of woolen fabrics in 2000, local production of woolen products was seriously affected. Additionally, two SMEs, Galeb and Čateks, are at the forefront of environmentally friendly production, certified with eco-label Öko-Tex.

On the other hand, Croatia has a long tradition of flax, hemp and silk cultivation, so as the sheep farming. Despite the numerous challenges, some of the equipment used in this intricate manual production processes are still in the usage, and the skills and knowledge needed to craft tools for various stages of textile processing were passed orally through the generations and survived.

2.1 Product design in Croatia

The Croatian sustainable design and fashion sector is still growing and faces challenges such as global competition and the need to educate consumers about the benefits of eco-friendly trends. However, Croatian designers are well positioned to capitalise on trends such as slow fashion and ethical production and offer unique, high-quality alternatives to fast fashion. Main trends identified in Sustainable Fashion are:

1. Zero Waste Design: incorporating zero-waste principles (8R: Reduce; Recover, Rethink, Repair, Recycle, Reuse; Regift, Refuse) into their collections, minimizing fabric waste and using recycled and durable materials to create timeless pieces.
2. Circular Fashion: embracing circularity by producing garments that can be recycled or are made from recycled materials, reducing the need for original resources.
3. Upcycling and Local Sourcing: using upcycled materials from storages to create new designs.

This movement not only contributes to a more environmentally friendly fashion industry, but also to the promotion of Croatian craftsmanship and local production on a global scale. Based on the statistical data of the Croatian Chamber of Crafts for the year 2023, the number of processing professions in the textile sector is 1,096. Long tradition and experience in craftsmanship are certainly a good basis for the implementation of new design trends and the modernisation of elements of rich heritage in the context of sustainability and durability [2].

Designers are often involved in projects with the social cooperatives, such as Humana Nova, which employs marginalised groups, collects textiles, alleviates poverty and actively contributes to the sustainable development of the local community and nature conservation through recycling and upcycling. General opinion of Croatian designers is that the biggest and fundamental problem is the lack of co-operation between stakeholders in the same value chain, which can result in isolation of designers, lack of support and unity. There are several examples of active associations, such as ArtiZanat, founded in 2022 in Zagreb, with the aim of creating a stronger local community, raising public awareness of the important social problems of today, and providing support to small craftsmen and producers - just as Zagreb's guilds used to do.

2.2 Sourcing of sustainable virgin materials

A comprehensive mapping process has been conducted to identify and gather all available data critical for the successful implementation and achievement of this project’s goals. First part of mapping is addressing availability of sheep wool in targeted Sisak-Moslavina county, and the results are presented in figure 3.

Analysis of data from the selected region reveals that 320 breeders, or 41% of all breeders, each own up to 10 sheep, totaling 1,618 sheep or 9.92% of the region’s sheep population. On the other hand, eight breeders (1%) own more than 200 sheep each, collectively holding 1,876 sheep or (11.5%).

Sheep in Croatia are mainly raised for meat, while the wool after shearing is mostly a problem that needs to be solved, as for now it is left to the discretion of each individual. Only a small part of wool is collected and exported, and the majority is buried or burned. Data are showing a great potential of 1.300,00 t/year of raw wool in the whole Croatia.

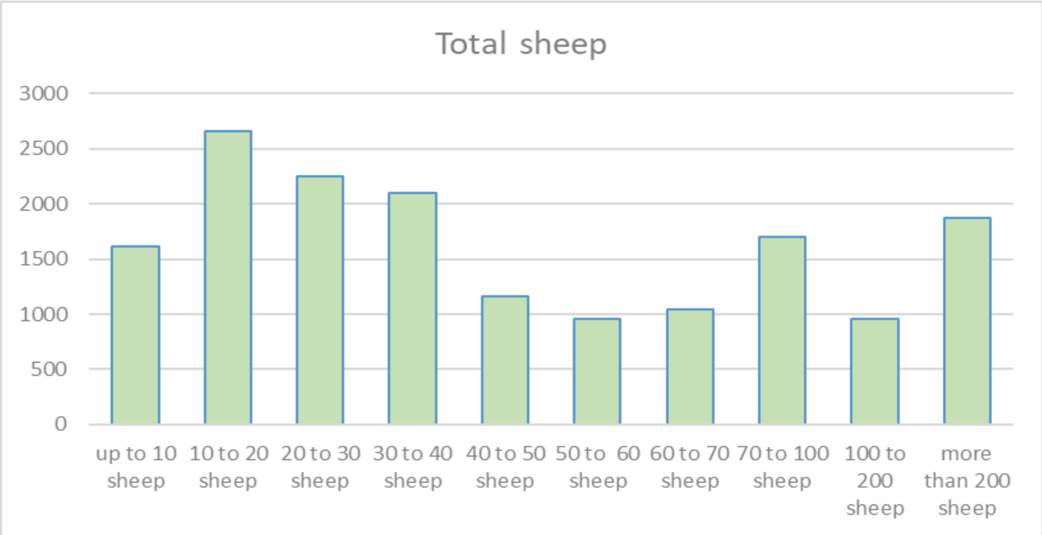

Figure 3: Total number of sheep in Sisak-Moslavina municipalities and towns

There is an additional example of successful usage of discarded raw wool, performed by Fema. This SME uses discarded raw wool as a resource to produce organic fertilizer and repellant. On an annual level, about 200-300 tons of sheep's wool is thrown into nature in Lika. By using this wool and creating new products, the environmental problem that threatened national parks and nature parks in Lika is solved. Apart from strong contribution to the preservation of the environment there is additional contribution to CO_2 neutrality. Fema is now using 100 t/year (collected only in Lika region) and is planning to enhance the capacity to 400 t/year.

The second part of mapping is addressing availability of hemp. Historically, hemp has been a significant crop in Croatia, cultivated already in the sixteen century. According to the literature the factory in Ozalj was using flex and hemp yarn produced domestically by locals, already in 1770 [3].
In the period dated from end of XVIII century till early XX century a dozen of processing plant so-called “kudeljara” were built in Croatia, mostly in Slavonia, Baranja and Sriiem. Those regions have the best climatological and soil management conditions and therefore are the most suitable for the cultivation of hemp. At that time, hemp was widely cultivated for its strong fibers, which were used in various textile products such as ropes, sails, and clothing. According to statistical data in 1937, 930.000 hectares were sown with hemp for industrial purposes in Europe (of which 55.000 ha in the Kingdom of Yugoslavia, 87.000 ha in Italy and 610,000 ha in the USSR). However, from the 1960s to the 1990s, production steadily declined.

The revival of hemp production began in 2003 when the Croatian Ministry of Agriculture allowed the cultivation of Cannabis sativa L. However, practical cultivation was initially hindered by regulatory challenges which caused significant legislative changes in 2019. This included the removal of hemp from the list of narcotic drugs, thus transferring regulatory oversight from the Ministry of Health to the Ministry of Agriculture. As of 2020, there were more than 80 hemp producers cultivating approximately 2.500 ha.. Hemp cultivation in Croatia is experiencing a revival, driven by its versatility and the increasing demand for sustainable and natural products. Today the production is expanding, with hemp being used in various sectors such as construction, textiles, food, cosmetics, and biofuels [4].

One of the stakeholders participating in projects questionnaire was the hemp cooperative (Zadružna konopljara - ZAKON) which operates in Pisarovina (Zagreb County) and uses hemp as the original raw material in its work. Their products go beyond the textile domain and include CBD oil, cosmetic products based on CBD oil, and building blocks made of hemp concrete. In the process of acquiring knowledge, they mostly used informal procedures, primarily the study trips. They have visited already built hemp houses or those in various stages of construction in four countries before starting the construction of the first hemp block house in their own organization. When designing houses, hemp is used in many ways. Their basic method is oriented towards the production and application of cone concrete blocks. In addition, hemp fibers are used to make solid or elastic panels for insulation. The literature states that wool, sheared without additional processing, as well as recycled wool, can be used for the same purpose. It is important to stress their opinion that consumer perception is very favourable, and the market demand for products made from natural and recycled materials is quite high.

Third part of performed mapping is dealing with sourcing for recycling. SMEs emphasises the problematics of low environmental awareness, lack of system at the national level, high price of recycled products and lack of infrastructure to enhance higher capacities. Additional difficulties are non-textile impurities and impurities from other waste categories which should end up in municipal waste, but ends up in textile collectors, due to low awareness and carelessness of citizens.
Humana Nova is the biggest enterprise which collects used clothes, sorts and recycles cotton for industrial rags. The remaining textiles are sent to SME Regeneracija Non-wovens (Rgnc Group) which separates the waste, removes the impurities (sponge, feathers, leather, metal parts) and proceeds with mechanical recycling resulting with the felt. Regeneracija is the only SME in the Republic of Croatia dealing with recycling and production of finished products 100% made of recycled textile materials.
One promising recycling attempt towards a circular economy in the apparel sector is fibre-to-fibre recycling, where end-of-use clothes serve as input material to produce new fibres and, eventually, new apparel [5].

2.3 Production

2.3.1 Production of handmade textile products

For the past twenty years, traditional hand-made textile production has been encouraged and revived by organizing workshops through the programs of associations. The results are modest, but with the persistence obstacles will be diminished and tradition revived. In almost every settlement there are several people who are engaged in home crafts for own fulfilment, but they also encourage others. Their manual work include embroidery, wool spinning, knitting, weaving, so as handmade replicas of national costumes. Occasionally, their work on the original tradition of a certain region, is guided by experts to avoid mixture of ideas from different climates and to keep autochthonous designs of different regions.

Traditional hand-made textiles have been encouraged and revived for thirty years by organizing workshops through association programs. The results are modest, but with everyone's persistence, the obstacles are reduced, and the tradition is revived. In almost every settlement, there several people who are engaged in home crafts for own fulfilment, but they also encourage others. Their handicrafts include hand embroidery, wool spinning, knitting, hand weaving, felting, as well as hand making replicas of folk costumes. Occasionally, their work on the original tradition of a certain region is led by experts to avoid mixing ideas from different climates and to keep the indigenous designs of different regions. At these educational workshops, the starting point is the hand-weaving of simpler utility items (Figures 4a and 4b), and the very demanding weaving of fine linen fabric on which patterns of motifs for folk costumes of Sunjska Posavina are tied by hand (Figure 4c).

a.	b.	c.

Figure 4: Examples of autochtonous designs. a. re-designed product, b. flax woven product, c. wool felted product [6-7]

2.3.2 Conventional production processes and technologies

There are no manufactures in Croatia that produces yarns from recycled fibers - only the products that have recycled textile materials in their composition. Additionally, most of the SMEs use imported yarn produced from recycled textile materials. The market for finished products made 100% from recycled textile waste accepts the fact they are made exclusively from recycled materials but sets unrealistically low expectations in terms of price. On the other hand, in the entire recycling process there is approx. 10% of waste material that can only be burned or deposited. Since landfilling is prohibited and incineration capacities, i.e. energy recovery, do not exist in the Republic of Croatia, this presents a huge problem and high cost.

2.4 End of product life

Social cooperative Humana Nova is a non-profit eco-social company which employs disabled and marginalized social groups and operates in Čakovec and Zagreb. They collect textile waste and in total recycle about 400 tons per year. Such a model is recognized in Europe as one of the best in the field of the REUSE network of active social companies. Collected waste textiles are first sorted into reusable and non-usable clothing. Usable, better-looking clothes are sold individually or by weight. Additionally, they cut and sew innovative products (e.g. bags, aprons, slippers, etc.) from recycled and eco-certified materials, which they sell in own "second-hand" stores and via the web shop. Almost all quantities of unusable waste textiles are processed in cooperation with Regeneracija Non-wovens.
Another stakeholder involved in collection of textile waste is Reto Center Zagreb. The Center, whose primarily aim is rehabilitation of addicts and empowerment of all vulnerable groups, is very active is collection of bulky waste. They regularly sell or donate usable clothes/shoes, as well as other used toys, books, handbags and antiques at very low prices. In doing so, they carry out the inclusion of socially vulnerable groups.

Excellent and innovative example of utilization of non-recyclable organic waste is system LOOPER, developed by DOK-ING Group. Using this innovative solution textile and footware waste becomes a valuable raw material for obtaining hydrogen or hydrogen-rich gas, i.e. green energy. It is important to emphasize that the principle of operation is gasification without the presence of oxygen, and in this way no harmful decomposition products are created, and there are no negative emissions of CO_2 into the environment. This technology is an excellent example of a circular economy because waste from different industries becomes a raw material that represents new value, and even the solid residue (ash) that is a by-product can be used for different purposes in the civil engineering and construction industry.

3. Conclusions

In summary, Croatia's textile and garment industry, while facing significant challenges, can progress by embracing innovation, sustainability, and specialized high-quality markets. Sustainable fashion movement in Croatia has been gaining momentum, driven by designers committed to eco-conscious practices, responsible sourcing, and ethical production methods. This trend reflects a broader global shift toward reducing the environmental impact of the fashion industry.

Significant part of the project is dedicated to organization of workshops. In addition to the immediate benefits for participants, these workshops will strengthen the local economy, fostering collaboration and solidarity within the community. They will provide not only education but also lasting resources and opportunities for further community development, preserving tradition, and inspiring innovation. The role of innovation is huge, as it has always been. Let's not forget that throughout history the textile industry has been the carrier of development and was creating the technical literacy of society. In general, the introduction of innovations and technology contributes to the empowerment of human resources and the development of their skills for work. Innovations and technologies help to improve the working conditions of production workers, thereby creating more attractive jobs with stimulating incomes. All these benefits contribute to raising awareness of the importance of sustainable practices in daily life and within the textile industry, promoting positive change within local communities.

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Review paper

DEVELOPMENT AND APPLICATION OF SMART TEXTILE MATERIALS

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Abstract: *Smart textile materials are an advanced class of textiles that incorporate functionalities beyond traditional uses, integrating technology to interact with the environment, users, or objects. These materials combine textile fibers with electronic components, such as sensors and actuators, to respond to various stimuli, enabling a range of applications in fields such as healthcare, sports, fashion, and defense. The development of smart textiles has been driven by advances in materials science, electronics, and nanotechnology. Innovations have allowed for the creation of fabrics that can monitor vital signs, regulate temperature, change color, or even generate energy. In healthcare, smart textiles are used for monitoring patients' physiological conditions, while in sports, they can improve performance through real-time data collection. In fashion, they offer aesthetic features like color-changing fabrics or integrated lighting. Despite the potential, challenges remain in terms of durability, comfort, and integration of electronic components with textile fibers. As technology advances, smart textiles are expected to evolve further, becoming more functional, efficient, and widely adopted in everyday life.*

Keywords: *smart textiles; functional materials; technology integration; sensory; technology integration*

1. Introduction

Smart textiles are textiles with enhanced functional capabilities. The primary objective of this extended functional range is to enable the interaction of the textile with its environment, including the human user. According to the definition provided by the European Committee for Standardization (CEN) in technical report (TR) 16298:2011, smart textiles are intelligent systems consisting of both textile and non-textile components, which actively interact with their environment, a user, or an object.

Data is collected and processed through sensors, and a defined response is generated via actuators or an information display on an additional device. Smart textiles, particularly when integrated with digitally networked services, offer significant support in a wide range of contexts. Their potential applications span various sectors, including sports, healthcare, home and living, mobility, and construction, thereby opening entirely new markets and business models for both consumer and technical products. Textile-based electronics, in particular, hold great promise for achieving high user acceptance, as textiles are ubiquitous in human environments, both in close proximity to the body and as part of the surrounding environment.

Currently, most smart textiles are available only as demonstrators, which attract considerable attention but are not yet available on the market in significant quantities or at short notice. These prototypes are typically the result of extensive manual labor, and transferring these efforts to large-scale production remains problematic, particularly at the intersections of textile technology, electrical engineering, and information technology [1]. The role of smart textiles in sports is growing, with cycling being one of the key areas where these innovations are making an impact. These textiles are improving various aspects of cycling, such as safety, health tracking, and performance optimization.

2. Historical Development of Smart Textiles

The evolution of smart textiles reflects humanity's broader relationship with materials, beginning as early as 27,000 years ago with the invention of the first fabric [2]. Textiles have historically served dual purposes: protecting individuals from environmental factors and functioning as mediums of self-expression, whether artistic, cultural, or economic. This intrinsic value of textiles has been amplified by key technological advancements, such as William Lee's knitting frame (1589), John Kay's flying shuttle (1733), and James Hargreaves' spinning jenny (1765), which collectively laid the groundwork for the Industrial Revolution [3],[4]. In modern history, the integration of electronic components into textiles marks a transformative period. The first instance of electronic textiles, or E-textiles, appeared in 1883, with illuminated headbands used in the ballet *La Farandole* [5]. Advancements in miniaturized electronics and material science during the late 20th century significantly expanded the possibilities for embedding electronic components into fabrics. The invention of conductive polymers by Heeger et al. in 1977 was a pivotal breakthrough, earning a Nobel Prize in Chemistry in 2000 [6], [7]. These materials enabled the development of electrically conductive textiles, with the first relevant patents following shortly thereafter [8].

The transition toward greater adoption required enhanced integration of electronics at the fiber level. Key patents from the 2000s detailed the encapsulation of semiconductor devices within textile fibers, representing a significant milestone in the development of electronically functional yarns [9],[10]. While the concept of conductive fibers predates E-textiles and can be traced to the second century [11], the field's modern iteration has seen exponential growth, particularly after 2010. A surge in research output reflects this trend, with over 250,000 studies published between 2010 and 2018. This growth has been fueled by the development of energy-efficient textile solutions, including thermoregulating fabrics and textile-based energy storage systems [12],[13]. The historical significance of smart textiles lies in their ability to merge traditional material utility with advanced technological functionality. They not only revolutionize applications in health monitoring, energy harvesting, and adaptive clothing but also open new avenues for sustainable and multifunctional fabric design. Recent comprehensive reviews and publications continue to explore these advancements, contributing to the rapid evolution of the field [14],[15].

3. The Interactivity and Sensory Capabilities of Smart Textiles

What distinguishes smart textiles as revolutionary is their ability to perform functions that traditional fabrics cannot, such as communication, transformation, energy conduction, and growth. In this context, the human body can be viewed as a communication device, with our five senses serving as the tools for input and output allowing us to give and receive information about both internal bodily states and external environmental conditions. Smart textiles interact with all of these senses: they can be seen, heard, felt, smelled, touched, and potentially even tasted. By incorporating these sensory interactions, smart textiles enable the collection of information about the wearer through various stimuli, such as pressure, temperature, light, low-voltage current, moisture, and more [16].

Figure 1: Illustration of the division of smart textile materials with the human [17]

Smart textiles revolutionize functionality by enabling capabilities such as communication, transformation, energy conduction, and data collection. They interact with all five senses, responding to stimuli like temperature, pressure, and moisture, allowing the human body to serve as a dynamic communication device.

Textiles and clothing similarly influence sensory integration, shaping personal, cultural, and social interactions. For individuals with sensory processing challenges, certain fabrics like wool can provoke discomfort, affecting their ability to engage in daily activities. Adaptive clothing can mitigate these barriers by modifying sensory inputs, improving sensory processing, and facilitating meaningful participation.

The growing role of textiles in therapeutic applications underscores their potential to enhance inclusivity and accessibility. By understanding sensory processing needs, the textile industry can innovate designs that accommodate diverse users, fostering functionality and comfort. This review highlights the dual role of textiles as enablers or barriers, guiding future research in sensory-oriented textile design [18].

3.1 Innovations for Cycling

Smart textiles have become increasingly significant in sports, offering enhanced functionality by integrating advanced materials and technologies. These textiles monitor physiological parameters, improve safety, and optimize performance. In cycling, smart textiles have particular relevance, as they provide critical innovations for safety, health monitoring, and performance enhancement.

For instance, the CLARA smart vest integrates ultra-bright LEDs, improving cyclist visibility in low-light conditions and reducing the risk of accidents. The Hövding3 airbag system uses a woven polyamide collar and accelerometer to detect abnormal movements and deploy an airbag in under 0.1 seconds, offering head and neck protection during accidents. This system can also connect to smartphones for real-time emergency alerts and data sharing. The DynaFeed system employs carbon nanotube films to monitor heart rate and activity, providing real-time data on cyclists' biometrics without discomfort.

Additionally, innovative smart fabrics, such as advanced textile fibers made by combining multiscale porous elastic polyurethane (MPPU) with graphene nanosheets, are capable of self-cooling and real-time monitoring of body temperature and pressure. These fibers sense pressure and temperature in real-time, offering self-sensing and self-cooling capabilities, ensuring cyclists stay comfortable and safe during prolonged rides while enhancing performance by monitoring physiological signals.

a. b.

Figure 2: a. CLARA smart vest with LED lights and b. DynaFeed system [19]

These developments demonstrate how smart textiles revolutionize cycling gear, offering not only protection but also insights into physical performance, which is essential for improving training efficiency and overall athlete safety [18].

4. Research and Practical Application of Smart Textiles in Education

Innovation plays a crucial role in shaping the modern fashion industry, demanding the integration of cutting-edge technologies into the design and production processes. Smart textiles represent one of the most transformative areas within this domain, providing opportunities to merge functionality with aesthetics in unprecedented ways. These advanced materials, capable of sensing and responding to external stimuli such as mechanical, electrical, or chemical changes, exemplify the synergy between fashion and technology. Their potential extends beyond fashion trends, offering practical solutions for real-world challenges and enhancing user experience.

In the educational context, the study and application of smart textiles foster interdisciplinary learning and hands-on innovation. By engaging students in projects that explore these materials, educators create a platform where creativity intersects with engineering and technology. For instance, the work of students such as Adnan Hajrulahović, who developed a prototype of a cyclist jersey with integrated LED strips, demonstrates the practicality of smart textiles in addressing both functionality and safety concerns. This type of project highlights how smart textiles can improve visibility and protection for cyclists, directly showcasing their societal benefits.

Figure 3. *Photo by Ammar Selmanovic* : Cyclist Jersey with LED Strips (a project by student Adnan Hajrulahović)

This innovative jersey incorporates LED strips powered by AAA batteries. LED strips are strategically positioned on the back and rear sections of the sleeves. These placements maximize visibility for drivers approaching from behind, particularly in low-light conditions, while also aligning with natural arm movements to enhance signaling during turns.

The design ensures comfort and functionality, retaining the jersey's breathability, stretch, and moisture-wicking properties. The LED system is lightweight, energy-efficient, and seamlessly integrated, providing bright and reliable illumination without compromising the aerodynamic profile of the garment.

This project highlights the potential of smart textiles in improving road safety and serves as a valuable educational exercise. It showcases how wearable technology can address real world challenges while fostering interdisciplinary skills in fashion, engineering, and design. This work is a strong example of innovation in smart textiles, offering a blueprint for future advancements in functional sportswear.

5. Conclusion

Smart textiles represent a revolutionary synergy between materials science, technology, and design, enabling fabrics to interact with users and environments in unprecedented ways. Their applications in fields such as healthcare, sports, and fashion demonstrate their potential to address practical challenges and enhance quality of life. The integration of sensory capabilities, data processing, and advanced functionality positions smart textiles as key drivers of innovation. Educational initiatives play a pivotal role in advancing this field by fostering interdisciplinary exploration and hands-on applications. Projects like the cyclist jersey with LED strips by student Adnan Hajrulahović highlight the importance of incorporating smart textiles into academic curricula. Such initiatives not only prepare students for emerging industries but also contribute to the development of practical solutions that bridge theory and application. As the technology matures, smart textiles will continue to transform industries, underscoring the value of collaborative efforts in education, research, and industry to unlock their full potential.

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Professional paper

THE ARTISTIC CREATIVITY OF HENRI MATISSE AS A SOURCE OF INSPIRATION FOR THE DEVELOPMENT OF THE COLLECTION AND THE PATTERNS OF WOMEN'S TROUSERS

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Abstract: *The paper represents part of the artistic creativity of the representative of Fauvism, Henri Matisse, whose bold use of bright and pure colours had a decisive influence on the European art scene at the beginning of the 20th century. Matisse's art became the inspiration for the creation of a unique fashion collection of women's trousers that not only retains his revolutionary aesthetic, but also combines the richness of colour with a fashion statement. The patterns of the trousers are inspired by the fashion of the 60s of the last century.*

The experimental part of the paper describes the development of the design, the description of the collection, the construction and modelling of selected trouser models and the use of textile printing in the development of the collection itself. Two trouser models from the collection were realised in collaboration with the Croatian company Naftalina.

Keywords: *Fauvism; Henri Matisse; trousers; 60s; fashion collection*

1. Introduction

Henri Matisse left an indelible mark on the art world, encouraging artists around the world to break free from conventional norms and experiment with colour, form and expression. The Fauvist dissonance of form and pure colour opened the door to new approaches in art and had a lasting influence on its further development. Matisse had a decisive influence on the European art scene at the beginning of the 20th century with his bold use of bright and pure colours and his expression.

As a basic human need, clothing has had several meanings for centuries, one of which is to protect the human body from cold and dirt. Although trousers are a common item of clothing today, they have a long history behind them. The rapid development of social and technological changes in the 20th century encouraged women to free themselves from heavy bondage, multi-layered dresses, tight corsets and lack of body freedom, giving them a sense of freedom, femininity and elegance that they felt when wearing trousers, and they became a key symbol of the time. The most important personalities of this era who contributed to their importance and fame are Coco Chanel and Elizabeth Smith Miller.

In this work, Matisse's art became the inspiration for the creation of a unique fashion collection of women's trousers that not only reflects his revolutionary aesthetic, but also combines the richness of colour with fashionable expression. The work also explores the fashion period of the 1960s, which is considered one of the most brilliant in the history of world fashion. Elements such as wide legs, contrasting combinations of colours and textures and geometric shapes became iconic symbols of the period. During this period, the fashion industry underwent significant changes, and financial independence and the desire to express one's own style became key factors in fashion design.

The experimental part of the paper presents the author's concept for the design of women's trousers. It is based on the design, pattern construction and modelling of selected trouser models as well as on the use of textile printing in the development of the collection. The aim was to realise two selected trouser models that represent a fusion of artistic expression and fashion creativity [1].

2. Henri Matisse – life and work

Henri Matisse is considered to be one of the most influential French painters of the 20th century and one of its leading moderators. He was one of the leading representatives of the Fauvist movement around 1900 and throughout his career strove for expressiveness in vivid colours and simple forms. Matisse helped to establish a new approach to art. He believed that the artist should be guided by instinct and intuition. With his exuberant compositions full of bright colours, he changed the language of art. The young Matisse initially studied law in Paris and toyed with the idea of becoming a pharmacist, but then he unexpectedly discovered his vocation [2].

He began painting in 1890 after his mother brought him painting materials to pass the time while he was recovering from appendicitis. It was then that he discovered his passion for painting, 'a kind of paradise', as he later described it. He finally decided to become an artist, much to his father's disappointment. At the beginning of 1891, he returned to Paris to study art at the Académie Julian. He became friends with Albert Merquet, with whom he enrolled at the École des Beaux-Arts, and they later became students of William Bouguereau and Gustave Moreau. Initially he painted still lifes and landscapes in a traditional style, and over time he acquired considerable skill in this field. Matisse was influenced by the works of earlier artists such as Jean–Baptiste–Siméon Chardin, Nicolas Poussion and Antonie Watteau, but also by modern artists such as Édouard Manet and Japanese art itself. Chardin was one of Matisse's most respected painters – as an art student, he made copies of four of Chardin's paintings in the Louvre [3].

In 1896, he met the Australian painter John Russell, who introduced him to Impressionism and the paintings of Vincent van Gogh. He introduced him to the Impressionists' colour theory. As Vincent van Gogh was a friend of Russell's, he gave him one of his drawings as a gift. At this point, Matisse's style changed completely: he abandoned his earthy colour palette and enlivened his paintings with bright and expressive colours, which can best be seen in his painting 'The Dinner Table' (Figure 1). It is one of Matisse's paintings from his early creative period, but the idea of balance and tranquillity found here was to remain a consistent theme in his work for the next 50 years.

Figure 1: Henri Matisse – 'The Dinner Table', oil on canvas, 1896 – 1897

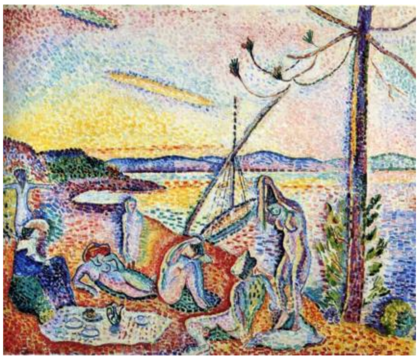


Figure 2: Henri Matisse – 'Luxe, Calme et Volupté', oil on canvas, 1904

Matisse said: *"I dream of an art of equilibrium, purity and serenity, free of problematic or depressing darkness"* [2]. In the following years, he studied the works of other artists and borrowed money by buying works by painters he admired, including drawings by Vincent Van Gogh, Paul Cezanne's 'Three Bathers', Gauguin's 'Young Man with Tiare Flower'. He then changed his technique, and from 1898 to 1901 Matisse began to use the Divisionist technique, which he had adopted after reading Paul Signac's essay 'Eugene Delacroix and Neo-Impressionism'. During this period, Matisse simplified the forms in his paintings, used bold, broad brushstrokes and high-contrast contours and increasingly employed local colour variations. His preference for bright and expressive colours became even more pronounced after he spent a summer in St. Tropez with the Neo-Impressionists Signac and Henri Edmond Cross. In this year, he painted his most important works in the Neo-Impressionist style, including 'Luxe, Calme et Volupté' (Figure 2) [2].

Around 1904 he met Pablo Picasso, who was twelve years younger than Matisse. Although Matisse and Picasso had different styles, their interaction and dialogue helped to shape modern art. They became lifelong friends, but also rivals and were often compared to each other. A key difference between them was that Matisse drew and painted from nature, while Picasso worked more from the imagination. The subjects painted by both artists were women and still lifes, with Matisse placing his figures more faithfully in fully realised interiors. Their mutual inspiration and occasional rivalry contributed to their constant development and experimentation. Their work not only further developed painting, but also enriched the understanding of art as a whole [2].

2.1 The artistic creativity of Henri Matisse

As one of his most famous works of art, 'Harmony in Red' expresses the artist's inner state, Figure 3. The tablecloth and the wall are in the same colour scheme. The decoration on these surfaces is also the same – dark blue oriental floral patterns that make a strong impression on the viewer. In the top left corner there is a window through which you can see a landscape painted in cold colours to give an impression of spatial depth. Small flowers and blossoming white branches of a tree bring harmony and tranquillity to this astonishing picture. The contrast of warm and cold colours distinguishes between two spatial plans. Sharp colour changes, elements of wood art and primitivism combine perfectly to create a concentrated image of the French master's original talent. The work was originally called 'Harmony in Blue', but the artist later changed the colours on the canvas, creating a masterpiece – a work that is loved by many.

Matisse's work is a major phenomenon of early 20th century French art. Figure 4 shows a group of red dancers floating in a moment of pure and innocent freedom and joy, holding hands tightly as they spin in space. Matisse depicts reality in his own way, his dancers do not have ideal forms, they seem to come from another dimension, but they are attractive and beautiful at the same time.

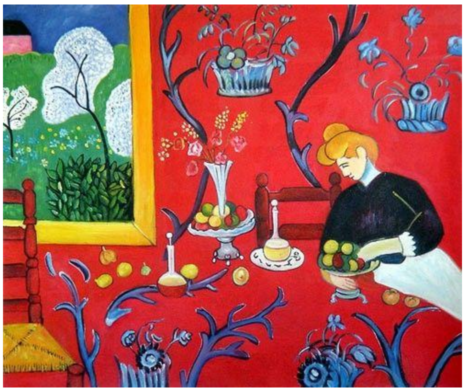


Figure 3. Henri Matisse – 'Harmony in Red', oil on canvas, 1905

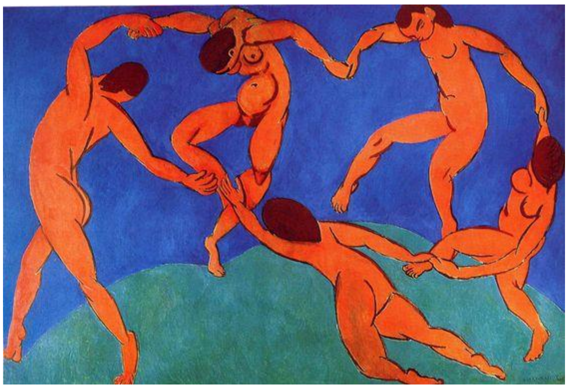


Figure 4. Henri Matisse – 'The Dance', oil on canvas, 1905

Matisse's collection of Blue Nudes represents a significant part of his late work and is characterised by its simplicity and abstraction (Figure 5). The 'Blue Nudes' consist of four large colouristic linocuts and accompanying drawings and studies. These compositions depict female nudes, which are characteristic of Matisse's artistic understanding of the human body and the figure as such. The special feature of this collection is the use of blue, which dominates the works and creates contrasts of light and shadow. In this collection, Matisse uses minimal lines and shapes to depict female figures. Although they are simplified into abstract forms, the figures retain their sensuality and grace.

Figure 5. 'Blue Nudes'

The Blue Nudes collection epitomises Matisse's ability to express beauty and vitality despite the limitations that accompanied him in his later years. This series of works is a testament to his innovation and enduring passion for the art of the figure [2].

3. The appearance of trousers in women's clothing

The 20th century brought dramatic changes in the world of fashion and society, and trousers became a key symbol of these changes. Then the first trousers for women appeared, the so-called bloomers, which became a symbol of emancipation and the fight for women's rights. During the Second World War, trousers became an indispensable part of women's workwear as they took on tasks in industry while the men were at the front. After the First World War, the zeitgeist changed considerably. Vitality and activity were desirable qualities in people, and sport and tourist destinations became an integral part of life. At that time, women recognised the potential of trousers as an item of clothing. They needed more comfortable clothing for sports, skiing or the beach, and trousers emerged as the only logical solution that allowed women to participate in sports and leisure activities [4]. The increasing preoccupation with sport and leisure in everyday life made trousers an acceptable choice for women. However, when it came to mass production and the emergence of trousers in women's fashion, their use was determined by the appearance of film icons. Fashion magazines followed the new social cues and by 1939, trousers became a compulsory part of a woman's wardrobe, with Vogue (1939) recommending: 'Your wardrobe is incomplete without a pair or two of well-cut trousers'. The beginning of the Second World War marked important changes in the fashion industry. Most Parisian fashion houses were closed or forced to relocate to England. Restrictions are introduced in the textile industry, banning certain shapes and fabrics. Clothing made according to the new standards was called 'utility clothing'. Women on both sides of the Atlantic became more actively involved in production and took on many traditionally male tasks and responsibilities. In America, the campaign 'We Can Do It!' was launched. with the popular character Rosie the Riveter. She was the icon of a strong, working woman who changed the previous idea of the role of women as mothers and housewives. The campaign invited unemployed women and housewives to work in the production of military equipment. The work uniform of these labourers consisted of overalls or trousers and a shirt, and a headscarf was an essential accessory. Some of the American volunteers also wore their work clothes in their free time and complemented them with make-up and jewellery. While the men were at war in Europe, the women took over the work in the factories to supply them with food, weapons, ammunition and other things they needed for the war. As dresses and skirts were impractical for factory work, it was only then that they began to wear trousers, which made it easier for them to move around and do their work [5].

The Second World War liberated women in many ways, changing their attitudes to fashion and showing them new opportunities and roles in a developed society. As earlier in history, traditional gender divisions and roles return after labour. Women have to take on the role of housewife and mother again and dress more feminine. Trousers were therefore only accepted in the workplace. The rights they had acquired after the war were taken away again when the men returned from the front. It was felt that women were no longer needed in the workplace, and society once again regarded them only as housewives. Women's only role was to bring up children and be in the kitchen. However, a few women did not give up their comfort in trousers, which is why they were declared prostitutes. Looking at the period between the above-mentioned war and today, women's clothing has changed a lot. Today, they communicate with the clothes they wear. The fact that women today wear different types of trousers shows that they are not only equal to men in terms of clothing, but also in other social and civic areas of life.

3.1 The fashion of the 1960s

The return of traditional femininity has not left much room for trousers. The youth culture grew stronger and reached its peak in the 1960s in London, where numerous boutiques were opened. The London of the 1960s, also known as Swinging London, epitomised the synergy between culture and fashion. The fashion scene developed with a whole series of more or less educated designers opening their shops in Carnaby Street and Soho. The 1960s are considered the most glamorous period in the history of world fashion. It is not surprising that the characteristic elements of this period can still be seen on the catwalks today. Bold straps, colour combinations in rainbow colours, large accessories, regular geometric shapes and artificial fabrics suddenly created a completely new idea of fashion. The financial independence of a large number of young people who want to show off a certain style of clothing leads to a change in the concept of the fashion industry. This marks the beginning of the development of a modern infrastructure and the sale of certain clothing styles is regulated by law. Baggy trousers and masculine styles, which had been so popular in the post-war years, became commonplace. The fashion of the 60s was characterised by contrasting combinations of colours and textures [6].

3.2 Coco Chanel and Elizabeth Smith Miller

Coco Chanel acted as a fashion revolutionary and introduced the ladies' suit, the little black dress and trousers as new items of clothing in women's wardrobes [7]. She believed that women should have the same freedom as men and that corsets and skirts restricted them physically. She created a new style for modern women (Figure 6). She freed them from corsets and tacky adornments and offered them navy blue shirts and wide trousers because 'nothing is more beautiful than the freedom of the body'. The turning point came when Coco realised that she could not ride a horse in a long skirt, so she literally took off the male rider's trousers and put them on [8]. She allowed women to move and breathe freely, just as men could move freely in their clothes. Chanel's silhouettes were flowing, the patterns loose but perfect, and her work is considered a form of female emancipation [8]. Coco popularised trousers as a feminine garment and she herself loved wearing them – allegedly borrowing them from her lovers – and then incorporated them into her collections in the early 1920s, pairing them with oversized shirts or tank tops. After that, the trousers became synonymous with comfort, but also with the equality of women with the stronger sex [7].

Figure 6: Coco Chanel in trousers

Figure 7: Bloomers

The 'dress reform' that emerged in England and America in the mid-19th century as a reaction to the fashions of the time was seen as crucial in liberating women from the functional limitations imposed on their activities by the conventions that reinforced a male-dominated society [9]. It was a rebellion against the fashions of the time, which required women to dress voluminously and restrictively, and was both a practical necessity and a focus of social reform. Elizabeth Smith Miller, one of the proponents of Victorian dress reform, was the first to wear wide trousers gathered at the ankles under a shorter dress or knee-length skirt, which Amelia Bloomer popularised in her magazine The Lily and which were named bloomers after her (see Figure 7). She wrote descriptions and instructions on how others could make them. In this way, she promoted a new look for women. Elizabeth was working in her garden and was frustrated when her long, heavy skirts prevented her from working. She decided to shorten her skirt with scissors and wear trousers underneath, which allowed her to do her work unhindered. This new fashion trend quickly became a hit among the early feminists of the suffragette movement. Although it was short-lived, it broke the mould of social norms. It was changed several times and eventually abandoned because the criticism attracted too much attention in the media [10].

4. Experimental

The experimental part of the paper consists of the author's design concept, conceptual solutions for a collection of women's trousers, construction and modelling. Based on the selected models, a contemporary collection of women's trousers was designed in co-operation with the Croatian company Naftalina [1].

4.1 Concept design

The original inspiration for the design of the contemporary women's trousers collection is Henri Matisse and the 1960s. Researching and studying the works and creations of Henri Matisse throughout his life attracted great interest in the strong and expressive colours, the two-dimensional composition and the ornamental patterns that formed the basis for the design of the women's collection. The depictions of textiles in his paintings, which appear as wallpaper on the walls, bedspreads and even on the clothing itself, also made a strong impression. Research and studies in the 1960s attracted great interest in the wide patterns that became popular in the post-war period. Following the chosen inspiration, the way people dressed during this period is examined in detail, what materials were used, what samples, colours and patterns were available and what the designers of the time actually wanted to express with such designs. The research is divided into two types – primary and secondary research.

Primary research is the personal gathering of information, in this trouser collection it is the research and study of the life and work of Henri Matisse and the 1960s to find interesting samples and patterns that can be combined in a contemporary collection. Secondary research is when someone else does the work, for example by using existing research that appears in various media, on the internet, in books or magazines. The balanced combination of primary and secondary research creates a solid topic based on external sources with personal references. The majority of the research is based on the designer and their perspective as they use their personal skills to gather the information needed [1,11].

4.2 Collection description

The collection consists of 12 models of women's trousers (Figure 8). The author (P.B.) has created a design inspired by the revolutionary concepts of Fauvism, emphasising freedom of expression. The collection represents an innovative and visually sophisticated approach to garment design. Using sublimation printing technology, the selected imagery was digitally printed onto polyester fabric to create a pair of trousers that emphasise the unique connection between art and fashion. In addition to transcending the boundaries of art, visual representations of canvases were transferred to textile material, creating a unique synthesis between fine art and fashion. They can be worn for everyday occasions and with various clothing combinations. The colour as a basic element of this women's trousers collection becomes an essential component - pure, intense, dynamic and expressive. Colour is used to create the illusion of three-dimensionality on a two-dimensional textile material, avoiding the usual use of classic perspective. Each pair of trousers in this collection becomes a kind of canvas for painting. The patterns of the trousers are inspired by the fashion of the 1960s. The wide trouser legs stand out in particular and are a defining feature of the collection.

Figure 8: Project drawings of models of the author's collection of women's trousers [1]

The collection is divided into two parts. The first part of the collection is inspired by the early phase of Matisse's work, where the emphasis is on pure, bright and expressive colours, which form the basis of his painterly work and have a direct impact on the design and aesthetics of the collection. The second part is inspired by his later phase of life, in which he experimented with the collage technique, which represents a clear departure from the beginnings of his work. The collage technique, which became an important means of expression in the later years of the artist's work, is recognised as another dimension of the collection. Through these two fundamental components, the collection becomes a complex description that emphasises aspects of Matisse's work in the field of fashion, focusing on the expression and interpretation of the art of clothing to achieve the ultimate goal [1].

4.3 Application of textile printing to the development of collection

Digital printing technology adds a completely new dimension to pigment printing, as it combines the advantages of pigment printing as such, the most important of which are its applicability to all types of textile materials in terms of raw material composition and the simplicity of the process, which does not require complex post-treatment and sophisticated fixing procedures (such as vapour fixation when using reactive dyes), as well as the preservation of the natural surface structure with minimal intervention in the tactile and physical-mechanical properties of the textile material. This so-called 'sinking' of the pigment into the textile material, as printers like to say, means a certain loss of colour brilliance, but on the other hand brings added value in the complex interplay of colour and structure. This is why some images and patterns are in the textile and not on the textile, which emphasises the commonality of the image content and the interplay of the image elements with the structural and constructive elements of the textile material [1,12,13].

The printing technique on fabric used in this paper is sublimation printing, Figure 9a. This is a printing technique in which a digitally printed image is transferred to objects or materials using heat in such a way that the dye evaporates into the coating or material. This printing technique is based on the sublimation process, in which printing inks are transferred from a solid state to a gaseous state without passing through a liquid phase. Sublimation printing enables the precise transfer of colours and details onto fabrics, ceramics, metal and many other surfaces. During the printing process, the ink reaches a temperature of 180–200 ^{0}C, which leads to rapid evaporation and penetration into the structure of the product to be processed in a gaseous state. Therefore, this printing technique is only used on objects that have a special coating that accepts sublimation dye or are made of materials that directly accept sublimation dye. This type of printing is only carried out on white or light-coloured materials. Sublimation printing requires special inks and equipment, including printers that use ink tanks and thermal heads to precisely vaporise the ink and transfer it to the material. With sublimation printing, the colours are vibrant and the printing is very precise, and the higher the polyester content and quality of an item, the higher the quality of the print [1,14].

The design and pre-press were created in Corel Draw, while the printing itself was carried out by Epilog Studio, a company founded in 2007 that produces large and small format prints. The design of the Model 01 trousers was designed using combinations of Matisse's artworks, which were brought together to create a single visual identity that characterised the early phase of his work. The second design of the Model 12 trousers represents a marked departure from the beginnings of his work and marks a different dimension of the collection, referring to the collage technique in which abstract motifs characterise the interpretation of the art. The aim was to emphasise the pure, bright and expressive colours and shapes that form the basis of his painterly work. The textile design patterns were printed on polyester fabric (Figure 9b), from which the pattern pieces were then cut out and later joined together to form the finished garment [1].

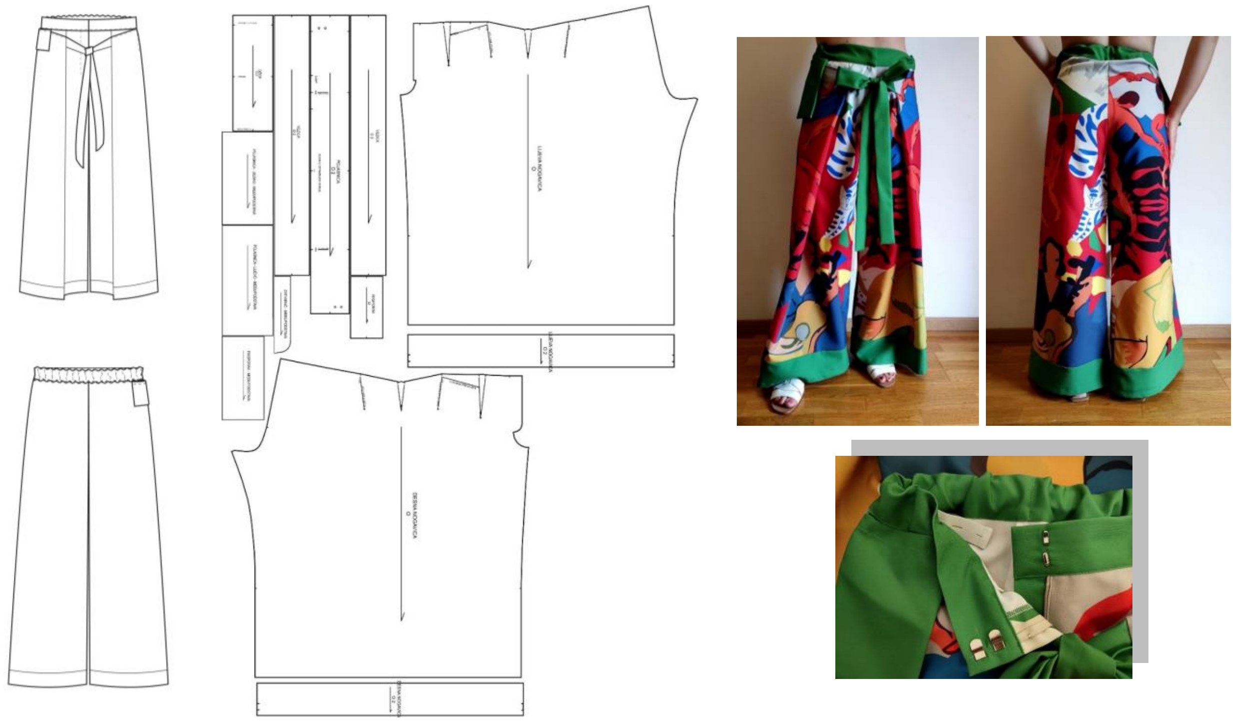
a. b.

Figure 9: a. Sublimation printing, b. Textile design pattern [1]

5. Results and discussion

5.1 Pattern parts prepared for tailoring and finished designer models from the women's trousers collection

The finished pattern parts of the women's trousers models 01 and 12 from the author's collection as well as the sewn models were made to measure by the author of the work (P.B.) and are shown in Figures 10 and 11. The modelled pattern parts of the women's trousers Model 01 are shown in Figure 10a and consist of the left and right trouser leg, which are cut from one piece, then the waistband, the pocket and the ties. The modelled pattern pieces of the women' trousers model 12 are shown in figure 11a and consist of the front and back part of the trousers, the pocket, the pocket flap and the front and back flap at the waist position on the inside. The CAD system Optitex was used for modelling and adding seam allowances. The trouser models are made from polyester fabric onto which the selected pattern was printed using the sublimation printing process. The selected trouser models from the author's collection were realised with the help of Naftalina employees.



a. b. c.

Figure 10: a. Technical drawing of Model 01 from the collection, b. Pattern parts, c. Presentation of finished trousers with buttoning detail [1]

a. b. c.

Figure 11: a. Technical drawing of Model 12 from the collection, b. Pattern parts, c. Presentation of finished trousers with buttoning detail [1]

6. Conclusion

The aim of this paper was to present a collection of women's trousers inspired by the life and work of Henri Matisse. A key figure in Fauvism, he shaped the art world with his bold use of colour, form and expression. His revolutionary aesthetic served as inspiration for the creation of a unique fashion collection that combines the richness of colour with fashionable expression. For the design of the trouser models, combinations of works of art by Matisse were used, which were brought together to create a uniform visual identity.
The collection consists of 12 different trouser styles, and the end result was two unique trouser styles that fit the author's body measurements and combine artistic expression with fashion creativity.

The theoretical part of the paper deals with the history of the creation of trousers, focussing on the period of the 1960s, which is considered one of the most glamorous in the history of world fashion. This era was characterised by social changes, cultural revolutions and technological advances, and women's trousers became a symbol of liberation from conventional norms and an expression of individuality. Key figures who contributed to the importance and popularity of trousers were Coco Chanel and Elizabeth Smith Miller. Despite the changes, trousers are likely to remain a basic element of the wardrobe, adapting to the times and changing circumstances and bearing witness to the evolution and revolution in the world of fashion and art.

The connection between fashion and art is deep and complex, and their mutual influence has shaped the way we perceive, create and express ourselves throughout history. Art and fashion inspire each other and encourage artists and designers to experiment and innovate.

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Professional paper

DEVELOPMENT OF ECO-FRIENDLY PRINTING PASTES USING NATURAL DYES EXTRACTED FROM MULBERRY BRANCHES

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Abstract: *The circular economy framework encompasses several critical areas, including waste management, natural resource preservation, energy efficiency, and the textile industry. Within textiles, sustainable strategies are increasingly prioritised, particularly regarding the use of natural dyes. Historically, textiles, whether composed of natural or synthetic fibres, have been dyed and printed to align with consumer preferences. However, the widespread use of synthetic dyes, predominantly synthesized from fossil fuels through hazardous chemical processes, has raised significant environmental concerns. These dyes not only contribute to pollution but also have adverse effects on ecosystems and human health. As a result, the growing demand for eco-friendly products has shifted focus toward textiles made from natural fibres and coloured using sustainable, environmentally friendly natural dyes.*
This study aimed to explore an innovative approach for extracting natural dyes from mulberry residues generated during the seasonal pruning of mulberry trees and to develop an eco-friendly printing paste from these dyes. Mulberry residues, an often-overlooked by-product of agricultural activity, present an untapped source of natural dye that can be repurposed for textile applications. To extract these dyes, a Soxhlet extractor was employed using water as a solvent. The isolated extracts were then utilized in a direct printing process, with printing pastes formulated using non-aggressive and environmentally friendly chemicals to minimize environmental impact.
A thorough evaluation of the printing quality was conducted to determine the feasibility of these natural dye formulations in textile printing applications. Among the tested formulations, the printing paste labelled TBG 3, which included ammonium iron(II) sulphate as a mordant, was identified as the most effective for achieving high-quality prints on cotton fabric. This printing paste demonstrated superior colour intensity, adhesion, and overall performance. Another formulation, TBG 2, containing potassium alum as a mordant, also exhibited excellent properties, showcasing its potential as an eco-friendly alternative.
The results underscore the promise of natural dyes extracted from mulberry residues in sustainable textile applications. By utilizing agricultural by-products, this research contributes to waste reduction and promotes a more circular approach to resource utilization. Furthermore, the development of environmentally friendly printing pastes aligns with global efforts to reduce the ecological footprint of the textile industry. This study highlights the potential for integrating natural dye extraction and eco-conscious printing processes into modern textile production, advancing sustainability and meeting growing consumer demand for greener products

Keywords: *eco-friendly printing; dyes; textile; printing; mulberry residues*

1. Introduction

The rapid evolution of fast fashion has reshaped the global fashion industry, bringing about significant environmental and socio-economic challenges. Fast fashion, characterized by inexpensive and trendy clothing that mimics high-fashion designs and celebrity culture, quickly satisfies consumer demand by bringing these trends to mass markets at unprecedented speeds [1]. However, this model of production and consumption comes at a steep cost. Fast fashion has emerged as a major contributor to greenhouse gas emissions, waste production, and environmental degradation. Additionally, its reliance on cheap labour and poor working conditions exacerbates social inequities, while the overuse of water and chemicals in textile production presents severe ecological risks [2]. One of the most pressing environmental concerns associated with fast fashion is its extensive use of synthetic polymers, which contribute to microplastic pollution. These microplastics eventually infiltrate the food chain, posing potential long-term risks to both environmental and human health, many of which are yet to be fully understood [3]. Addressing these challenges necessitates a paradigm shift towards sustainable alternatives like slow fashion. The concept of slow fashion finds its roots in the broader "slow movement," which originated with Carlo Petrini's "Slow Food" initiative in 1986. This movement sought to counteract the rapid globalization of food production and the erosion of local culinary traditions. Over time, the philosophy of slowing down extended to various aspects of life, including fashion. Slow fashion emphasizes the conscious design, production, and use of clothing, prioritizing quality, durability, and environmental responsibility over transient trends. A cornerstone of slow fashion is the use of natural dyes derived from renewable sources, such as agricultural waste, which aligns with the principles of a circular economy [4].

Natural dyes, extracted from agricultural by-products like vegetable peels, seeds, and plant stalks, offer a sustainable alternative to synthetic dyes. These by-products are rich in proteins, fibres, vitamins, and minerals, making them valuable not only for their dyeing properties but also for their potential to reduce environmental pollution when repurposed effectively [5]. Methods such as green extraction, which employs eco-friendly solvents and renewable materials, further enhance the sustainability of natural dye production. These dyes have proven applications in textiles, pharmaceuticals, and food industries, owing to their biodegradability and minimal environmental impact [6-8]. The transition to natural dyes has gained momentum in recent years, driven by stringent environmental regulations and consumer awareness of the health hazards associated with synthetic dyes. Synthetic dyes are notorious for causing toxic and allergenic reactions, while their production generates wastewater that is heavily laden with salts and exhibits high biological and chemical oxygen demands (BOD/COD). In contrast, natural dyes have demonstrated superior compatibility with various natural fibres and even some synthetic materials, enabling their broader adoption across the textile industry [9].

The ongoing development of sustainable textile technologies highlights innovative approaches to reducing environmental footprints. Techniques such as using halogen-free natural dyes, hybrid pigments for low-temperature dyeing, and enzymatic pre-treatment of fibres represent promising advancements [10-13]. Moreover, natural dyes sourced from agricultural and food industry waste have shown significant potential. Studies have successfully extracted vibrant pigments from fruit peels, vegetable residues, and even fermentation by-products, underscoring the viability of these materials for industrial-scale textile applications [14]. A growing body of research validates the effectiveness of natural dyes under various conditions. For instance, experiments with dyes extracted from mulberry leaves and coffee beans have yielded diverse shades with high resistance to washing and rubbing, particularly when paired with mordants like mineral water or ash-based solutions [15]. Similarly, extracts from eucalyptus leaves have shown excellent UV protection properties when applied to silk and wool, achieving high durability under light and abrasion [16]. These findings reinforce the feasibility of integrating natural dyes into modern textile processes. Despite these advancements, challenges remain. The scalability of natural dye production and the standardization of dyeing procedures require further exploration. Moreover, creating robust databases of natural colour charts and optimizing extraction techniques to enhance dye fastness is essential for mainstream adoption. Addressing these gaps through interdisciplinary research can pave the way for a more sustainable and responsible fashion industry.

This article aims to consolidate recent developments in natural dyeing technologies and their applications in textile production. By exploring innovative solutions and best practices, it seeks to contribute to the growing discourse on environmental sustainability and the transition towards a more equitable and eco-friendly textile industry.

2. Material and methods

2.1 Extraction of the dye

In this study, we utilised dried mulberry branches collected during spring pruning. The branches were provided by the Faculty of Agriculture and Life Sciences, University of Maribor from their collection of Slovenian mulberry descendants. The dried mulberry branches used in the extraction process were first ground for use in a solid-liquid extraction procedure. The extraction was conducted using a Soxhlet extractor, yielding a liquid extract as the result. For each extraction procedure, 12.4 g of ground mulberry branches were wrapped in filter paper and combined with 300 mL of solvent. Distilled water was employed as the solvent for this process. The extraction process lasted two hours. Following the completion of extraction, a laboratory rotary evaporator (BÜCHI, Heating Bath B-490, Switzerland) was used to efficiently remove the solvent from the obtained extract. This ensured a pure and concentrated sample for subsequent use.

2.2 Printing paste preparation

The preparation of the printing paste followed the formulation provided in [17]. Due to the inadequate viscosity of the base printing paste without the extract, the original formulation was modified by increasing the concentration of the natural thickener, 8 % alginate (The CHT Group, CHT-Alginate MV).
To prepare the appropriate printing paste, a 4 % aqueous solution of extract was utilized. This solution was prepared by dissolving 13.81 g of the solid extract residue in 345.25 mL of distilled water. The printing pastes were mixed using an Ika-Werk RE 166 mixer (Janke & Kunkel), operating at 1500 rpm for 20 minutes. Using the prepared extract solution, three different printing pastes were formulated:

- Printing Paste 1: Prepared without the addition of mordants.
- Printing Paste 2: Included potassium aluminum sulfate(VI) dodecahydrate (Merck, Germany) as the mordant.
- Printing Paste 3: Contained ammonium iron(II) sulfate (Kemika, Croatia) as the mordant.

Each printing paste was adjusted to achieve optimal consistency and composition for subsequent application. To ensure the proper viscosity of the base printing paste, the prepared pastes were analyzed using a rheometer (MCR 302, Anton Paar, International).

2.3 Printing process

For the printing process three standard fabrics were chosen:

- standard cotton fabric (100% cotton, DIN ISO 2267:2016, WFK 10A, width 100 cm),
- standard wool fabric (100% wool, WFK 60 A, width 75 cm),
- standard silk fabric (100% silk, WFK 70 A, width 90 cm).

These fabrics were sourced from WFK-Testgewebe GmBH, Germany, and were not pre-treated with optical brighteners or any other chemical pre-treatments.

A flat-screen printing technique with a magnetic squeegee was performed using prepared printing pastes. The stencil which was used for the printing process allowed us to further analyse the colour characteristics of the prints and evaluate the sharpness quality of the impressions.
After the printing process, the printed fabrics were dried at 50 °C for 2 minutes to remove the water content of the printing pastes. Subsequently, the fabrics underwent curing to fix the dye onto the fabric and enhance dye fastness. The curing process was carried out at 130 °C for 5 minutes. Drying and curing were performed using a Werner Mathis AG, Textilmaschinen-Laborapparate CH-815Z drying machine.
To remove any uncured printing pastes, a subsequent cold rinsing step was performed, which involved immersing the samples in 1.5 L of cold water for 10 minutes. This was followed by hot washing in 1.5 L of hot water (90 °C) with the addition of 5 g of the surfactant Tanaterge for 10 minutes. Finally, the detergent was removed through a hot-to-cold rinsing process under running water, which lasted for 2 minutes.

2.4 Analytical methods

Analysis of print sharpness

The length of the print of the measurement wedge was determined for each sample using a vernier calliper. The sharpness of the print was then calculated using Equation 1, where S stands for the sharpness of the print (expressed as a percentage), L_p stands for the measured length of the printed line or mark on the fabric and L_o stands for the original length of the line or mark on the stencil.

$$S = \frac{L_p}{L_0} \times 100 \tag{1}$$

Colour characteristics and degree of penetration

The colour values of both unprinted fabrics and printed samples were measured using a reflection spectrophotometer (Datacolor SF600, Switzerland), including specular reflection under D65 light (daylight). Measurements were taken on the samples evaluating both the face and back sides of the fabric.
The spectrophotometer generates a reflection curve characteristic of the measured colour. Differences in colour between printed fabrics were calculated using Equation 2 where ΔE^*_{ab} stands for colour difference vector, L* for lightness vector, a* for green-red axis vector and b* for blue-yellow axis vector. The penetration depth was determined using Equation 3 where P_i stands for degree of penetration, $(K/S)_l$ for depth of colour tone on the face side of the print and $(K/S)_h$ for depth of colour tone on the back side of the print.

$$\Delta E^*_{ab} = \sqrt{(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2} \qquad (2)$$

$$P_i = \frac{100 \times \left(\frac{K}{S}\right)_h}{\sqrt{\left(\frac{K}{S}\right)_l + \left(\frac{K}{S}\right)_h}} \qquad (3)$$

3. Results and discussion

Print sharpness

From the results shown in Table 1, we determined that, regardless of the fabric type or the warp and weft direction, the use of printing paste 1 resulted in the lowest print sharpness. By using thickeners, the results were significantly improved. The use of printing paste 2 yielded the best results, with a minimum sharpness of 80 %. These prints showed no signs of bleeding or spreading of printing pastes beyond the print contours.
The improved print sharpness observed with printing pastes 2 and 3 can be attributed to the addition of thickeners, which substantially increased the viscosity of printing paste, effectively preventing its spreading beyond the print contours. It is well-documented in the literature that viscosity significantly influences print sharpness. Table 1 provides an overview of the print sharpness of the printed samples.

Table 1: Print sharpness

Sharpness [%]			
Standard fabric	**Printing paste 1**	**Printing paste 2**	**Printing paste 3**
Cotton - warp	71.1	90	75
Cotton - weft	70.5	88.4	74.6
Wool – warp	65.5	80	70
Wool – weft	65.1	79.5	69
Silk – warp	75.5	82.2	77.7
Silk – weft	75	81.7	77

Degree of penetration

The degree of penetration is strongly influenced by the structure and composition of the fabric, as well as the viscosity of the thickening agent. The results indicate that, in most cases, the penetration degree exceeded 50%. The lowest penetration value was observed on the cotton fabric, where printing paste 1 was applied, while the highest penetration was seen on the cotton fabric where printing paste 3 was used. TBG 1 appears to have a more suitable viscosity compared to TBG 3, which results in a more favourable penetration degree and consequently less dye migration through the fabric.
Our findings show that, based on penetration degree, the use of printing paste 1 and 2 is most suitable for cotton fabrics, while printing paste 3 is more appropriate for silk fabrics. The degree of penetration is summarized in Table 2.

Table 2: Degree of penetration

Degree of penetration [%]			
Sample	**Cotton**	**Wool**	**Silk**
Printing paste 1	33.91	83.06	59.03
Printing paste 2	42.37	81.24	55.96
Printing paste 3	105.73	76.28	60.76

Colour Characteristics

Reflection values of printed cotton, wool, and silk fabrics were measured on the face side in the range of 350–700 nm. Obtained L*, a*, b* and ΔE values are shown in Table 3, while Table 4 shows photos of standard fabric colours and obtained printed colours of all three printing pastes.

- Cotton:
  Unprinted cotton, being white, showed the highest brightness, as expected for white fabric. Printed samples displayed lower *L** values, indicating darker tones. The darkest shade was observed in a sample printed with printing paste, which also had the highest red content. The yellow content was detected in all samples, with the highest in printing paste 3. Colour differences (ΔE) were greatest in printing paste 3, followed by printing pastes 1 and 2.
- Wool:
  Unprinted wool exhibited the highest brightness, with similar L* values across printed samples. The sample, printed with printing paste 2, had the highest green content, while the yellow content was consistent across all samples due to the natural colour of the wool. Wool showed minimal retention of printing pastes, and none of the prints remained effective on the wool fabric.
- Silk:
  Silk, like wool, is a protein fibre and exhibits unique results. The highest green content was found in the sample printed with printing paste 2, while the yellow content remained similar across all samples due to the fabric's natural light-yellow colour. Colour differences in printed silk samples compared to unprinted wool were small and nearly invisible to the naked eye.

Table 3: Colour characteristics of printed samples and standard textiles

Sample	L*	a*	b*	ΔE^*_{ab}
Cotton – standard	93.98	0.27	4.39	/
Cotton + printing paste 1	89.39	1.45	9.94	7.3
Cotton + printing paste 2	91.75	0.57	8.31	4.5
Cotton + printing paste 3	88.32	2.47	13	10.5
Wool – standard	88.75	-0.07	14.68	/
Wool + printing paste 1	87.68	-0.07	16.34	1.9
Wool + printing paste 2	88.19	-0.51	15.91	1.4
Wool + printing paste 3	88.65	-0.43	15.11	0.6
Silk - standard	92.26	0.01	7.96	/
Silk + printing paste 1	87.9	1.2	12.6	6.5
Silk + printing paste 2	90.04	-0.05	11.52	4.2
Silk + printing paste 3	88.04	1	11.02	5.3

Table 4: Photos of obtained colours in comparison with standard fabric colour

	Standard fabric	Printing paste 1	Printing paste 2	Printing paste 3
Cotton				
Wool				
Silk				

4. Conclusion

In conclusion, the study demonstrates that various factors significantly influence the printing performance on textile fabrics, including the type of fabric, the printing paste (TBG), and the printing process. The use of printing paste 3 on cotton fabric resulted in the highest colour retention, while silk fabrics performed well with both printing pastes 2 and 3. Wool fabric showed no colour retention, likely due to its chemical structure, making it unsuitable for printing with the tested printing pastes. The print sharpness was highest with printing paste 2 while printing paste 1 showed the lowest sharpness due to its viscosity. Regarding penetration, the results showed that fabric structure and printing paste viscosity played significant roles, with printing paste 3 achieving the highest penetration on cotton fabric.
Further analysis of antioxidants was conducted as part of the study, though it is not described in detail in this paper. Significant results were obtained, with printing paste 3 showing the best antioxidant properties, even when metal ions were present. Additionally, silk combined with printing paste 3 provided the best antioxidant results. Wastewater analysis showed that a significant portion of the extract was washed out, with cotton retaining more antioxidant properties than silk or wool.
The study also concluded that the most suitable printing paste formulation for printing on cotton was with the addition of alum (ammonium iron(II) sulphate). However, improvements in the printing paste composition are needed for better overall results. While the sharpness and antioxidant properties of the prints were satisfactory, issues like iron contamination in wastewater and penetration rates suggest further optimization is required, especially with respect to the environmental impact and waste management.

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Professional paper

BANANA PSEUDOSTEM SAP FOR IMPROVING UV PROTECTION AND FLAME RETARDANTS OF COTTON FABRIC

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Abstract: *Banana is one of the oldest cultivated plants. It belongs to the Musaceae family and is widely known in human nutrition. However, the pseudostem of the banana plant that remains after one-year pruning needs to be disposed of adequately. In most cases, these are unecological procedures such as burning or disposal in nature, thus creating biowaste that should be avoided as much as possible. For this reason, it is desirable to apply a circular economy model that includes the use of all parts of the plant. The pseudostem of the banana plant is rich in fibers and sap that can be used in textile technology, thus reducing the production of biowaste. This paper investigated the effect of an extract from the banana pseudostem (banana pseudostem sap) for the purpose of improved protection against UV radiation and protection against burning of chemically bleached cotton fabric. After the extraction, the banana pseudostem sap was subjected to evaporation to obtain a dry residue necessary to determine the optimal concentrations to obtain the desired effects. Chemically bleached cotton fabric was treated with two different concentrations of dry extract from the banana pseudostem by the bath exhaustion process. Before the processing itself, the samples were pretreated with metal salt (mordant) potassium aluminium sulphate dodecahydrate* $KAl(SO_4)_2 \cdot 12H_2O$ *in order to better bind the banana pseudostem sap to the fabric. UV protection was measured with a transmission spectrophotometer, while flamability was tested by measuring the limiting oxygen index (LOI), burning rate and micro-combustion calorimeter (MCC). Due to the brown colour of the banana pseudostem sap, the colour parameters of the cotton material were also investigated. Banana pseudostem sap is a valuable raw material for ecological and functional textile processing, which can be used not only as a natural dye for dyeing textile material, but also improving UV protection and burning behaviour of cotton fabric while maintaining the aesthetic qualities.*

Keywords: *banana pseudostem sap, waste, cotton, UV protection, flame retardants*

1. Introduction

Banana is the oldest cultivated plant in the Musaceae family. It is native to Southeast Asia and the western Pacific. It requires warm, sunny places with plenty of moisture, as it is a tropical plant. Given the climate change in recent years, the banana plant can often be seen in home gardens throughout Croatia as an ornamental plant. It can grow to a height of 5 to 12 meters, and consists of a stem called a pseudostem, which consists of a soft central core and tightly wrapped leaf sheaths that unroll from the stem and turn into banana leaves when ripe, then a yellow flower spike at the top of the stem, and fruits that hang like clusters. The above-ground part of the plant is annual, while the perennial stem is located in the ground [1]. For this reason, the banana pseudostem need to be cut every year, and the cut parts become waste. 70 to 80 tons/hectare of pseudostems are discarded and burned annually. In order to prevent excessive waste generation and greenhouse gas emissions, which affect resource scarcity and climate change, few studies have been conducted on the utilization of waste parts of the raw material to contribute to a circular economy [2].
Although the pseudostem of the banana plant contains 80-85% liquid, it is considered an effective organic fertilizer due to higher concentration of NO3-N, NH4-N, K, P, Ca, Mg, Zn, and Fe in it. Phytochemicals such as amino acids, 3-amino-2-naphthoic acid, cyclopentene-1-acetic acid, aminobenzoic acid, etc. are also present, which play a significant role in plant growth [3].
Due to the composition of the sap, waste parts from the banana pseudostem have also found application in textile finishing. Banana pseudostem sap can be used for UV protection [4], flame retardants [5-7], scouring [8-10] and because of yellowish colour of banana pseudostam sap can be used as natural dye for cellulose fabrics [11].

a) b) c)

Figure 1: a) Banana plant, b) banana pseudostam and c) banana pseudostem cross-section

In this work chemically bleached cotton fabric was treated with two different concentrations of dry extract from the banana pseudostem by the bath exhaustion process. Before the processing itself, the samples were pretreated with metal salt (mordant) potassium aluminium sulphate dodecahydrate $KAl(SO_4)_2 \cdot 12H_2O$ in order to better bind the banana pseudostem sap to the fabric. UV protection was measured with a transmission spectrophotometer, while flamability was tested by measuring the limiting oxygen index (LOI), burning rate and micro-combustion calorimeter (MCC). Due to the brown colour of the banana pseudostem sap, the colour parameters of the cotton material were also investigated.

2. Material and methods

Banana pseudostamp was cut into smaller pieces to make extract the sap from pseudostamp required for dyeing cotton fabric. The extraction was performed in a machine to separate the banana pseudostamp sap from the other solid parts of the banana pseudostamp. The extracted sap was evaporatied to obtain a dry extract.

Figure 2: Preparation of banana pseudostem sap

Chemically bleached cotton fabric (CB) produce by Čateks d.d (canvas, 190 g/m^2) was treated with a dry extract from banana pseudostam sap at a concentration of 50 % and 100 % (based on the mass of the material), without (CB_50, CB_100) and with the addition of metal salt (mordant) potassium aluminium sulphate dodecahydrate $KAl(SO_4)_2 \cdot 12H_2O$ (CB_50_Al, CB_100_Al) (Kemika, Zagreb).

2.1 Pretreatmant and treatmant of cotton fabric

Pretreatment of the textile material with metal salt (mordant) was performed with 5 % mordants (based on the mass of the material) in a bath ratio of 1:30 in a Polycolor Mathis apparatus at 50 °C for 30 minutes. After pretreatment with metal salt, the cotton fabric were rinsed with cold water.

Treated cotton fabric with banana pseudostamp sap was performed with a bath ratio of 1:30 in a Polycolor Mathis apparatus at 80 °C for 60 minutes. After treatment the cotton fabric were rinsed with cold water.

2.2 UV protection

UV protection were measured with a transmission spectrophotometer UV/VIS sprektofotometru Cary 50/Soloscreen (Varian) according AS/NZS4399:1996

2.3 Burning and thermal behavior

Burning behaviour of fabrics was determined with Limiting Oxygen Index (LOI) in LOI Chamber (Concept Equipment) according to EN ISO 4589-2:2017 *Plastics — Determination of burning behaviour by oxygen index — Part 2: Ambient-temperature test.*

The burning rate is carried out in Horizontal combustion testing chamber (Concept Equipment) according to HRN ISO 3795:2001, *Road vehicles, and tractors and machinery for agriculture and forestry -- Determination of burning behaviour of interior materials* and the evaluation of the material's resistance to ignition is made on based on burning speed and total burning length. The burning rate in is calculated according to the equations:

$$B = \frac{s}{t} \times 60\ [\mathrm{mm/min}] \qquad (1)$$

where is B – burning rate [mm/min], s – burnt distance [mm] (254 mm for all samples), t – time to burn distance [s]

For better understanding of the change in cotton, thermal properties under the heat Microscale Combustion Calorimeter (MCC) test were done according to ASTM D 7309 on MCC-2, Govmark, USA.

2.4 Spectral characteristics

Due to the brown colour of the banana pseudostem sap, the colour parameters of the cotton material were also investigated using a Spectraflash SF 300 remission spectrophotometer, Datacolor, measuring geometry d/8°, D65, measuring hole size 27 mm. The spectral characteristics (L*, a*, b*, C*, h) of untreated and treateed cotton fabric were determined spectrophotometrically according to ISO 105-J01:1997 *Textiles - Tests for colour fastness - Part J01: General principles for measurement of surface colour.*

3. Results

In Table 1 the UPF values of the treated samples with two different concentration of banana pseudostam sap were presented. From result, it can be concluded that excellent protection against UV radiation is achieved already at banana pseudosam sap with concentrations of 50% based on the mass of the material with or without aluminium mordant. The chemically bleached sample (CB) as well as the sample treated only with aluminum mordant (C_Al) have non-reteable UV protection. Therefore, increasing the concentration of banana pseudostemp sap increases the UPF value, and the protection against UV radiation is better. Also, in samples that have been pretreated with aluminum mordant (CB_50_Al and CB_100_Al), the UPF values increase by 35% compared to the CB_50 sample and by 63% compared to the CB_100 sample.

Table 1: UPF values of treated cotton fabric with banana pseudostamp sap

Sample	UPF	τ_{UV-A}	τ_{UV-B}	Stand. dev.	Stand. err.	UV protection	
CB	11,633	7,529	10,520	1,004	1,245	10	Non-rateable
CB_50	66,157	1,124	2,345	9,375	11,625	50+	Excellent
CB_100	351,512	0,171	0,961	94,715	117,447	50+	Excellent
CB_Al	14,207	5,768	9,117	0,941	1,167	10	Non-rateable
CB_50_Al	89,423	0,746	2,731	34,976	43,371	50+	Excellent
CB_100_Al	574,934	0,102	0,706	165,232	204,888	50+	Excellent

The results of the LOI index and the horizontal burning test are given in Table 2. The chemically bleached untreated sample (CB) has the lowest LOI index, which is expected. Increasing the concentration of banana pseudostem sap increases the LOI index. The highest value has a sample CB_100_Al (LOI 21,6). Samples CB_50, CB_100, CB_100_Al belong to the group of slow burning fabrics, while the others belong to the group of flammable fabric. Treatment with banana pseudostem sap can be used as a treatment for flame retardancy, since the samples glowed during the test.

The highest burning rate in the horizontal burning test has a sample CB_Al (253 mm/min), while the lowest is for CB_100 (142 mm/min). Increasing the concentration of banana pseudostamp sap to 100 % based on the mass of the material, reduces the burning rate and increases the protection by 68% for CB_100 and 58,3% for CB_100_Al compared to untreated (CB). It can be concluded that the aluminum mordant does not affect the burning rate in the horizontal test.

Table 2: LOI and burning rate of treated cotton fabric with banana pseudostamp sap

Sample	LOI [%]	T_{80} [s]	B [mm/min]
CB	17.8	69	239
CB_50	20.0	48	162
CB_100	21.2	57	142
CB_Al	17.8	67	253
CB_50_Al	19.8	49	166
CB_100_Al	21.6	53	151

The thermal properties of the samples after processing by microcombustion calorimeter (MCC) are shown in Table 3. The CB sample has the highest heat release capacity of 226 J/g-K, the maximum specific heat release of 229,4 W/g, the heat release temperature of 383,0°C, the residue yield after pyrolysis of 0,358 g/g, and the specific heat of combustion of combustible gases of 18,37 kJ/g. The CB_100 sample has the lowest heat release capacity of 138 J/g-K, the lowest maximum specific heat release of 138,2 W/g, and the lowest specific heat release of 7,9 kJ/g. From the results, it can be concluded that the CB sample shows the highest heat storage and release capacity, as well as the highest energy value of combustible gases, which makes it the most unsuitable for applications where such characteristics are desirable. On the other hand, the CB_100 sample shows the lowest degree of heat release, which makes it the most suitable in the context of high thermal efficiency. Samples pretreated with aluminum mordant does not affect the reduction of the degree of heat release.

Table 3: MCC test results of treated cotton fabric with banana pseudostamp sap

Sample	**Heat release capacity η_c [J/g-K]**	**Maximum specific heat release Q_{max} [W/g]**	**Heat release temperature T_{max} [°C]**	**Specific Heat release h_c [kJ/g]**	**Yield of pyrolysis residue Y_p [g/g]**	**Specific heat of combustion of fuel gas $h_{c.gas}$ [kJ/g]**
CB	226	229.4	383.0	11.8	0.358	18.37
CB_50	188	185.0	367.9	9.9	0.182	12.10
CB_100	138	138.2	354.4	7.9	0.240	10.39
CB_Al	208	163.6	341.6	12.9	0.074	13.93
CB_50_Al	188	189.2	370.2	9.6	0.180	11.70
CB_100_Al	159	160.0	355.0	8.3	0.154	9.81

The hues of the untreated sample (h°(CB)= 84,29), samples pretreated with aluminum mordant (h°(CB_Al)= 85,27) and all samples treated with banana pseudostem sap are located in the yellow area, more precisely in the first quadrant by angle closer to the b* coordinate, which shows that the hues are brownish. The highest lightness has CB_Al = 93,52, while the lowest is CB_100_Al = 76,83. The colour value (C*) of all treated samples increases with increasing banana pseudostem sap concentration (Table 4 and Table 5).

Table 4: Spectral characteristic of treated cotton fabric with banana pseudostamp sap

Sample	**L***	**a***	**b***	**C***	**h°**
CB	93.17	0.57	5.66	5.69	84.29
CB_50	79.46	2.89	12.17	12.51	76.65
CB_100	76.41	3.55	13.68	14.13	75.45
CB_Al	93.52	0.46	5.57	5.59	85.27
CB_50_Al	82.91	2.30	10.61	10.85	77.78
CB_100_Al	76.83	2.91	12.37	12.71	76.75

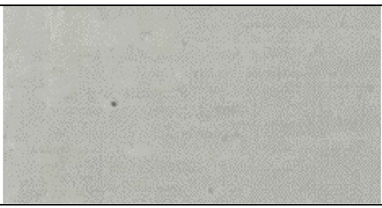
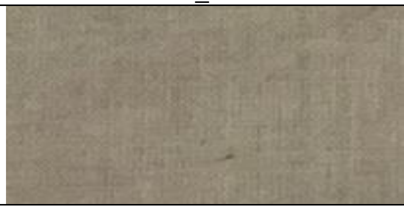
		
CB	CB_50	CB_100
		
CB_Al	CB_50_Al	CB_100_Al

Table 5: Cotton fabric treated with banana pseudostamp sap

4. Conclusion

Banana pseudostem sap is a valuable raw material for ecological and functional textile processing, which can be used not only as a natural dye for dyeing textile materials, but also provides additional UV protection and slows down the burning process while maintaining the aesthetic qualities of the material. Further research into methods for treating textile materials by impregnation of banana pseudostam sap instead the bath exhaustion process is certainly recommended. If the bath exhaustion process is to be continued, further optimization of the bath ratio and extract concentration is recommended, for example BR 1:20 instead of BR 1:30, in order to achieve the better results in terms of protection and aesthetics of textile materials.

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Professional paper

PRESERVING HERITAGE, PROMOTING SUSTAINABILITY: UPCYCLING SLAVONIAN DOWRY TEXTILES INTO OUTERWEAR

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Abstract: *This paper explores the intersection of cultural heritage, sustainability, and textile design by documenting the transformation of vintage dowry textiles from the Slavonian region into modern outerwear. Heirloom carpets and blankets, traditionally gifted in dowries during the past century and valued for their longevity and symbolic status, were reimagined into jackets and coats under the creative vision of student designer Ines Barić. By extending the life of these materials, the initiative conserves resources while preserving cultural narratives and traditions. This paper highlights the historical importance of dowry textiles and their adaptation in contemporary fashion, illustrating how circular practices in design can advance both ecological sustainability and cultural preservation. The initiative also presents selected garments from the Miraz collection, relevant to the theme, showcased through photographs and technical sketches. Repurposing about 20 kg of textiles to create a collection of 15 garments significantly reduced environmental impact by saving resources and avoiding the CO_2 emissions, water use, and energy required for producing new materials.*

Keywords: *Cultural Heritage; Sustainable Fashion; Circular Design; Upcycling; Textile Reuse*

1. Introduction

Fashion design can be a powerful medium for blending cultural heritage with sustainable practices. The textile industry faces significant environmental challenges due to its reliance on petrochemical fibers and water-intensive cotton production, which contribute to CO_2 emissions and resource depletion [1,2,3]. Circular design, which includes textile reuse and recycling, has been identified as a crucial strategy to mitigate these impacts [4,5]. This paper discusses the transformation of vintage dowry textiles from the Slavonian region into contemporary outerwear as an attempt to preserve history as well as the environment.

The term “dowry” refers to the property that a woman or her family delivers to the husband at the time of marriage. Legally, this became the husband's property; however, in practice it often remained in the wife's possession, with the husband acting as its manager. Dowries included a variety of assets, but the most common were textiles, often handcrafted by the bride herself, with intention of showcasing her skills and creativity. For her collection *Miraz*, fashion design student Ines Barić used fabrics that had been part of her grandmother's dowry and were passed down to her as a symbol of family history. Barić's research has shown us that the recycling of old heirlooms into jackets and coats can definitely be the main factor for sustainable fashion through circular design. Barić’s efforts in reusing about 20 kg of vintage fabric to be recycled can only be the way for fashion to run lower the environmental impact of the industry by means of new life to the already existing material and recycling. This paper investigates the potential of projects to promote sustainability while protecting cultural heritage through art-informed methods that connect the past and the future. The paper also presents practical examples from the collection to illustrate these concepts.

2. Methods

This study employed a practice-based research approach, combining qualitative analysis with creative experimentation to explore the integration of cultural heritage and sustainability in fashion design. The methodology can be divided into three phases: material selection, design development / garment creation and documentation.

2.1. Material Selection

The primary materials used for this collection were heirloom textiles inherited from the designer's grandmother, including carpets, blankets and lace doilies, originally part of a dowry from the Slavonian region. The reuse of heirloom textiles aligns with circular economy practices that advocate for reduced waste and resource conservation [6]. The selection aligns with current research that highlights the environmental benefits of reusing and recycling textile waste to reduce the demand for new material production [1,4,5].

2.2. Design Development and Garment Creation

The collection consists of five outfits, 15 garments in total, but this study focuses on three outfits, specifically the jackets, which were developed and designed to highlight the creative possibilities of upcycling dowry textiles into modern fashion. During the design process, pattern-cutting techniques were used to optimize material usage and minimize waste [3,7,8]. This required careful planning to align garment construction with principles of circular design.

Outfit 1 includes a jacket crafted from a vintage blanket alongside other garments, preserves the blanket's original structure and texture for cultural authenticity. The 100% wool blanket originally measured 170 x 140 cm before tailoring (Fig. 1).

Figure 1: Upcycled wool blanket jacket with coordinated pants and shirt

Outfit 2 consists of a wrap coat made from a plush double-bed blanket (240 x 180 cm) with a floral motif, paired with a shirt created from pillowcases. Particular attention was given to preserving the decorative ruffles of the original pillowcases as three-dimensional features in the final design (Fig. 2).

Figure 2: Wrap coat from a plush double-bed blanket with coordinated pants and shirt

Outfit 3 features a jacket constructed from a carpet, with seams reinforced by inserting fringed tape to minimize raw edges. It is paired with a patchwork shirt made from lace curtains and doilies, and an undersized long-sleeve T-shirt designed to compress and gather the lace fabric (Fig. 3).

Figure 3: Upcycled carpet jacket and lace patchwork shirt with compression T-shirt and coordinated pants

2.3. Documentation

The design process and resulting garments were documented through photography and written analysis. Additionally, the environmental impact of the collection was assessed by estimating the reduction in carbon dioxide emissions, water consumption, and energy use achieved by repurposing approximately 20 kg of textiles collected by Barić from her grandmother. Figure 4 shows the fashion technical figure drawings for outfits 2 and 3, illustrating the detailed design and construction of each piece.

Figure 4: Fashion technical figure drawings for outfits 2 and 3

3. Results

The collection *Miraz* demonstrated the feasibility of transforming traditional Slavonian dowry textiles into modern outerwear while preserving their cultural heritage. By upcycling vintage materials like carpets, blankets, and lace doilies, each piece in the collection illustrates innovative methods for incorporating historical craftsmanship into sustainable fashion. This approach aligns with the principles of circular design, as seen in research by Roos et al. [4], which emphasizes enhancing the perceived value of reused materials. The examples presented in this paper underscore how creative reuse can effectively combine sustainability with cultural preservation, a theme also highlighted by Sandin and Peters [5].

3.1. Design Outcomes

The collection *Miraz* features three distinct outfits, each reinterpreting vintage textiles into wearable outerwear while maintaining a connection to their heritage. For instance, Outfit 1 preserved the texture and structure of a vintage blanket, ensuring the authenticity of the original material while adapting it to modern fashion needs. Outfit 2 creatively reimagined a floral-patterned blanket and pillowcases, incorporating their original decorative elements as part of the design. This approach echoes the idea of adding value to reused textiles discussed by Roos et al. [4]. Outfit 3 emphasized both durability and tradition by repurposing a carpet into a functional outerwear piece with symbolic significance. These design choices reflect a holistic approach that balances aesthetic, sustainability, and cultural heritage [9].

3.2. Environmental Savings

The environmental savings from upcycling approximately 20 kg of textiles can be estimated based on life cycle assessment (LCA) data, which is crucial for measuring the environmental impact of products from creation to disposal. LCA studies [4,12,14,15,19] provide clear insights into resource use, emissions, and waste, enabling informed decisions to improve sustainability and reduce environmental footprints, as documented in scientific resources:

1. **CO_2 Emissions:** Studies show that wool production can generate significant CO_2 emissions, with 1 kg of clean wool producing approximately 1.8 kg of CO_2 [10]. Wool carpets tend to have higher emissions due to their weight, ranging from 1,200 g/m² to 5,000 g/m² depending on density [10,11,12]. Upcycling the wool carpet from Outfit 3 (150 cm x 200 cm) saved 9.7 kg of CO_2, while upcycling the wool blanket from Outfit 1 (170 cm x 140 cm) saved about 5.1 kg of CO_2. Additionally, upcycling 5 kg of cotton textiles saved around 10.5 kg of CO_2 [13,14]. These findings support the idea that upcycling reduces emissions compared to new material production.

2. **Water Use:** Approximately 24 260 liters of water were saved. According to Duan (2010) [15], the water footprint of wool is estimated at 2000-2500 liters per kilogram. Studies show that wool's total water use can exceed 10,000 liters per kilogram when considering factors like sheep rearing, feed production, and processing. Cotton is known to consume up to 2700 liters of water per kilogram during its lifecycle, making it one of the most water-intensive materials [15]. It is important to mention that newer estimates place the

global average even higher, around 10,000 liters per kg of cotton, depending on the region and farming practices [16,17].

3. **Energy Use:** Approximately 31.5 kWh of energy was saved. Wool carpets and blankets have varying energy footprints depending on production methods. Wool carpets typically consume around 5 kWh per square meter [18,19], amounting to approximately 15 kWh of energy for a 3.00 m² carpet. A wool blanket (2.38 m²) would require roughly 12 kWh of energy, assuming similar manufacturing processes. Cotton textiles, such as those in Barić's collection (~5 kg), contribute about 4.5 kWh of energy [18]. These estimates underscore the higher energy intensity of wool products compared to cotton, largely due to the specific processes involved in wool processing and textile production.

These metrics illustrate the significant environmental impact reductions achievable through upcycling compared to the production of new materials, as shown in Table 1. Circular design approaches offer a unique opportunity to address cultural, environmental, and economic challenges simultaneously [20,21,22].

Table 1: Environmental Impact of Textile Reuse: Savings in CO_2 Emissions, Water, and Energy according to LCA data

Metric	Wool Carpet (3 m²)	Wool Blanket (2,38 m²)	Cotton Textiles (~5 kg)	Total Savings
CO_2 Emissions (kg)	~9.7 (5.3 x 1.8)	~5.15 (2.86 × 1.8)	~10.5 (2.1 × 5)	~25.35 kg
Water Use (liters)	~6000 (2000 × 3)	~4760 (2000 × 2.38)	~13500 (2700 × 5)	~24 260 liters
Energy Use (kWh)	~15 (5 × 3)	~12 (5 × 2.38)	~4.5 (0.9 × 5)	~31.5 kWh

4. Conclusion

In conclusion, this collection highlights the use of dowry textiles that were passed down to fashion design student Ines Barić from her grandmother as a symbol of family history. In the Balkans, dowry textiles have long been a symbol of family history, showcasing craftsmanship and artistry passed down through generations. They carry deep sentimental value, representing family stories and traditions. By repurposing vintage and upcycled fabrics, the designer has maintained the cultural significance of these textiles while giving them a contemporary look in the form of outerwear pieces. In addition to the cultural and aesthetic value, the designer's approach aligns with the growing movement toward sustainability in fashion, as evidenced by Life Cycle Assessment (LCA) data. Studies show that repurposing vintage textiles significantly reduces environmental impacts, including CO_2 emissions, water usage, and energy consumption, compared to the production of new materials, as shown in this paper. Therefore, by choosing upcycled fabrics, Barić not only preserved family heritage but also contributed to a more sustainable fashion industry. The designer's work was recognized with a second-place award in the *Past2Future Fashion Competition*, which aims to support young designers from the Balkans in exploring the blend of traditional heritage and future-focused design. Additionally, the collection was featured as the cover story in *Gmaro Magazine* for the July issue, Vol. 36, bringing further attention to this innovative concept.

Acknowledgments:

The collection *Miraz* was designed by Ines Barić, a fashion design student at the University of Zagreb Faculty of Textile Technology. The project was developed under the mentorship of Professor Art Jasminka Končić, PhD, and Duje Kodžoman, PhD, senior assistant. The photographs were taken by Stella Mešić, with makeup artistry provided by Marija Soldo, and the model featured is Mia Panić.

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Professional paper

DESIGN OF THE WOMEN'S SHOE COLLECTION INSPIRED BY THE ARCHITECTURE OF PETER EISENMAN

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Abstract: *This study investigate the possibilities of applying Peter Eisenman's principles of architectural design to shoe design. The aim was to connect the architecture and design of the author's shoe collection and to create functional conceptual solutions for women's shoes inspired by the deconstructive principle. In the work, a functional mini-collection of women's shoes was realized, consisting of three developed model samples (prototypes) of shoes of different types and uses. The shoe prototypes are produced as part of industrial shoe production and go through all phases and processes from the initial design concept to the development of the model samples and final production. The overall design concept of the collection presented can be developed further depending on the intended use or special requirements and transferred to the design of men's or unisex shoes for different target groups.*

Keywords: *Deconstructivism, Peter Eisenman, shoe design, model development*

1. Introduction

Design as the conception and creation of new products is present in all branches of production, including shoe production. Shoes are a basic human need and have been protecting feet from dirt, cold and various surfaces for centuries. Throughout history, footwear has evolved from a simple foot covering to a status symbol and has now become an indispensable fashion accessory. Shoe designers play a key role in creating the look, style, colors and patterns of the final product and are also responsible for the comfort and efficiency of the materials. In addition to the artistic vision, designers must also consider the functionality and practicality of the shoes. In addition to the designers, the professionals responsible for the development and production process of shoes include a production manager, a shoe programmer, a pattern maker and engineers [1,2]. The shoe design process is long and complex and often begins with a specific inspiration or idea. The inspiration can come from various sources, e.g. the environment, personal experiences or art. It is important that the inspiration is the result of personal observation and does not come from fashion magazines or the work of other designers Inspiration can be found in museums, galleries, architecture, books, cinema, street culture or everyday life. The theme of the collection comes from the inspiration and is crucial to the presentation of the design. A good theme encourages the development of ideas for the shape, volume and color of the footwear. The inspiration and theme of the design are presented to the team in the concept design, which serves as a guide for the entire team to create and produce a new footwear design

After exploring the chosen inspiration, the shoe design phase follows, where sketches are made and different materials, textures and colors are experimented with to develop conceptual solutions. Every designer has their own approach to drawing, but regardless of style and technique, the goal of drawing shoes is communication, i.e. a visual representation of the design and purpose of the shoes. A drawing or sketch is a tool that is explored and developed, and sometimes the best design solution is only achieved after several attempts. Depending on the purpose of the shoe, designers may use different drawing styles. After selecting the sketches, the designers create project drawings for further development of the ideas. Design drawings are detailed representations of the individual parts of a shoe, including the upper, lining and sole, and serve as a guide for the construction of the shoe [1,3].

The shoe development process is complex and involves several stages. After the drawing, a specification sheet is created that contains all the details about the construction, the materials used, the colors and the technical processes. Before the entire collection is designed, a prototype or test sample of the shoe is created. The prototype allows the designer to see their design in 3D and the team of experts to identify any errors or areas for improvement [2].

2. Experimental

The experimental part of the work consists of the author's conceptual design, conceptual solutions for the women's shoe collection, the development of model samples (prototypes), model making and construction.

2.1 Conceptual solutions for the collection of fashion shoes

The inspiration for the design of the shoe collection was found in the works of Peter Eisenman, an internationally renowned architect and educator. Eisenman's architecture is characterized by deconstructivism, an approach that can be described as breaking up or tearing down the constructed structure. This approach does not stand for a new architectural style or a rebellion against architecture or society, but for the release of the possibility to play with form and volume. The term deconstructivism first appeared in the 1980s as an idea of the French philosopher Jacques Derrida. Eisenman's projects are often characterized by asymmetry and fragmentation, with classical elements overlapping and rotating to create unexpected spatial relationships.His works are based on geometric models, which he translates into architectural works. For Eisenman, form is a field of possibilities resulting from the interaction between internal forces and external constraints. Some of Eisenman's most famous works are House VI in Cornwall, the Connecticut Memorial to the Murdered Jews of Europe in Berlin, and Phoenix College Stadium. House VI is a small building made of plywood, glass and white orthogonal forms, which for Eisenman represents a record of a process rather than an object in the traditional sense. In designing this house, Eisenman used simple patterns that he built one inside the other, creating a hierarchy of relationships. The drawings for House VI show a simple starting point for the design, namely a cube divided into four squares and nine square grid patterns (Figure 1) [4,5].

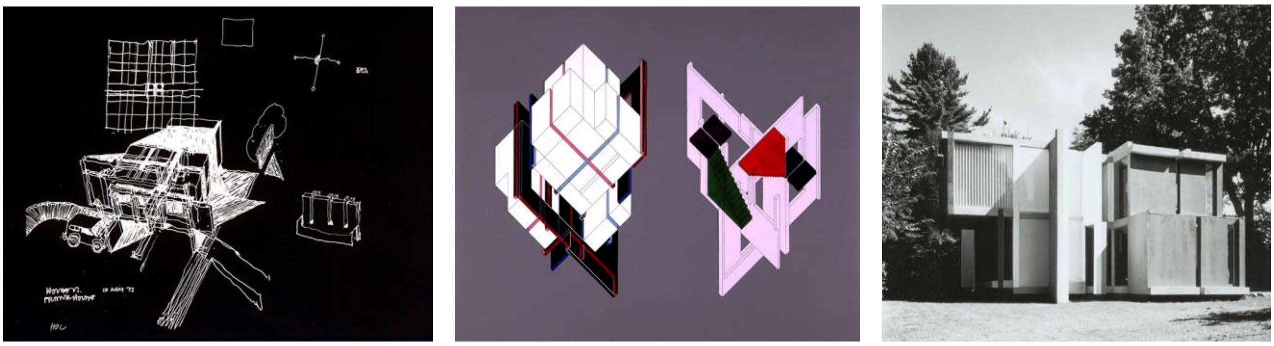
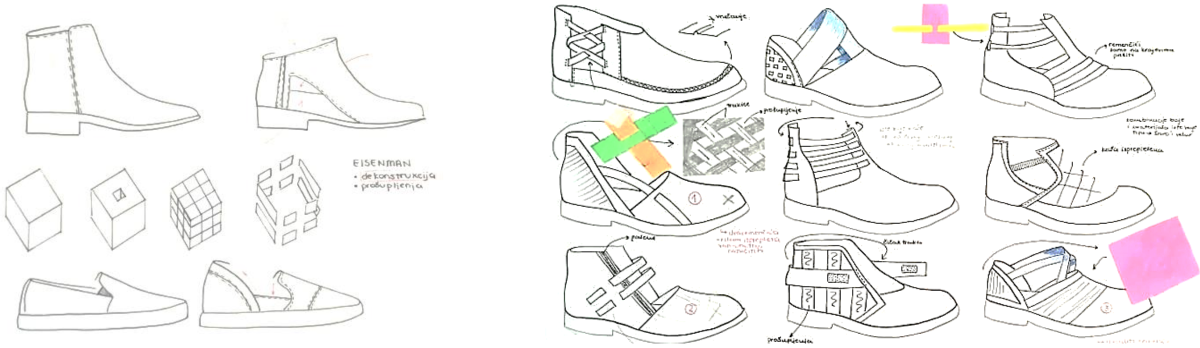


Figure 1: Peter Eisenman House VI Cornwall, Connecticut 1972-1975.; concept, graphics and house [5]

Eisenman designed his building, House VI, based on a cube whose sides he extracted, enlarged, reduced, removed, hollowed out, and thus creating a completely unusual and asymmetrical building that is also functional. The concept of conceptual solutions for women's shoes was inspired by this approach and implemented in a similar way. Classic Oxford shoes and ankle boots, the outlines of which were sketched, replaced the cube. The outline was drawn several times, and the pattern parts were made according to a system of subtraction, hollowing, addition, rhythm change and dynamics, just like the walls in the examples of Eisenman's House VI. The more sophisticated the designs became, the more different ways were found to connect the cut-out parts in interesting and sometimes irregular shapes (Figure 2). The aim was to achieve asymmetrical footwear and a combination of high-fashion design and functionalism [6].



a. b.

Figure 2: Concept design: a. based on the work of P. Eisenman, b. concept sketches for the shoe [6]

In developing the sketches, linear, thinned-out segments, straps and bands were emphasized as the visible link between all the models, running through the holes in different parts of the upper. Three conceptual solutions were selected for implementation and the selection of materials for production began. The choice fell on a traditional material in shoemaking, namely cowhide. Special attention was paid to the color coordination; three different colored leathers were chosen for each model, which contrast and harmonize with each other. For the first ankle boots the colors yellow, red and black were chosen, with the black color matching the black sole (Figure 3a). For the second model, which is based on the basic cut of the Oxford shoe, the colors green, purple and violet were chosen (Figure 3b).. For the third model, a sneaker, pastel shades of turquoise, purple and pink were chosen (Figure 3c).

a. b. c.

Figure 3: Conceptual solutions: a. ankle boots, b. shoes, c. sneakers [6]

2.2 Construction and modeling of a mini collection of shoes

Based on the conceptual solutions developed for the planned creation of a mini shoe collection, the appropriate molds and soles were selected according to the type of footwear. Based on the selected shapes and soles, as well as the appropriate built-in parts (assembly hub, toe cap), the construction of the upper cut parts is carried out. For the construction of footwear, it is necessary to make an average copy of the mold, i.e. the three-dimensional shape of the mold is transferred to a flat surface. A copy of the mold is made by sticking the mold with paper tape on which the circumference of the fingers, the center of the mold and 2/3 of the heel are marked. Then the inner and outer copies of the mold are removed, which are then glued to stable paper, and an average copy of the mold is made, on the basis of which the creation of the model basis and construction is started [7]. The upper model parts are constructed on the model basis and since the models are asymmetrical, both the outside and the inside are drawn on the construction and the seams are marked. Figure 4 shows the mold, copies of the outside and inside of the mold and the construction for the first model, the ankle boots.

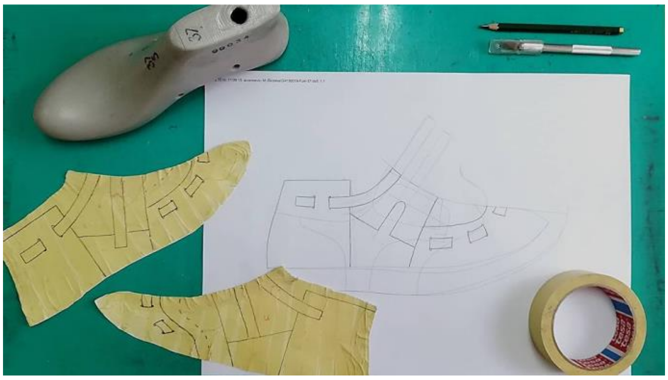
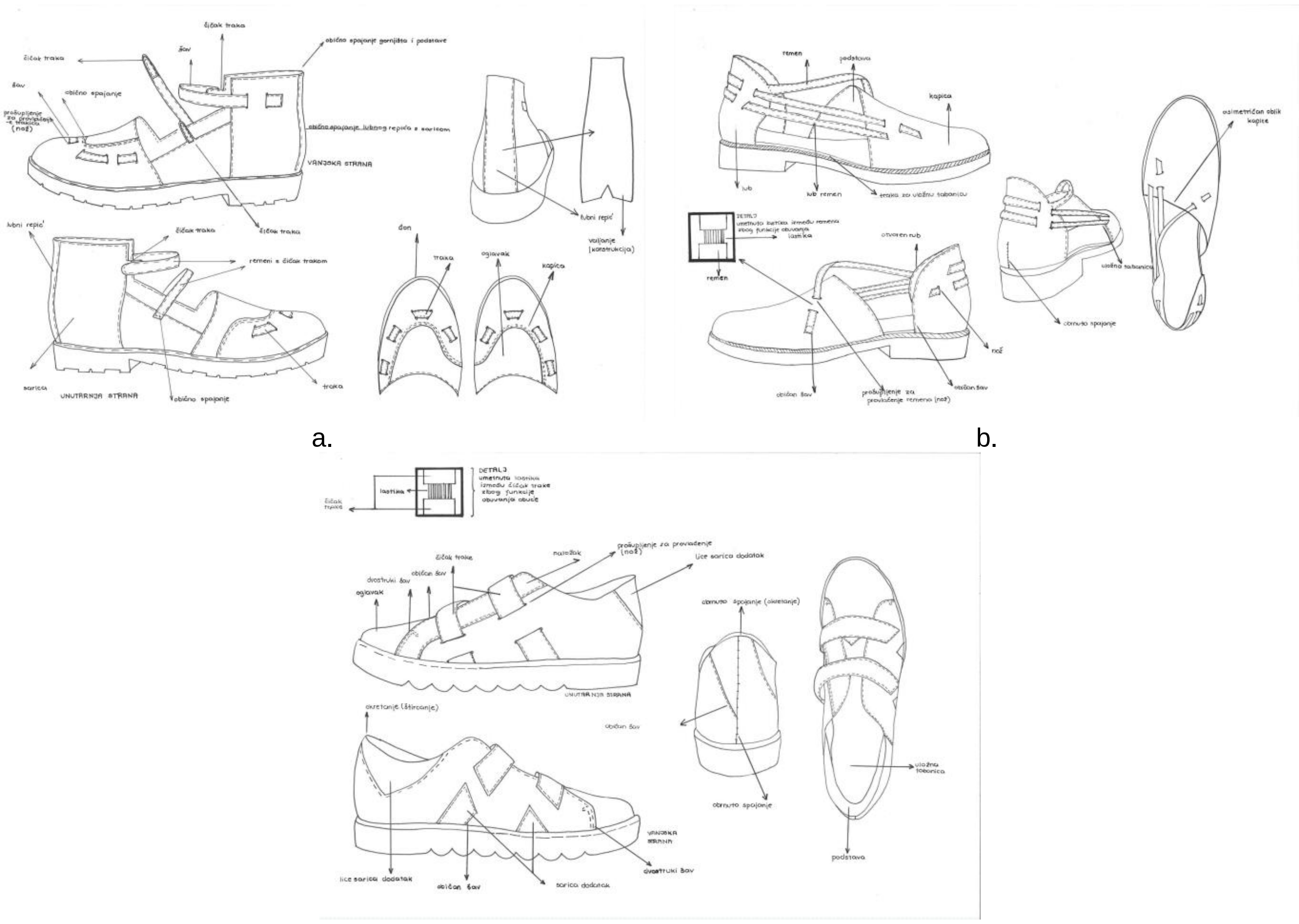


Figure 4: View of the mold, external and internal copies of the mold and the finished construction of the prototype of the ankle boot [6]

When the construction is completed, the next step is to make the project drawing. These are precise and clear technical representations with several views (external and internal profile, front and back). In the drawings, the idea is presented in detail, the cuts, auxiliary materials and connection methods are clearly defined and additional technological information is provided. The project drawings serve as an important means of communication within the team during the preparation and prototyping phase.



a. b.

c.

Figure 5: Project drawings of the prototype of women's shoes: a. ankle boots, b. shoes, c. sneakers [6]

3. Results

The process of shoe development continues with the creation of a prototype, which is produced according to the industrial phases of shoe production in the tailoring, sewing, assembly and finishing phases. Some phases used in the production of women's shoe models are innovative because they are not typical of mass production and are not commercial. In the first model, the caps of the left and right shoes are different colors, although they are one pair (Figure 6a). In the second and third models, there are elastic bands between the front of the belt and the face cutout (Figure 6a,b). The elastic bands have the function of tightening the shoes, but are not visible on the finished product as they are located under the notched holes through which the straps run.

a.

b.

c.

Figure 6: Innovative way of inserting the elastic due to the functionality of putting on the shoes a) gluing the elastic between the front of the belt and the waste of the front; b) template for the technical marking on the elastic; c) belt detail on the finished product [6]

The realized prototypes of a mini-collection of women's shoes - shoes, ankle boots and tennis shoes - are shown in Figure 7.

Figure 7: The realized prototypes of a mini-collection of women's shoes; ankle boots, shoes, and tennis shoes

4. Conclusion

Peter Eisenman's exploration of deconstructivism and the principles of architectural design led to the combination of architecture and design in the shoe collection. The result is functional conceptual solutions for women's shoes that are inspired by the principle of deconstruction.

The realized mini-collection of women's shoes has an attractive design, consisting of three developed model samples (prototypes), which were produced within the framework of industrial shoe production according to all stages and procedures from the initial design idea through the overall development of the model samples to the final production. Innovative steps based on complex constructions or detailed design solutions, which are not common in industrial shoe production and are not characteristic of mass production, were used in the production of the shoes. The first model pattern is a different color of the cap inside a shoe, and in the second and third models, an innovative detail is the elastic band, which is used for the functionality of putting on the shoes, but is not visible on the finished product, as it is located under the notched holes in the skin through which the elastic band passes.

The overall design concept of the women's shoe collection presented in the work can be further developed depending on the intended use or special requirements and transferred to the design of men's or unisex shoes for different end consumer target groups.

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Professional paper

DIGITAL TECHNOLOGIES TO REDUCE TEXTILE WASTE IN CLOTHING INDUSTRY

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Abstract: *Traditional clothing technologies tolerate 15-25% textile waste in the production process. Using commercially available digital tools it is possible to improve garment designing and manufacturing phases and with it to reduce amounts of still generated pre-consumer fabric waste. Using 2D and 3D designing software zero waste design or flexible design concepts could be used. Management software for the clothing industry significantly improve material requirement planning, material inventory and cut planning processes and reduce the largest part of the fabric waste obtained in the manufacturing phase of garments. New generation interlining fusing presses eliminate fabric shrinkage and with it material waste which is obtained by adding material buffers around fused cut components in markers.*

Keywords: *pre-consumer fabric waste, digital technologies, 3D designing software, management systems, cut planning software, fabric shrinkage*

1. Introduction

Traditional clothing production technologies put the main emphasis on improving the efficiency and productivity of the work process, the quality of finished products, but tolerate the occurrence of certain textile waste in the production process. Most textile materials are manufactured as 2D products that have a certain width and certain length. However, most of the cut components from which 3D garments are made have complicated 2D shapes and their mutual fitting on a flat 2D material surface without material waste is practically impossible [1]. That is the main reason why the largest part of pre-consumer textile waste is created by cutting the garment components. Next to these objective reasons of waste generation in the clothing industry, there used to be also subjective ones - ungrounded purchase of raw materials, weak material inventory system, and inefficiently planned work process in a cutting room. Currently, due to mentioned objective and subjective reasons, the fashion industry tolerates 15-25% of high-quality fabric pre-consumer waste [1,2].

2. Digital tools to reduce pre-consumer textile waste

2D designing, marker making and grading software are already widely and long-time use. Different kind of management software and 3D designing software are also know however still less utilized by garment manufacturers. Cloud-based software which unites all separate software for clothing designing and manufacturing phases in one system, could be the most effective to improve product quality, work efficiency, as well as reduce maximally pre-consumer material waste.
Seven possible improvements to reduce fabric waste using commercially available digital tools will be described in the paper (see Table 1):

- two improvements in garment designing phase - influencing and reducing objective reasons of the textile waste,
- five improvements in garment manufacturing phase - reducing subjective reasons of the textile waste.

Table 1: Possible improvements to reduce fabric waste using commercially available digital tools

	Improvements to reduce pre-consumer fabric waste	Work methods	Digital tools used
		The designing and garment development process	
1.	Designing garments that eliminate textile waste	Developing garments using zero waste design (ZWD) concept	2D and 3D designing software
2.	Creating flexible design of clothing items	Using certain flexible constructive parameters that can be changed within the tolerance intervals making markers for production orders.	The cloud-based software which unites pattern making and grading, visualisation of 2D patterns as 3D real size garments and also cut planning software.
		Manufacturing process	
3.	Purchase of precisely calculated necessary quantities of materials	Eliminating the purchase of extra material that is used in case of its quality problems or due to an inefficient planning of material spreading process	• Material requirement planning software
4.	Improvement of marker efficiency	Finding the most efficient combinations of ordered garment sizes and mutual positions of garment components in each marker	• Raw materials inventory software • Cut planning software
5.	Usage of the maximum width of the material in each roll	Recording the width of each roll and when different widths appear, creating markers for each separate group of materials with different widths	• Raw materials inventory software • Cut planning software
6.	Reduction the amounts of unused material at the end of the rolls	Creating the most efficient material spreading plan for each production order, taking into account the precise length of material in each fabric roll	• Raw materials inventory software • Cut planning software
7.	Elimination of the necessity to use buffers around the garment components that will be fixed with fusible interlinings	Using new generation fusing presses that ensure fusing interlinings without shrinking of the material	• Fusing presses with extended heating chambers and digital control of fusing parameters

3. Garments created using zero waste design concept

ZWD refers to the practice of designing garment styles so that their components arranged on a piece of fabric do not create any material waste (or this waste is used creating other products) [3,4]. As pre-industrial societies treated fabric as a precious resource, national clothing of many countries, such as Egypt, Greece, Rome, India, Japan and Korea are good samples of zero waste design [5]. In today's fashion industry the zero waste design aims can be reached using three methods: fabric draping method, knitting garments or using specific 2D pattern making principles. In case of 2D pattern making the garment, components are consciously shaped so that curves of one component (necklines, armholes, others) match to curves of the next placed components to cover entire fabric surface. Shaped lines can be also replaced by pleats, darts and gatherings, to create 3D shapes using straight lines of the components (see Fig.1) [3]. As the shape of each component has a direct effect on the other one nearby, designing and pattern making are thought out simultaneously.

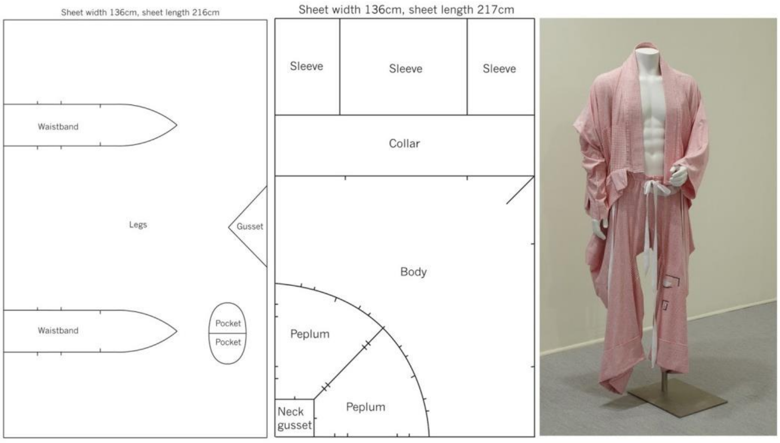


Figure 1: Zero-waste patterns for pyjamas by Timo Rissanen [6].

Such creative designing process can be supported by different 2D and 3D designing software like: Modaris 3D by Lectra, AccuMark 3D by Gerber, PDS 3D Optitex, CLO 3D by CLO, VStitcher by Browzwear, Tuka 3D by Tukatech, 3Dress by Morgan Technica. However, currently the method is very much challenging for fashion designers as it demands specific knowledge and experience. The traditional grading methods cannot be used to obtain more than one size of a ZDW garment style - changing (enlarging or reducing) size of pattern pieces it will not be possible to create other markers with zero material waste.

4. Garment styles with flexible design using tolerance intervals

It is well known that marker efficiency and with it amounts of pre-consumers material waste obtained in the cutting room is influenced by two factors – the shapes of pattern pieces and their mutual placement. Currently, the industry is using different software to find the most efficient mutual placement of pattern pieces on the fabric. Further improvements of used methods to create even more efficient placement of pattern pieces in markers is practically impossible [2]. Till now there have been no methods created to influence fabric use efficiency with the second important factor – the shapes of pattern pieces. However, experiments have showed that the original design idea can be kept unchanged using slightly different values of certain construction parameters, for example, widening and length of certain garment styles (see Fig.2), [7,8,9]. But, when changing the values of any construction parameter, the shapes of pattern pieces change too, and with it, hundreds of new possibilities to place pattern pieces on the fabric appear. The values of these flexible construction parameters should be used at certain tolerance intervals in which the visual perception of the style does not change. The tolerance intervals have to be determined by the designer of the style and used later in its manufacturing process [7,8,9]. Simple forms of such method is already used by industry when in material lay planning process it is noticed that some styles create unacceptable fabric waste. Then minimal changes in a constructive solution of the style are performed to improve marker efficiency and with it eliminate unacceptable material waste.

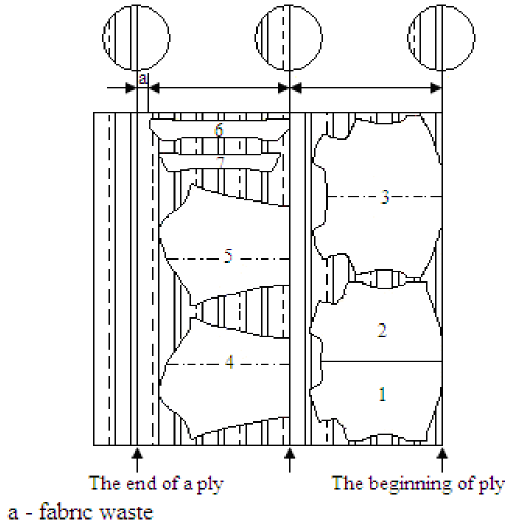
Figure 2: The principle of the widening reduction for a bell skirt.

The use of tolerance intervals for the length of garments is also advisable creating sectional markers for striped and checked fabrics (Fig. 1a). They could help to reduce or eliminate material waste which appears

because of the necessity to produce all goods with the same coordinated pattern. Such markers always have to be started at the same position of the fabric pattern repeat. Often, because of this demand, a certain part of fabric in all its width has to be cut off creating serious material waste [8,9] (see Fig.3).
To find tolerance intervals and use them later in the production process of garment styles a cloud-based software should be created from following parts:

- pattern making and grading software (Modaris by Mectra, AccuMark by Gerber, PDS 2D by Optitex, TUKAcad by Tukatech, Pattern Designer and Nest expert by Kuris, and many others)
- visualization of 2D patterns as 3D garments (Modaris 3D by Lectra, AccuMark 3D by Gerber, PDS 3D Optitex, CLO 3D by CLO, VStitcher by Browzwear, Tuka 3D by Tukatech, 3Dress by Morgan Technica, others),
- cut planning software (Flex Offer by Lectra, AccuPlan by Gerber, CutPlan by Optitex, Mastermind by Morgan Technica, Cut Planner by Gemini, FKAD Wom Plan by FK Group, Spread&Cut Planner by Kuris, Cut Planning by Polygon, others).


a.



b.

Figure 3: Separate sections of laid fabric (a) and a sectional marker for striped material b)

5. Efficient material requirement planning, material inventory and cut planning processes

Ungrounded purchase of raw materials, weak material inventory system and inefficiently planned work process in a cutting room are the main reasons for fabric waste obtained in garment production process (see Table 1). Companies often purchase extra amounts of fabrics to save production in case of material quality problems and imprecisely calculated needs for raw materials. Most often unused roll ends accumulate in warehouses without their further inventory and use. In case of width difference in fabric rolls, the markers are created for narrowest ones. The extra width of the wider rolls is cut off in full their length creating long strips of fabric waste [10].

5.1. Management systems for clothing industry

Described problems can be successfully eliminated using management systems specially developed for the clothing industry [11]. The main part of such software is its centralized database. It ensures the possibility to view and edit style, inventory, labour, costing, an order, cut planning and manufacturing information. The data is transparent and easily available for all members of authorized staff. Often the management system also includes material requirement planning software. Optimal material purchase is calculated using a set of special techniques and data from the database - previous bills of material and production orders, as well as current inventory data.
The management systems include two inventory systems: finished goods inventory and raw material inventory. The raw materials inventory system is able to transfer and maintain inventory levels between different warehouses and contractors. The system ensures information about raw materials on-hand, ordered

raw materials, raw materials in work process, available inventory amounts, as well as raw material utilization and raw material requirements.
Based on inventory data, cutting orders or finished goods requirements, material purchasing software can automatically generate a purchase order for needed items and post them directly to suppliers. Thus, materials are delivered just before their processing. There is no need to do long term purchases of regularly used materials, such as, interlinings, elastic bands, packing material, labels creating risks of accumulation of unused material waste.

5.2. Cut planning software

The part of the management system coordinating the work process in a cutting room is a cut planning software. It links together ERP (Enterprise Resource Planning), fabric management system, CAD and CAM, exchanges information in between these systems and creates the best solutions to cut material for manufacturing orders in a maximally efficient way with minimal material waste. Currently the most well-known cut planning software is: Flex Offer by Lectra, AccuPlan by Gerber, CutPlan by Optitex, Mastermind by Morgan Technica, Cut Planner by Gemini, FKAD Wom Plan by FK Group, Spread&Cut Planner by Kuris, Cut Planning by Polygon, and others.

5.2.1. Methodology

Cut planning software imports customer orders from internal or any external system. It runs different cutting plan scenarios (markers and their combinations) to see their impact to the fabric use, cutting time, productivity and choose the best of them. Defining which markers are necessary for the order it creates the optimal cutting plan. To perform the created cutting plan the system firstly selects (using material inventory data) fabric rolls that can be 100% consumed then it takes those pieces that result in the least end and width loss. If reusable fabric remnants appear, they can be used, giving preference to the smallest pieces. Most important steps of the automated cut planning process are: running of different planning scenarios, establishing the marker processing time, performing marker calculations, spreading planning and processing of manufacturing reports.

5.2.2. Running of different planning scenarios

After the user fills up all necessary order data (order quantity for each fabric type, fabric, initial marker and spreading settings), the program tries all possible size combinations in markers. Based on a model information and marker library (data from previously used the same or similar styles) the program estimates length and efficiency of every yet uncreated marker. Finally, the program selects and displays the best marker combinations for a certain order.

5.2.3. Establishing the marker processing time

The yet uncreated markers are classified by their importance depending on the number of sizes in a marker, lies in a spread and garment pieces produced from the marker. More time to find the best fabric consumption is given to progress the most important markers. Marker progressing time can be determined automatically (the program distributes the time for each marker considering the marker's size) or semi-automatically (the user can indicate how much time he wants the program to spend for each marker).

5.2.4. Performing marker calculations

Getting ready markers back from CAD, the program obtains the exact length and the efficiency of every performed marker. The fabric amount needed to produce the order is calculated now using data of marker length. The available info is also used to calculate statistics regarding average fabric use per product, per fabric type or total, fabric input, total average efficiency, etc.

5.2.5. Spreading planning

Trying to respect the maximum number of fabric plies in the lay, the program generates all spreads. Fabrics with similar properties are grouped together for one spread to reduce spreading time. If a disproportionate number of layers (a very small number) appears for separate spreads, the program can make automatic balancing.

6. Elimination of fabric shrinkage fusing cut components with interlinings

Material shrinkage fusing adhesive interlinings is one more problem that generates pre-consumer fabric waste. The main reason for fabric shrinkage is a heat or thermal shock that occurs when the material is exposed to a sudden and rapid change in temperature. It causes structural stress and irreversibly changes the properties of the material. Fabric shrinkage can complicate or prevent joining of fused cut components with other parts of a garment [12,13]. Traditionally, to eliminate this problem a certain amount of material (buffer) is added around the contours of the cut components or their blocks in markers (see Fig.4,5) and two step cutting is performed [10.12]:

- the first step - the components that will be fixed with an fusible interlining or their blocks are cut larger, with a buffer of 10 – 30 mm (see Fig.4,5),
- the second step - after fixing the interlining, fine cutting of the components is performed and the excess material left after fabric shrinkage is cut off.

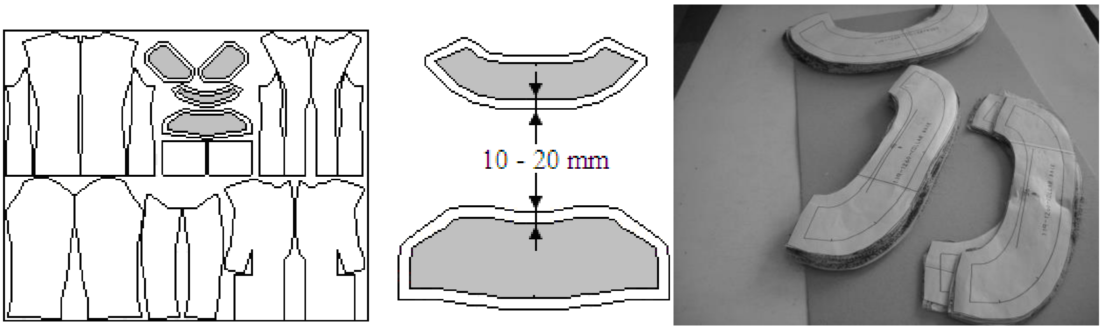


Figure 4: Material buffer added around the contours of the cut components

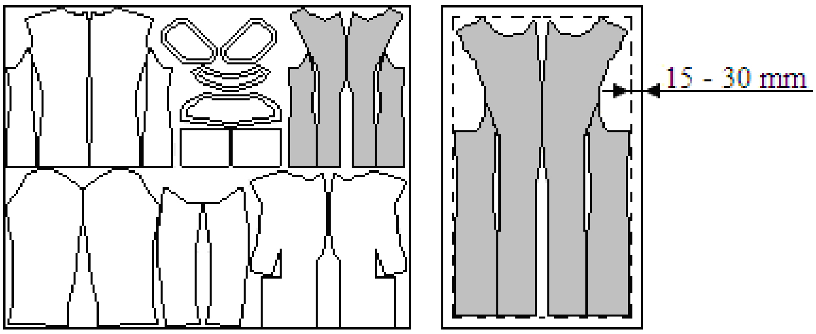


Figure 5: Material buffer added around the blocks of cut components

Further use of these irregularly shaped narrow cut off strips is impossible. Their recycling is also difficult - the adhesive of the interlining complicates the separation of fibers during mechanical recycling, and the different origin of the fibers in a base material and an interlining, as well as the presence of the adhesive complicates their chemical recycling.
To avoid fabric damage and shrinkage while fusing interlinings the heating temperature has to be raised gradually extending material heating time. This can be ensured using an advanced continuous work process fusing presses with long heating chambers and a very sensitive digital heating system [12,13]. In the work process of such fusing press, the cut parts of the garments and their interlinings are placed on the conveyor belt which brings them into a heating chamber with several - five, seven, even nine, twelve individually controlled heating zones (see Fig.6). During the operation of the press, each zone has its own temperature, and with that, it heats the cut components and the interlinings gradually and over a longer period. In addition, the temperature of the upper zones that heat up interlining and the lower zones that heat up the base fabric can be set differently depending on the properties of these different materials. Extended heating time and gradual temperature rise ensure qualitative fusing at lower temperature and without fabric shrinkage or any other damage.

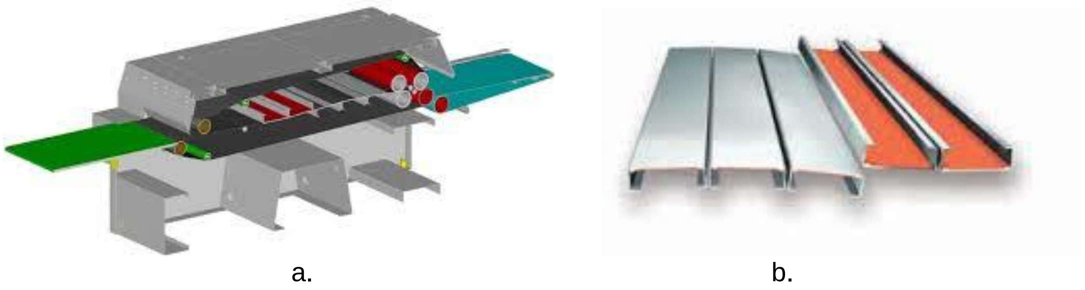


Figure 6: Schematic picture of a fusing press by company VEIT (a) and 3 heating elements for a base fabric with 3 hearing elements for an interlining of a cheating chamber (b)

Advanced fusing presses with long heating chambers and digitally controlled heating systems are manufactured by many companies, most well-known are: VET-Group (Germany), Meyer (Germany), The Marin Group (Italy), Oshima (Taivan).

7. Conclusions

Clothing industry tolerates 15-25% textile waste which is generated because of objective and subjective reasons in the garment designing and manufacturing process. Currently available digital technologies can help successfully to reduce pre-consumer material waste generated in garment manufacturing phase. With the help of management systems for the clothing industry, material inventory and work process planning in a cutting room have to be improved to increase material use efficiency. New generation fusing presses with digital heat control systems can eliminate fabric shrinkage and with-it textile waste obtained fusing interlinings. There are also possibilities to reduce objective reasons of material waste obtained in the clothing designing phase. The design of the garment style should become more dependent on its further manufacturing conditions. Designers should use zero waste design or flexible design concepts to eliminate material waste or make it maximally minimal.

Acknowledgments
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Professional paper

DESIGNING KNITTED FABRICS INSPIRED BY BIOMIMETICS

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Abstract: *This paper explores the field of biomimetics in textile design, specifically focusing on the application for creating innovative knitwear patterns that mimic forms found in nature. By investigating the integration of biomimetic principles in knitting, this paper aims to illuminate the innovative and sustainable possibilities that arise when nature becomes a mentor for design. The paper further addresses the integration of biomimetic principles into knitwear patterns, which can lead to the development of unique textures, shapes, and surfaces. The principles will initially be explained based on comparisons with forms found in nature, and then through the works of artists such as Neri Oxman, a renowned designer and architect exploring the intersections between nature and technology; Iris Van Herpen, known for her avant-garde fashion creations that often draw inspiration from organic forms found in nature; and Japanese knitting pioneer Issey Miyake. This research on knitting techniques is based on a series of variations inspired by porous structures from nature, with a particular focus on wooden and botanical patterns observed through microscopic lenses. A collection of knitted samples was produced on a flat knitting machine, mostly using both needle beds.*

Keywords: *Knitwear, biomimetics, nature, technology, pattern*

1. Introduction

Plant tissues and cells often exhibit unique patterns when viewed under a microscope. Similarly, certain loops in knitted fabrics create textures reminiscent of the arrangement of plant cells. The way plant fibers are organized in microscopic images can resemble the lines formed by different patterns of knitted loops. For example, ribbing has a vertical arrangement that may remind one of the fiber arrangement in plant tissues.

Drawing inspiration from microscopic images of the plant world and then experimenting with various loop variations, color combinations, and yarn finesses is crucial for finding the best combinations that evoke qualities transferred from the microscopic world into knitwear.

The very word "biomimetics" is derived from the Greek words "bios" (life) and "mimesis" (imitation), encapsulating the essence of this scientific discipline. The origins of biomimetics can be traced back to ancient civilizations, where observations of natural forms led to the development of various technologies and inventions. The term "biomimetics" was coined in the 1950s by American biophysicist Otto Schmitt [1]. He used this term to describe the process of using biological systems as models for engineering and design solutions. This marked the formal recognition of biomimetics as a distinct scientific discipline. The invention of Velcro, attributed to Swiss engineer George de Mestral, is actually an example of biomimetics within the sphere of textile design [1].

2. Contemporary biomimetic research in textiles

Contemporary biomimetic research inspires today's scientists, engineers, and designers to explore natural solutions to complex challenges.

Neri Oxman, an architect, designer and inventor, has made a significant impact on the world of design by seamlessly merging art, science and nature through her groundbreaking work in the field of biomimetics. Her innovative approach, founded on the belief that nature, as the ultimate innovator, offers a vast treasure trove of solutions that can be used to solve contemporary challenges, has gained international recognition and revolutionized the way we think about design, materials and sustainability. By studying natural systems and organisms, she seeks to emulate not only their beauty, but also their efficiency and functionality [2]. Her project, "Silk Pavilion", demonstrated how silkworms can form architectural structures by naturally responding to environmental signals. This project exemplifies the potential of biomimetics to create living, responsive environments that coexist harmoniously with nature [3].

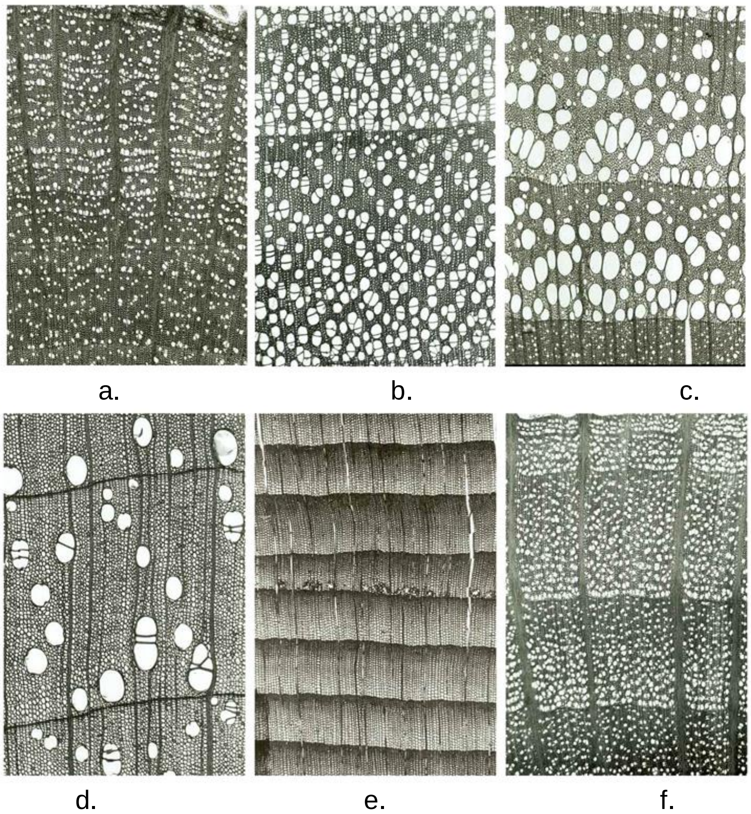
Iris van Herpen's work is an example of the successful integration of art and science. Her fascination with biomimetics is evident in the way she embraces the organic forms, patterns and textures found in nature. By carefully observing organisms such as plants, animals, and microorganisms, he translates their details into designs. Her designs prioritize the use of environmentally friendly materials and processes [4].

Issey Miyake is known for his innovative and unique approach to knitwear. He has created a variety of knitwear pieces that incorporate his signature design aesthetic, which often involves experimenting with knitted fabrics and textures. Notable examples of Issey Miyake's knitwear include "Pleats Please" and "A-POC (A Piece of Cloth)" [5].

3. Experimental

The final design, pattern, texture, and appearance of a knitted product are influenced by a multitude of factors. Each of these elements interact to create a unique and visually appealing finished piece. The type of yarn used has a significant impact on the final product. The fineness of the yarn, as well as the color, significantly affect the final outcome. The patterns and hues in nature are a testament to the aesthetic mastery of evolution. Design can mimic these patterns, creating textiles that are not only visually captivating, but also grounded in nature's artistic sensibilities.

The pattern is determined by the way the loops are created during the knitting process. The pattern determines the texture and appearance of the knitted fabric [6]. Produced using two needle beds, these knitted fabrics have visible face and back loops when stretched. Working on both needle beds allowed for simultaneous manipulation of the front and back surfaces of the textile and a wide range of creative possibilities for texture. The cross-sectional patterns of different types of wood (Fig. 1) are an inspiration that has been transferred to the knitted fabrics using different knitting techniques [7].



a. b. c.

d. e. f.

Figure 1: Inspiration: cross-sectional patterns of different types of wood; a. Ribes alpinum L.; b. Populus alba L.; c. Hippophae rhamnoides L.; d. Betula alba; e. Abies alba Mill.; f. Ribes rubrum L. [8]

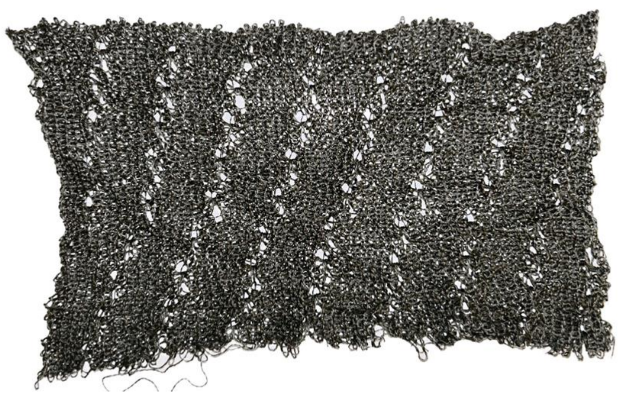
Ribbed knitted fabrics consist of a number of rows of face and back loops, resulting in a characteristic vertical striped appearance. Ribbed knitted fabrics have a vertical arrangement of loops that can resemble the arrangement of fibers in plant tissues (Fig. 2). Typically, this type of knitted fabric is used extensively for collars and hems of clothing because of its excellent stretch and recovery properties. Garments made from this structure fit well to the body and are usually designed to do so.

a.

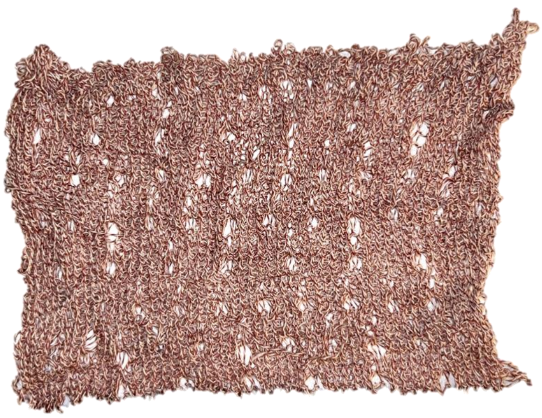
b.

Figure 2: Weft double-faced knitted fabrics; a. single-sided ribbed pattern in green wool yarn, fineness 70 tex; b. single-sided ribbed pattern, plaiting in light green wool yarn, fineness 70 tex and dark green wool yarn, fineness 70 tex [7].

A tuck pattern refers to a specific knitting technique where two or more yarns are placed on the hook of a knitting needle and a tuck is created. The result is a recognizable type of interlacing that adds texture to the knitted fabric. By experimenting with the arrangement of tuck and plain loops, a wide range of unique textile designs can be achieved (Fig.3).



a.



b.

Figure 3: Weft double-faced knitted fabrics; a. the opening created with a tuck loop, tuck shifted by one needle in each new row, in dark green wool yarn, fineness 70 tex; b. the opening created with a tuck loop by randomly selecting needles, in cotton yarn of fineness 50 tex [7].

Tuck knitted fabrics created by leaving the knitting needles open for several consecutive courses, usually 4 to 8, creates a creased effect (Fig. 4). These creased knitted fabrics are the result of manipulation of the knitting process where, unlike with traditional knitting where the needles are closed after each course, the needles remain open for several consecutive courses.

Figure 4: Weft double-faced knitted fabric, tuck loops created by alternating 3 and 5 tuck loops on the same needle, in green wool yarn of 70 tex, cotton yarn of 50 tex, and dark green wool yarn of 70 tex fineness [7].

Eyelet knitting is a technique used to create fabrics that have intentional holes, imitating plant tissues. The loops are transferred from one needle to another, creating gaps or holes [6]. By controlling the pattern and frequency of transfers, a variety of designs can be created, from subtle textures to more pronounced mesh patterns (Fig 5).

a.

b.

Figure 5: Weft double-faced knitted fabrics; a. combined plain and eyelet pattern with horizontal stripes in 50 tex cotton yarn and 70 tex wool yarn; b. combination of eyelet and float pattern in 50 tex cotton yarn and 70 tex wool yarn and horizontal green stripe in 70 tex wool yarn [7].

Wavy knitted fabrics are double-faced knitted fabrics that involve creating a wavy pattern on one surface (Fig. 6). The wavy pattern is achieved by a combination of knitting on both needle beds then just one needle bed. Double jersey is knitted in a certain number of courses on both needle beds, followed by a certain number of single jersey courses using one needle bed [8].

a.

b.

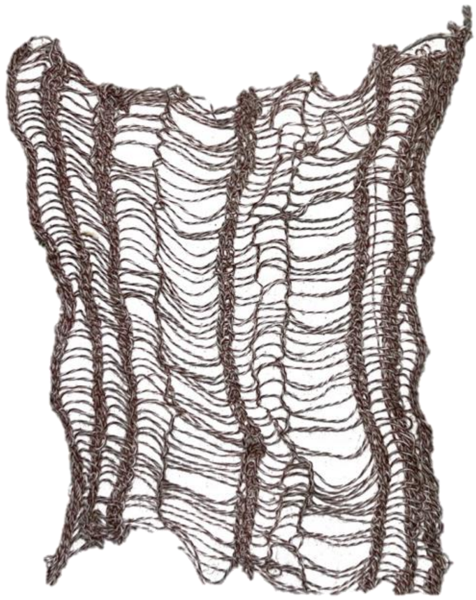
Figure 6: Weft double-faced knitted fabrics; a. double jersey and wavy pattern in green wool yarn of fineness 70 tex; b. double jersey and wavy pattern in cotton yarn of fineness 50 tex [7].

Jacquard pattern refers to a knitting technique that creates more complex multi-colored patterns and designs on a knitted fabric. In jacquard pattern, depending on the design, one yarn floats while the other knits loops of the intended design on the face of the fabric, in this case inspired by plant structures (Fig. 7).

Figure 7: Weft single-faced knitted fabric, single-bed two-color jacquard in dark and light green wool yarn, fineness of 70 tex [7].

Depending on the method of floating the yarn, knitted fabrics can imitate spiderweb shapes. Floatings are created by laying the yarn over needles that do not form loops, allowing it to "float" before being knitted again over a certain number of needles, Fig 8, [9].

a.



b.

Figure 8: Weft double-faced knitted fabric; a. pattern with floatings of light green wool yarn of fineness 70 tex, cotton yarn of fineness 50 tex, and dark green wool yarn of fineness 70 tex, in horizontal stripes; b. pattern with floatings of cotton yarn of fineness 50 tex [7].

4. Conclusion

Through the application of biomimetics in the creation of knitted fabric, this experiment shows the importance of cooperation between nature and technology. By imitating patterns from nature, textiles are created that are not only aesthetically appealing, but also functional and sustainable. The collaboration of human creativity and the ingenuity of nature paves the way for a future where ecological awareness and technological innovation merge to create textile products that are in harmony with the aesthetic and sustainable principles of nature.

This paper explored various knitting techniques, including single-sided and double-sided weft knitted fabrics in variations of tuck, pleat, rib, wave, jacquard and eyelet patterns. Each of these patterns has its own characteristics and contributes to the variety of textile designs, unique textures, and surfaces inspired by plant structures.

Ultimately, this work illustrates how biomimetics can enrich textile design, opening new horizons for creativity and sustainability in the fashion and textile industries.

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