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RHEOLOGY OF FLUIDS IN TEXTILE COATING PROCESSES: A GENERALIZED APPROACH

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Abstract: *Surface coating and thin film formation processes are critical stages determining product performance across numerous industries, including coatings, textiles, electronics, and biomedicine. Although classical coating theories are generally established upon Newtonian fluids with constant viscosity, some of the modern industrial inks, polymeric solutions, and suspensions exhibit rheological behaviors that deviate from Newtonian characteristics. Particularly, many coating materials used in the textile sector fall into the category of non-Newtonian fluids. However, this theoretical foundation is not sufficiently taken into account in industrial textile coating processes. Applications in industrial production are generally carried out based solely on initial viscosity measurements and process conditions. The extent to which operating conditions change the rheological properties of the fluid throughout the process is also vital for coating processes. This study reviews the effects of non-Newtonian fluids on the coating processes of textile substrates through rheological models and application cases. Within the scope of the study, the effects of parameters such as shear rate, temperature and pressure on viscosity were initially analyzed, and the viscosity variation of non-Newtonian fluids is modeled on the basis of the Power Law model. Research indicates that static viscosity values alone are insufficient for optimizing coating quality; instead, the rheological responses at application-specific shear rates must be accurately modeled. In this context, this study moves beyond traditional 'initial viscosity' measurements, presenting a roadmap for a rheological modeling-based optimization approach.*

Key words: *textile, coating, rheology, non-newtonian fluids, shear rate* **.**

1. INTRODUCTION

Surface coating and thin film formation constitute dynamic processes that determine the final properties of a material. Therefore, a detailed investigation of the rheological models of the fluids used in these applications is of great importance. A wide range of fluids with distinct rheological behaviors are utilized in textile coating applications. Over the past years, research on shear-thickening fluid (STF) coated textiles has progressed from early studies on Kevlar-based fabrics for ballistic protection to advanced applications in woven structures. The initial phase established STF's role in high-energy impact absorption, lateral researches emphasized spacer fabrics, composites, and simulation-based modeling. The latest studies focused on multifunctional protective textiles, integrating artificial intelligence-driven performance prediction. This evolution highlights the transition of STF textile research from defense-oriented applications to broader industrial and high-performance protective innovations The success of these processes is directly related to the science of rheology, which examines the deformation and flow characteristics of the employed fluid. In addition to STFs, various types of non-Newtonian fluids are also utilized in textile coatings. A thorough analysis of the rheological behaviors of these fluid types is essential for the standardization of high-quality products in industrial-scale production.

During coating operations, the fluid is subjected to varying mechanical stresses at different stages such as pumping, spreading, leveling, and drying. Therefore, defining the relationships among the fundamental characteristics of the fluid—namely shear rate (γ), shear stress (τ), and viscosity (μ), which is a measure of resistance to flow—is of critical importance.

2. RHEOLOGICAL BEHAVIOR AND CLASSIFICATION

Fluids are generally classified into two primary categories, Newtonian and non-Newtonian, based on their response to applied shear stress. In Newtonian fluids, the viscosity remains constant, being independent of the shear rate.The schematic representation of a Newtonian fluid in laminar flow between two layers separated by a distance dy is illustrated in Fig. 1. Under steady-state conditions, when a shear stress is applied to the fluid by a force F, it is balanced by an equal and opposite internal frictional force within the fluid. The shear stress ($\frac{F}{A}$, τ_{yx}) is defined as the product of the shear rate ($-\frac{\mathrm{dV}_x}{\mathrm{dy}}$, γ_{yx}) and the viscosity of the fluid medium (μ). For Newtonian fluids, this relationship is mathematically expressed in Equation 1 [1].

$$\frac{F}{A} = \tau_{yx} = \mu\left(-\frac{\mathrm{dV}_x}{\mathrm{dy}}\right) = \mu\gamma_{yx} \quad (1)$$

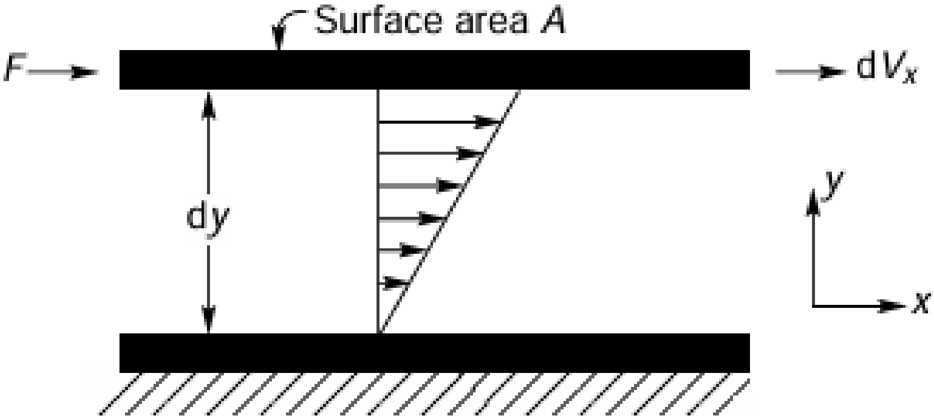

***Fig. 1**: Schematic representation of unidirectional shearing flow*

However, the majority of modern coating formulations exhibit non-Newtonian behavior, giving rise to a more complex rheological response.

2.1. Dynamic Parameters Influencing Viscosity

In coating processes, viscosity is not solely governed by shear rate; surrounding environment and time-dependent effects also play a critical role in defining the flow regime:

- **Temperature Effects:** An increase in temperature reduces intermolecular interaction forces, resulting in a decrease in viscosity. This temperature–viscosity relationship is commonly described by the Arrhenius model. Precise temperature control during coating operations is therefore essential for accurate regulation of film thickness and uniformity.
- **Pressure:** Although frequently neglected, pressure effects become significant in high-pressure spraying and extrusion coating processes. Elevated pressure can reduce the available free volume within the fluid, leading to an increase in viscosity.
- **Shear Duration (Time-Dependent Flow Behavior):** Certain fluids exhibit time-dependent viscosity variations even under constant shear conditions. Thixotropy refers to a progressive decrease in viscosity over time due to microstructural breakdown, whereas rheopexy describes a time-dependent increase in viscosity resulting from structure buildup. Following coating application, the thixotropic recovery rate is a critical parameter governing the material’s ability to rebuild its internal structure and remain adhered to the surface without flowing or sagging [2].

2.2.Non-Newtonian fluid behaviour

The viscosity of non-Newtonian fluids varies depending on the magnitude or the duration of the external force applied to the fluid. In contrast to Newtonian fluids, the relationship between shear rate and shear stress is non-linear; thus, these materials do not adhere to the linear Newtonian Law of Viscosity. The viscosity of such fluids may exhibit variations that are either time-independent or time-dependent in nature [1].

2.2.1. Time-independent fluid behaviour

Time-independent fluids are characterized by the fact that the shear rate at any given point is determined solely by the shear stress at that point. These fluids can be classified into three categories: shear-thinning (pseudoplastic) fluids, viscoplastic fluids, and shear-thickening (dilatant) fluids.

In shear-thinning (pseudoplastic) fluids, viscosity decreases with increasing shear rate. However, this behavior may vary at extreme shear rates. Many shear-thinning polymer solutions exhibit Newtonian behavior at both very low and very high shear rates.

In the case of viscoplastic fluid behavior, materials possess a certain yield stress that must be exceeded for flow to commence. As long as the applied stress remains below this threshold, the material does not exhibit fluid-like behavior and instead behaves as a solid body. Once the required yield stress is exceeded, materials that display a linear flow curve are referred to as Bingham plastics and are characterized by a constant plastic viscosity. In contrast, materials that do not exhibit a linear flow relationship beyond the yield point are classified as yield-pseudoplastic materials.

In shear-thickening or dilatant fluid behavior, viscosity increases with increasing shear rate. Although less commonly encountered than other fluid types, concentrated suspensions of kaolin [3], metal oxide [4], and cornstarch [5] in water can be given as examples of this category.

The flow curves of fluids exhibiting time-independent behavior are presented in Fig. 2 [1].

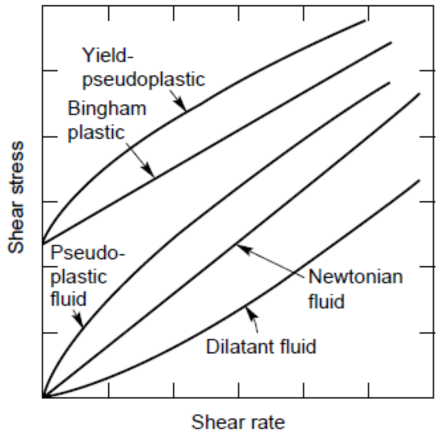

***Fig. 2**: Time-independent Fluids*

2.2.2 Time-dependent fluid behaviour

The flow behavior of many fluids used in industry cannot be described solely on the basis of shear rate. In materials exhibiting time-dependent flow behavior, viscosity varies as a function of the duration for which the fluid is subjected to a constant shear. As discussed among the dynamic parameters influencing viscosity, the decrease in viscosity with increasing duration of shear exposure is referred to as thixotropy, whereas an increase in viscosity over time is defined as rheopexy [1].

3. MATHEMATICAL MODELS OF VISCOSITY IN NON-NEWTONIAN FLUIDS

In non-Newtonian fluids, viscosity is not constant and varies as a function of shear rate, shear stress, and, in some cases, time. To describe this complex behavior, several mathematical models have been developed. These models aim to capture the relationship between shear stress (τ) and shear rate (γ) under different flow conditions.

One of the most widely used models is the **Power-Law (Ostwald–de Waele) model**, which expresses the shear stress–shear rate relationship in Equation (2).

$$\tau = K\gamma^{n} \tag{2}$$

Here, n is referred to as the power-law index (or flow behavior index), while K denotes the consistency index. For shear-thinning fluids, n < 1, whereas for shear-thickening fluids, n > 1 [6].

4. FORCE BALANCE IN FLUID COATING PROCESSES

The fluid coating process is essentially a fluid in motion. The net force acting upon a given volume is defined by the rate of change of momentum of the fluid surrounding it at any instantaneous moment (specifically, the sum of the momentum flux integrated over the entire control surface and the rate of change of momentum within the volume).

The net force F_x acting in the x-direction on a fluid element moving with the velocity of the fluid is the sum of the force due to the weight of the volume element (body force) F_{xB} and the force resulting from the stresses acting upon it along the x-axis, F_{xS}, as shown in Equation 3. The same expression is defined for a differential mass element as in Equation 4. Here, u_x denotes the velocity of the fluid element in the x-direction; ρ is the density of the fluid element; g is the acceleration due to gravity; β is the angle the fluid element makes with the x-axis; t represents time; and τ_{xx}, τ_{yx}, τ_{zx} define the stress components acting in the x-direction [6].

$$F_x = F_{xB} + F_{xS} \tag{3}$$

$$\rho\frac{\mathrm{du_x}}{\mathrm{dt}} = \mathrm{g}\cos\beta + \left(\frac{\partial\tau_{xx}}{\partial x} + \frac{\partial\tau_{yx}}{\partial y} + \frac{\partial\tau_{zx}}{\partial z}\right) \tag{4}$$

Determination of Coating Thickness

Coating thickness varies depending on the application method, viscosity, applied force, the gap distance between the substrate and the applicator, density, and velocity. Taking blade coating as a representative example, the coating thickness (W) is calculated as shown in Equation 5. Here, h defines the height between the blade and the surface, η represents the fluid viscosity, σ denotes the surface tension of the fluid, ρ signifies the fluid density, g is the acceleration due to gravity, and u_0 defines the coating velocity.

$$W = \frac{h}{2} + \frac{1}{12\eta}\left(\frac{\sigma}{2h^2} + \rho g\right)\frac{h^3}{u_0} \tag{5}$$

In blade coating, the coating thickness is fundamentally equivalent to half of the blade gap; however, an additional minor term is incorporated, which is directly proportional to the surface tension and the gap width, while remaining inversely proportional to the fluid viscosity and the line speed [6].

5. COATING METHODS ACCORDING TO FLUID PROPERTIES

The application of fluids onto textile surfaces can impart a wide range of functional properties to the material. These properties vary depending on the type of fluid applied, including coloration, water repellency, flame retardancy, and antibacterial activity.

Various methods can be employed to coat textile surfaces with different fluids, such as knife coating, roller coating, dip coating, and spray coating. [6].

5.1. Newtonian Fluids and Textile Coating

In Newtonian fluids, viscosity is independent of the shear rate. More clearly, the fluid viscosity remains constant throughout the process. It is not affected by the application speed. In the textile industry, these are generally encountered in low-viscosity solutions, dyes, and simple polymeric finishes. Application is generally performed using well known dip coating method at foulards, as illustrated in Figure 3.

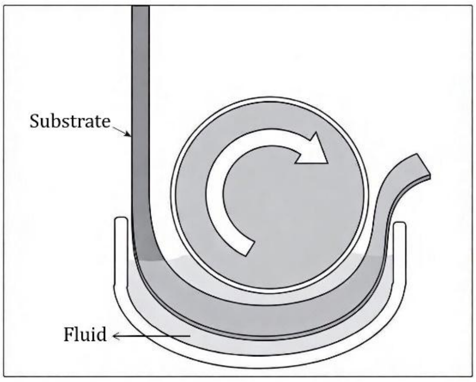

Fig. 3: *Application example of dip coating*

5.2. Shear-Thinning Non-Newtonian Fluids and Textile Coating

In the textile industry, coatings applied using shear-thinning fluids include those based on polyurethane [7], PVC [8], acrylate [9] and polyacrylamide systems [10].These coatings can be applied through various coating techniques. Due to the reduction in viscosity with increasing application rate, such fluids can more readily penetrate into the fabric structure.

Although numerous coating applications utilizing shear-thinning fluids are present in the literature, very few studies specifically address their rheological behaviors. For instance, in their study, Karim et al. (2021) examined the utilization of shear-thinning, non-Newtonian xanthan gum solutions alongside Newtonian polyethylene glycol (PEG) solutions in curtain coating processes, systematically assessing the resultant coating performance. For the assessment of coating performance, the contact line, air entrainment, air bubble formation, and heel (buildup) formation were taken into consideration.

While heel formation at low speeds and air entrainment at high speeds were observed in Newtonian liquids, air entrainment was significantly delayed in non-Newtonian liquids. Heel formation initiated at lower speeds as the concentration increased (as viscosity rose). The maximum operable flow rate increased with viscosity. Shear-thinning prevented air entrainment by reducing viscous bending near the contact line [11].

5.3. Shear-Thickening Non-Newtonian Fluids and Textile Coating

The development of shear-thickening fluid (STF) coated textiles has followed a distinct trajectory over the past two decades, reflecting both technological advancements and evolving application demands. In the early phase (2000–2015), research was primarily directed toward Kevlar-based fabrics and ballistic protection, establishing STF impregnation as a viable strategy for enhancing energy absorption and mitigating high-energy impacts. This foundational work laid the groundwork for subsequent investigations into the protective potential of STF-treated textiles. During the middle phase (2016–2020), the scope of research expanded to include spacer fabrics and composite structures, with particular emphasis on numerical simulation and performance modeling. These studies provided deeper insights into the mechanisms of impact resistance and structural stability, thereby broadening the scientific understanding of STF–textile interactions. In the most recent phase (2021–2026), attention has shifted toward advanced applications in woven fabrics, integrating artificial intelligence-driven performance prediction and multifunctional protective capabilities. This progression underscores the maturation of STF textile research, transitioning from defense-oriented ballistic studies to versatile industrial and protective fabric innovations that combine mechanical robustness with adaptive functionality.

Shear-thickening fluids (STFs) represent advanced colloidal suspensions that enable the transition of textiles from passive protective materials to dynamic, impact-responsive systems, owing to their intrinsic capacity to absorb and dissipate mechanical energy. An STF system generally consists of two main phases:

- **Solid Phase (Dispersed Particles):** Silica nanoparticles constitute the predominant solid-phase component in shear-thickening fluid formulations. Additionally, calcium carbonate, corn starch, or polymer spheres (PMMA) can be utilised. Particle size (generally between 100 nm and 500 nm) and concentration determine the degree of fluid hardening.
- **Liquid Phase (Carrier Medium):** The liquid phase serves as the dispersing medium for suspended particles. Polyethylene glycol (PEG) is most commonly employed in textile and defense-related applications due to its non-volatile nature, thermal stability, and favorable physicochemical interactions with silica nanoparticles.

Numerous studies in the literature focus on the coating of textile products for defense applications. Egres et al. (2005) investigated the resistance of shear-thickening fluids (STF) composed of silica nanoparticles and polyethylene glycol (PEG) specifically against cutting tools. Aramid fabric was utilized as the substrate in their study. The STF materials were applied to the fabric through a dip-coating and soaking process, followed by drying. The shear rate of the fluids was kept constant at 20 s^{-1}. Upon completion of the application, the amount of STF on the fabric increased the fabric weight by 20%. The results of the study indicated an improvement in cut resistance across all fabric samples [12].

In a study conducted by Yanen et al. (2024), STFs were prepared by dispersing materials such as silica, silicon carbide, carbon nanotubes, and graphene in PEG, which were then applied to Twaron fabric using the dip-coating method. Subsequently, ballistic tests were performed on the fabrics. Fabrics coated with a 5% weight addition exhibited superior performance compared to untreated fabrics [13].

6. DISCUSSION AND CONCLUSION

There are many processes in the textile industry, such as finishing, functional treatment, dyeing, printing, and coating, where materials are exposed to and treated with a fluid. Particularly in traditional textile coating processes, essential information regarding the coating material is limited with fluid’s viscosity, and it is usually assumed that viscosity remains constant. Many fluids used in coating processes are non-Newtonian, and their viscosity generally changes during the procedure.

Wheras in shear-thinning processes—where viscosity decreases with movement—process conditions should be evaluated individually, and standards should be established accordingly for different operating conditions. Studies on STFs show that application on fabrics is generally performed using the dip-coating method. Although the increase in viscosity in moving systems brings application challenges, studies should be conducted to determine optimum application speeds to enhance the applicability and effects of these materials.

Research on STF-coated textiles is expected to advance toward multifunctional protective systems that combine mechanical robustness with adaptive responsiveness. Emerging directions of STF coated textile products include the integration of nanostructured fillers to optimize rheological behavior, the use of artificial intelligence for predictive modeling of coating performance, and the development of hybrid textile architectures that enhance flexibility without compromising protection. Furthermore, future studies are expected to address long-term durability, scalability and the environmental sustainability of STF formulations. Transition from laboratory-scale innovations to widespread industrial applications is another rising expectations to built such novel product platforms of medical protective gear, sports equipment, and aerospace textiles.

In this context, for coating applications, not only the initial viscosity but also the complete rheological behavior of fluids must be analyzed according to variable operating parameters such as temperature, shear rate, and time. These evaluations, based on rheological modeling, are a necessity for achieving industrial consistency and standardization.

REFERENCES

[1] R. P. Chhabra and J. F. Richardson, *Non-Newtonian Flow in the Process Industries: Fundamentals and Engineering Applications*. Butterworth-Heinemann, 1999.

[2] H. A. Barnes, J. F. Hutton, and K. Walters, *An Introduction to Rheology*, vol. 3. Elsevier, 1989.

[3] E. Hong, C. M. Herbert, A. M. Yeneneh, and T. K. Sen, "Rheological characteristics of mixed kaolin–sand slurry, impacts of pH, temperature, solid concentration and kaolin–sand mixing ratio," *International Journal of Environmental Science and Technology*, vol. 13, no. 11, pp. 2629–2638, 2016.

[4] M. Wei, K. Lin, and L. Sun, "Shear thickening fluids and their applications," *Materials & Design*, vol. 216, p. 110570, 2022.

[5] E. E. Bischoff White, M. Chellamuthu, and J. P. Rothstein, "Extensional rheology of a shear-thickening cornstarch and water suspension," *Rheologica Acta*, vol. 49, no. 2, pp. 119–129, 2010.

[6] A. K. Sen, *Coated Textiles: Principles and Applications*. CRC Press, 2007.

[7] A. Patti and D. Acierno, "Structure-property relationships of waterborne polyurethane (WPU) in aqueous formulations," *Journal of Vinyl and Additive Technology*, vol. 29, no. 4, pp. 589–606, 2023.

[8] J. H. Eun, M. S. Kim, S. M. Sung, B. K. Choi, I. U. Jang, D. Kim, and J. S. Lee, "Effect of the viscosity of polyvinyl chloride resin and weaving structures of polyester fabric on the off-axis mechanical properties of PVC coated fabric," *Journal of Industrial Textiles*, vol. 51, no. 2_suppl, pp. 2897S–2920S, 2022.

[9] P. A. Williams, Ed., *Handbook of Industrial Water Soluble Polymers*. Oxford: Blackwell Pub., 2007.

[10] F. Davard and D. Dupuis, "Blade coating of fabrics: rheology and fluid penetration," *Coloration Technology*, vol. 118, no. 2, pp. 69–74, 2002.

[11] A. Mohammad Karim, W. J. Suszynski, S. Pujari, L. F. Francis, and M. S. Carvalho, "Contact line dynamics in curtain coating of non-Newtonian liquids," *Physics of Fluids*, vol. 33, no. 10, 2021.

[12] R. G. Egres Jr, M. J. Decker, C. J. Halbach, Y. S. Lee, J. E. Kirkwood, J. E. Kirkwood, et al., "Stab resistance of shear thickening fluid (STF)–Kevlar composites for body armor applications," in *Transformational Science And Technology For The Current And Future Force: (With CD-ROM)*, 2006, pp. 264–271.

[13] C. Yanen, M. Y. Solmaz, and E. Aydoğmuş, "Application of single and multi-solid phase STFs to Twaron fabrics: evaluation of energy absorption performances," *The Journal of The Textile Institute*, vol. 115, no. 12, pp. 2391–2402, 2024.

ANNALS OF THE UNIVERSITY OF ORADEA
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A BRIEF REVIEW OF DEVELOPMENT OF SENSORS AND SHIELDING IN MEDICAL REHABILITATION SYSTEMS

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Abstract: *The development of wearable devices for medical recovery has led to an increase in interest in sensor systems capable of continuously monitoring the patient's functional parameters. This aspect has led to the creation of textile sensors integrated into wearable applications, which are capable of measuring the body's vital parameters, which are necessary for identifying various movement stages, such as gait or limb motion, as well as for the continuous and accurate monitoring of parameters such as pulse rate, or the continuous and precise verification of values such as those of the pulse. Also, the accuracy of the recorded data can be influenced by electromagnetic interference from the surrounding electronic environment, which can lead to signal noise and decrease in the fidelity of the measurements.*

Key words: *smart textiles, human motion analysis, composite sensor, screens, interference.*

1. INTRODUCTION

The increase in the number of strokes has led neuromotor recovery therapies to adopt much more precise systems for monitoring vital parameters, but also configurations that are included in wearable applications so that they do not add additional weight or create injuries to the user. In response to these challenges, these studies focused on sensor systems based on smart textiles or on systems from the soft robotics industry. The integration of sensors into wearable textile applications shifted the visual monitoring performed by the medical staff to a continuous, real-time one, where the systems can provide quantitative information on joint angles [1], strength [2], muscle activity [3] or compensatory movements developed by the patient during the execution of motor tasks [4].

The development of electromagnetic shielding (EMI shielding) for medical recovery systems has seen a significant technological advancement in the period 2024–2026. The focus has shifted from rigid (metal) solutions to flexible, lightweight and biocompatible materials, essential for wearable monitoring equipment, rehabilitation robots and magnetic/electrical stimulation devices.

Yang et al. [5] analysed shielding materials with multiple functions: self-healing, thermal management and fire resistance, which are essential for the safety of long-lasting physiotherapy equipment. Absorption shielding is highlighted, instead of the reflection of waves, an element that helps reduce the effects of electromagnetic radiation. Xu et al. [6] highlighted the use of conductive polymers and the key factors that are used in the selection of conductive polymers, the design of chemical devices and the architecture of devices are highlighted. As materials used, hydrogels, elastomers and conductive composites are mentioned.

Another direction of research is given by the development of smart textiles that protect cardiac or muscle monitoring sensors against interference in the hospital environment. For this, smart biocomposites are used to monitor the structural condition. The challenges and prospects for the conversion of smart biocomposites are highlighted [7]. The aim is to directly integrate biocomposites into compression garments used in physical therapy but also to reduce negative influences (radiation, noise, etc.) in the treatment rooms.

Therefore, the development of devices for medical recovery requires a complex, component-based approach, in which sensor systems provide information on movement, force or bioelectrical activity, and electromagnetic shielding materials ensure the functional compatibility of these systems in real-world environments. The correlation of the two directions thus becomes essential for the realization of wearable systems capable of combining comfort, measurement accuracy and signal quality. This paper aims to study medical recovery systems that have integrated elements from the smart textile industry both for the monitoring process of vital parameters and for the protection of electromagnetic interference between devices and integrated electronic circuits.

2. SENSOR SYSTEMS USED IN MEDICAL RECOVER

Zhou et al. [8] developed a composite sensor based on graphene, TPU (thermoplastic polyurethane) and textiles with good properties in terms of electrical conductivity, UV resistance and durability over time. As a development principle, this sensor was based on the integration of a graphene-based conductive material into an elastic textile substrate sealed with a flexible polymer.

The textile substrate was obtained by knitting fibers with 90% acrylic and 10% Spandex in the structural composition. The conductive layer was obtained from graphene oxide [8]. From a functional point of view, the sensor has the ability to transform the deformation produced by the flexion-extension movement of the foot joint into variations of electrical resistance measured to correlate these values with the value of the angle of the joint. After calibration, this system was able to be included in a muscle training system where patients could control a character in a video game. The configuration proposed by the authors demonstrates the ability of this wearable system to accurately measure the angle of the knee by processing electrical signals in angular positions with the help of prior calibrations, so that it can be included in the medical recovery process with wearable devices.

In another paper [9], the authors aimed to create a system that can be positioned on the body capable of providing measurements on the movement of the joints, with emphasis on two relevant quantities in the functional analysis of the hand, namely the angle of flexion and the force exerted during movement. These two characteristics are important for characterizing the stages of motion, as they reflect both the amplitude of motion and the capacity to generate force. In this regard, the proposed solution consisted of a hybrid, self-powered sensor system that combines triboelectric and piezoelectric principles to overcome the limitations of conventional sensors, such as low sensitivity, the influence of environmental factors or the need for external power.

The triboelectric sensor is sensitive to deformation and allows the bending angle to be monitored, but its performance can be affected by environmental conditions and wear. In contrast, the piezoelectric sensor exhibits an adequate response to force variations, but is limited in sensitivity and signal-to-noise ratio. By combining these into a composite architecture, the system becomes able to distinguish between geometric deformation and mechanical stress, making it suitable for monitoring applications in neuromotor rehabilitation. The triboelectric sensor was used to determine the flexion angle and was made of Ecoflex. Its structure has two electrodes positioned on the same surface of the elastic layer. The resulting electrical signal is directly correlated with the bending angle, increasing with it.

The piezoelectric sensor was intended for force monitoring and was made of a layer of PVDF-HFP (polyvinylidene fluoride-co-hexafluoropropylene) electrospun nanofibers doped with BaTiO3 and PEI (polyethyleneimine) nanoparticles, having PEDOT:PSS (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) electrodes deposited on both sides. It provides an electrical response correlated with the applied force, allowing the separation of information related to mechanical stress from that associated with geometric deformation. The testing carried out was possible with the help of 20 volunteers, indicating small variations in the signal, with a margin of error of approximately 0.1–0.5 %, which supports the feasibility of using the system in the monitoring of neuromotor rehabilitation.

Lo Presti et al. [10] proposed a study on the development of a sensor system intended to identify the movement of the muscles at the trunk level. The authors developed a system of seven flexible sensors, based on the signal transmission behavior of an optical fiber, to monitor the additional movements performed by the patient as a result of spasms.

From a structural point of view, the system consists of an assembly of seven flexible sensors based on FBG (FBG – Fiber Bragg Grating), integrated into a wearable structure positioned along the spine, from the cervical to the lumbar area. These sensors were connected to an optical interrogation unit, responsible for detecting variations in reflected wavelength, as well as to a data acquisition and processing system. The choice of FBG sensors is justified by their high sensitivity to deformations, mechanical flexibility and the ability to measure variations distributed along a surface, which allows the faithful capture of trunk movements without restricting the user's mobility [10].

The operating principle is based on the modification of the wavelength reflected by the optical fiber following its deformation, a phenomenon that occurs as a result of the stretching or compression generated by the movement of the trunk. Thus, the movements of the body cause variations in the optical signal, which are subsequently correlated with the amplitude and direction of movements. This approach allows the transformation of biomechanical movements into signals, providing an indirect but accurate method of evaluating motor behaviour [10].

The evaluation of trunk movements was carried out using kinematic landmark sensors and a MoCap motion capture system, which served as a reference for the validation of the system based on FBG sensors. The kinematic pointers were represented by reflective points attached to different areas of the trunk, in correspondence with the positions of the wearable sensors, which are used to track the spatial movements of the body. The MoCap system works on the basis of optical cameras that detect the position of these markers in space and reconstruct their three-dimensional trajectories in real time, thus providing a direct and accurate measurement of movements [10].

The sensor system was designed to monitor the human trunk movements. Thus, the movements performed by the patients to move certain objects were followed. The additional movement that people who have suffered a stroke usually make, moving the shoulder towards the object, is followed. The additional shoulder movement causes deformation of the sensors mounted on the patient, and together with the movements monitored by the kinematic markers, these movements are identified. This aspect emphasizes the loss of neuromotor capacities with the passage through this medical event. Thus, by comparing the results achieved on healthy and post-stroke patients, trends in the use of elbow muscles are observed even when there were constraints on not using them. Therefore, the integration of this monitoring system was able to correctly identify the muscle activation patterns, both for healthy patients and those with neuromotor difficulties, its accuracy making it feasible for inclusion in monitoring systems in medical recovery [10].

3. SHIELDING AND SENSORS PROTECTION

In the field of smart fibers, it is very often used in applications such as: pressure sensors, temperature sensors, motion sensors, acoustic sensors, optical sensors. Thus, a developing field that has attracted the attention of researchers is textual, the combination of textiles and elements belonging to electronics.

A review of textronics for monitoring the body's vital signals from the perspective of integrating sensors at various levels of the textile manufacturing process chain—fiber, yarn, fabric, and clothing—is presented. Although a large number of research methods and prototypes have been developed, there are few details on the holistic quality and suitability of each approach for personalized and ubiquitous health monitoring systems. Several research reviews on wearable textile platforms provide recommendations for mechanical and chemical performance of the textile. The authors also recommend the analysis and clear reporting of biocompatibility, safety, comfort, experimental conditioning and pretreatment for the textile sensor system. On the other hand, studies on body-worn sensor networks (BSNs) identify and define critical performance parameters for successful BSNs, such as interoperability, reliability, security, validation, and sensor signal accuracy. It is also concluded that a textronic system must fulfil its double purpose, both as a biomedical sensor and as a clothing item, and the two aspects are inexorably linked. Characterization testing for textronics is thus affected by interdependencies. Only a coordinated interaction of textronic in a textile platform and a biomedical sensor should lead to the realization of a successful textronic system [11].

Textronics is the combination of textiles and electronic technologies, enabling the creation of smart textiles and e-textiles capable of measuring, reacting or communicating. The field includes sensors integrated into clothing, conductive materials, nanotechnologies and IoT solutions. The main applications are in medical, sports, safety, fashion, automotive and soft robotics. The major challenges are energy supply, durability in washing and stable integration of electronic components. Future trends include renewable energy textiles, integrated AI and sustainable materials [12].

Biosignals often need to be detected in sports or for medical reasons. Typical biosignals are pulse and ECG (electrocardiogram), breathing, blood pressure, skin temperature, oxygen saturation, bioimpedance. Long-term measurements on mobile patients or athletes require other equipment. Here, textile-based sensors and data connections embedded in textiles are preferred to avoid skin irritation and other unnecessary limitations of the monitored person. Thus, it is necessary to include communications, a power supply and a data processor.

Although the full integration of sensors and additional electronics into textile fabrics is not always easy at the recent stage of technology. Electrodes in direct contact with the skin can be prepared from a more skin-friendly material and in more comfortable shapes than, for example, ordinary ECG electrodes or the relatively rigid chest straps known from heart rate measurements in sports. Thus, a long-term ECG electrode based on textile electrodes and electronics integrated into textiles should be much more comfortable than the still common version.

So, the diverse and partially chemical physical properties of humans can be measured by textile sensors. For measuring electrical properties such as resistance, impedance, voltage or capacitance, which are possible through fibers, wires or conductive layers, and sometimes also through fine metal wires. The main challenges in the development of textile biosensors are the following: high contact impedance between dry skin and textile electrode; whether the sensors detect signals directly on the skin; and unwanted changes in the resistance and other electrical properties of the sensors, due to washing and wear [13].

Thus, passive wireless sensors are becoming increasingly important in industry, health and environmental monitoring. Among the advantages, it can be mentioned that it does not require batteries. They can operate in extreme environments (temperature, pressure). About the dimensions they are small, cheap and easy to integrate. For these sensors, the need for new materials with low dielectric losses and high stability is highlighted. A future area for improvement concerns the optimization of reading distance and noise immunity. Due to the promising results, the integration of nanogenerators for fully autonomous sensors can be tried [14].

In study [15] Zhang et al. presented the development of a flexible sensor based on Ni/CCF@PDMS (CCF–chopped carbon fibers, PDMS–polydimethylsiloxane), intended for monitoring bioelectrical signals such as sEMG (surface electromyography) and EOG (electrooculography) in environments with electromagnetic interference. The objective of the paper is to obtain a flexible structure capable of ensuring good contact with the skin and protection against electromagnetic interference, for the stable recording of weak biosignals.

The sensor was obtained by dispersing nickel particles and carbon fibers in the PDMS matrix, followed by mixing, ultrasonication, degassing, and mold casting, and then by printing Ag/AgCl electrodes on the flexible substrate. From an experimental point of view, the authors compared the Ni/CCF@PDMS sample with several reference variants and carried out tensile, adhesion, and electromagnetic shielding tests. The proposed variant provided a balance between deformation and breaking stress, reaching a deformation of 55.6% at a stress of approximately 1.49 MPa, and demonstrated an electromagnetic shielding effectiveness of 39.82 dB.

The feasibility of using the sensor was verified through sEMG measurements at the forearm level and EOG measurements during natural and forced blinking. The results highlighted stable signals, with reduced background noise, and a clear differentiation between the types of muscular contractions and blinking, confirming the potential of the sensor for biomedical monitoring applications.

4. CONCLUSIONS

This paper briefly reviews the accelerated evolution of flexible sensors, materials for medical recovery and emphasizes the need to integrate two major directions: advanced sensor systems for monitoring physiological signals and shielding materials. The reviewed studies demonstrated that the integration of flexible sensor systems with electromagnetic shielding materials represents a viable solution for the continuous and accurate monitoring of biomechanical and bioelectrical parameters in post-stroke patients.

Thus, the correlation between the 2 directions (flexible, hybrid or optical sensors and materials) is important in achieving an electronic system capable of being comfortable, accurate and reliable. Development in this direction is useful for creating a system with high potential in the medical field. Integration of advancements in interrelated areas is a future task.

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REFERENCES

[1] I. Poitras, F. Dupuis, M. Bielmann, A. Campeau-Lecours, C. Mercier, L. J. Bouyer, and J.-S. Roy, "*Validity and Reliability of Wearable Sensors for Joint Angle Estimation: A Systematic Review*", Sensors, vol. 19, art. 1555, 2019, doi: 10.3390/s19071555.

[2] S. Pratap, J. Narayan, Y. Hatta, K. Ito, and S. M. Hazarika, "*Glove-Net: Enhancing Grasp Classification with Multisensory Data and Deep Learning Approach*", Sensors, vol. 24, art. 4378, 2024, doi: 10.3390/s24134378.

[3] M. Al-Ayyad, H. A. Owida, R. DeFazio, B. Al-Naami, and P. Visconti, "*Electromyography Monitoring Systems in Rehabilitation: A Review of Clinical Applications, Wearable Devices and Signal Acquisition Methodologies*", Electronics, vol. 12, art. 1520, 2023, doi: 10.3390/electronics12071520.

[4] S.-H. Lee and W.-K. Song, "*Mitigating Trunk Compensatory Movements in Post-Stroke Survivors through Visual Feedback during Robotic-Assisted Arm Reaching Exercises*", Sensors, vol. 24, art. 3331, 2024, doi: 10.3390/s24113331.

[5] X. Yang et al., "*Recent advances in multifunctional electromagnetic interference shielding materials*", Chemical Communications, no. 61, pp. 17825-17845, 2025.

[6] D. Xu, Y. Yang, K. Numata, et al., "*Flexible Polymer-Based Electronics for Human Health Monitoring: A Safety-Level-Oriented Review of Materials and Applications*", Nano-Micro Letters, vol. 18, art. 213, 2026, doi: 10.1007/s40820-025-02059-7.

[7] G. S. Das et al., "*Nanocarbon-based sensors for the structural health monitoring of smart biocomposites*", Nanoscale Journal, no. 4, 2024.

[8] Y. Zhou, S. R. Zhou, "*Highly flexible, durable, UV resistant, and electrically conductive graphene based TPU/textile composite sensor*", Polymer Advanced Technology, 2022, doi: 10.1002/pat.5856.

[9] J. Shi and W. Wang, "*A hybrid sensory system for upper extremity stroke rehabilitation assessment*", Chemical Engineering Journal, vol. 520, p. 165860, 2025.

[10] D. Lo Presti, M. Zaltieri, M. Bravi, M. Morrone, M. A. Caponero, E. Schena, S. Sterzi, and C. Massaroni, "*A Wearable System Composed of FBG-Based Soft Sensors for Trunk Compensatory Movements Detection in Post-Stroke Hemiplegic Patients*", Sensors, vol. 22, art. 1386, 2022, doi: 10.3390/s22041386.

[11] I. Iftekhar et al., "*Electronic Textile Sensors for Decoding Vital Body Signals*", Intelligent Advanced Systems, vol. 4, art. 2100223, 2022, doi: 10.1002/aisy.202100223.

[12] Younes, B."Textronics: a review of their technological aspects and applications", *The Journal of The Textile Institute*, *115*(9), 1509–1525, 2024.

[13] T. Blachowicz, G. Ehrmann, and A. Ehrmann, "*Textile-Based Sensors for Biosignal Detection and Monitoring*", Sensors, vol. 21, art. 6042, 2021, doi: 10.3390/s21186042.

[14] D. He et al., "*Advancements in Passive Wireless Sensors, Materials, Devices, and Applications*", Sensors, vol. 23, no. 19, art. 8200, 2023, doi: 10.3390/s23198200.

[15] L. Zhang, X. Zhang, Z. Duan, H. Müller, and M. Atzori, "*A Ni/CCF@PDMS-based flexible and electromagnetic interference-shielding surface electromyography/electrooculography sensor*", Sensors and Actuators A: Physical, vol. 400, art. 117530, 2026, doi: 10.1016/j.sna.2026.117530.

ANNALS OF THE UNIVERSITY OF ORADEA
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RECYCLED COTTON FIBERS: PATHWAYS AND APPLICATIONS

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Abstract: *The global textile industry faces significant environmental challenges due to high resource consumption and growing volumes of post-consumer waste, particularly from cotton, one of the most widely used natural fibers. This paper examines the pathways and applications of recycled cotton fibers within the framework of a circular economy. Mechanical recycling, the most established method, involves shredding and fiber reconstitution, enabling the production of blended yarns and nonwoven materials, though it reduces fiber length and strength. Chemical recycling techniques, including solvent-based dissolution and regeneration, allow the production of high-quality cellulose fibers comparable to or exceeding virgin cotton in performance, suitable for demanding textile applications. Emerging biological and hybrid approaches, such as enzymatic treatments and combined mechanical-chemical processes, provide sustainable alternatives, preserving fiber integrity while reducing chemical and energy usage. The study highlights the influence of recycling methods on fiber, yarn, and fabric properties, showing that optimized blends containing up to 30% recycled cotton maintain adequate mechanical performance for apparel and home textiles. Advanced applications of recycled cotton, including nanocellulose, composites, and functional materials, demonstrate its potential beyond conventional textiles. Finally, recycling cotton fibers contributes to resource efficiency, waste reduction, and the development of sustainable, high-value materials, supporting the transition toward environmentally responsible textile production.*

Key words: *cotton, textile waste, circular economy, mechanical recycling, chemical recycling*

1. INTRODUCTION

The global textile industry is a major contributor to environmental degradation, driven by high resource consumption and increasing volumes of post-consumer waste. Cotton, one of the most widely used natural fibers, is associated with significant water usage, pesticide application, and land exploitation. As sustainability becomes a central concern, the transition toward circular economy models has emerged as a critical strategy for reducing the environmental footprint of textile production. Recycled cotton fibers offer a viable solution by diverting textile waste from landfills and reducing reliance on virgin cotton. Advances in recycling technologies have enabled the transformation of cotton waste into a variety of products, ranging from low-grade insulation materials to high-performance regenerated fibers and advanced functional materials. However, challenges remain in maintaining fiber quality, ensuring economic viability, and scaling recycling processes. This paper aims to analyze current recycling pathways for cotton fibers, evaluate their impact on material performance, and assess their environmental benefits within a circular framework. It also identifies key challenges and outlines future directions for research and industrial implementation.

2. RECYCLING TECHNOLOGIES FOR COTTON FIBERS

2.1 Mechanical Recycling

Mechanical recycling is the most established method for processing cotton waste and involves sorting, cutting, shredding, and opening textile materials into reusable fibers. This process is relatively simple and cost-effective, making it widely adopted in industry. However, mechanical recycling significantly affects fiber properties. The repeated mechanical stress shortens fiber length and reduces strength, which in turn impacts yarn quality and limits the proportion of recycled fibers that can be used in high-performance textiles. The quality of the recycled fibers strongly depends on the characteristics of the input waste, including fabric structure, blend composition, and previous processing history. Although recycled cotton fibers generally exhibit inferior properties compared to virgin cotton, particularly when produced by shredding fabric waste, this has historically limited their use in clothing production [1].

As a result, recycled cotton has mainly been directed toward coarser yarns through blending with other fibers. The paper [2] highlights key advancements in textile recycling, focusing on improving circularity for cotton, polyester, and their blends. Spectroscopic techniques, particularly Near-Infrared Spectroscopy (NIRS) combined with color sorting, are used to accurate and efficient classification of textile waste. Once properly sorted, materials undergo mechanical and/or chemical recycling, including decolorization when necessary. The authors have pointed out that for cotton, understanding the degree of polymerization (changes from virgin fiber through various recycling stages) is essential. This knowledge helps select the most suitable recycling processes and maximizes the number of useful lifecycles for cotton fibers.

Table 1: *Main recycling routes and end uses for waste cotton*

Pathway / Product	**Typical Outputs and Uses**	**Citations**
Mechanical -> yarns/fabrics	Knit & woven apparel, denim, mélange yarns	[1], [2], [3], [4]
Chemical -> regenerated fibers	Rayon/lyocell-like fibers, often equal/better than wood-based	[5], [6], [7], [8], [9]
Nonwovens & insulation	Building, clothing, acoustic/thermal panels	[27], [28], [29]
Advanced materials	CNCs, adsorbents, biofuels, electronics, composites	[30], [31], [32], [33]

Up to 25–30% mechanically recycled cotton can be blended into 30 Ne ring-spun yarn suitable for knit tops, with acceptable strength loss. In this sense, the paper [3] shows that recycled cotton fibers from pre- and post-consumer textile waste can be successfully reused by blending them with virgin cotton. Although the blend yarns exhibited higher unevenness, more imperfections, and reduced strength compared to 100% virgin cotton, they enable attractive mélange-style fancy yarns, with the environmental benefits of recycled materials outweighing the slight drop in quality and garment lifespan for today's sustainability-conscious consumers. Despite these limitations, mechanical recycling remains suitable for applications such as blended yarns, denim, and nonwoven products, particularly when optimized sorting and processing conditions were applied. Fabric studies show recycled-cotton woven fabrics can match mechanical properties and drape of carded cotton, suggesting real apparel potential. The study in [4] evaluated several key properties of woven fabrics made from recycled cotton yarns compared to conventional carded cotton yarns. Recycled cotton fabrics demonstrated superior tensile strength in the weft direction, likely due to higher weft yarn density, and showed significantly better abrasion resistance, with no yarn breakage even after 20,000 cycles, unlike carded cotton fabrics which failed earlier. In terms of bending rigidity, recycled cotton plain woven fabrics exhibited lower values, indicating softer handle and better drapability. However, due to the higher hairiness and short fiber content of recycled yarns, these fabrics displayed poorer pilling performance, especially in twill constructions.

2.2 Chemical Recycling

Chemical recycling processes involve the dissolution of cotton fibers and their regeneration into new cellulose-based fibers. Technologies such as lyocell-type processes use solvent systems (N-Methylmorpholine N-oxide or emerging alternatives like Ioncell®) to produce regenerated fibers with properties comparable or superior to those derived from wood pulp [5], [6]. This approach overcomes the limitations of fiber shortening associated with mechanical recycling, enabling the production of high-quality fibers suitable for demanding textile applications. However, chemical recycling is more complex and requires careful management of solvents, energy consumption, and processing costs. The regenerated fibers [6] showed very high wet and conditioned tenacities (about 54–62 cN/tex) with elongations at break of 9–13%, due to high molecular orientation that increases hydrogen bonding but slightly reduces flexibility and stretch. The authors suggest further optimization of cellulose degree of polymerization, scaling up the process, and exploring advanced applications such as composite or carbon fiber production.

Paper [7] describes the process of cellulose filaments obtaining by dissolving industrial cotton residue in two ionic liquids, [Emim]Cl (1-ethyl-3-methylimidazolium) and [Emim]OAc, with Dimethyl Sulfoxide as a cosolvent, followed by regeneration in water or ethanol. The resulting filaments were homogeneous and dense, retaining additives like optical brighteners. All filaments had reduced thermal stability, with the worst performance observed for the [Emim]Cl - ethanol combination, which also showed poor mechanical properties due to low polymerization and crystallinity. In contrast, other filaments had elastic moduli comparable to viscose and modal fibers (10 - 13 GPa). The [Emim]OAc - ethanol system provided the best balance of mechanical, thermal, and structural properties.

For cotton/polyester or cotton/elastane blends, selective dissolution or hydrolysis separates the components. Ionic liquids, deep eutectic solvents, switchable hydrophilicity solvents, acids, enzymes, and hydrothermal treatments are key tools. The paper [8] reviews chemical separation technologies for polyester/cotton blended textiles, focusing on methods to separate components through polyester depolymerization and cellulose dissolution. It analyzes key polyester depolymerization approaches, and cellulose separation via acidic hydrolysis and dissolution in non-derivatizing solvents. The authors of [9] examine the separation of cotton and polyester and elastane using methods such as dissolution, acidic hydrolysis, acid-catalyzed hydrothermal treatment, and enzymatic hydrolysis, followed by approaches for isolating elastane from other fibers through its selective degradation or dissolution. Recent developments focus on improving process efficiency, reducing environmental impact through closed-loop solvent recovery systems, and enabling the recycling of dyed and blended textiles.

2.3 Emerging Biological and Hybrid Approaches

Emerging recycling methods incorporate biological and enzymatic treatments to selectively break down cotton fibers or remove impurities. These approaches offer the potential for gentler processing, preserving fiber integrity while reducing chemical usage. Enzymatic treatments, particularly those using cellulases, enable the controlled breakdown of cotton fibers into valuable intermediates such as glucose or regenerated cellulose, while minimizing harsh conditions and environmental impact. The review paper of [10] emphasizes that chemical and biotechnological approaches, such as acid hydrolysis, achieving up to 70% glucose recovery, and enzymatic recycling, which can reduce energy consumption by around 20% compared to conventional methods, enable the effective conversion of textile waste into valuable resources, while scalable technologies including advanced solvent recovery systems, optimized pretreatment processes, and fluidized-bed pyrolysis (increasing bio-oil yields by up to 25% over fixed-bed reactors) are essential for enhancing efficiency, sustainability, and industrial applicability.

Advances in microbial fermentation further allow these sugars to be converted into bio-based chemicals, fuels, or new polymer precursors, supporting circular material flows. Emerging technologies such as Biocelsol, which utilizes dissolving-grade pulp to produce regenerated cellulose fibers [12], along with processes like bioethanol production via enzymatic fermentation, biogas generation through anaerobic digestion, biochar formation by carbonization, and biodegradable composting, represent promising biological routes for textile recycling; however, due to the complexity of textile waste compositions [13].

Hybrid systems combining mechanical, chemical, and biological steps are also being explored to optimize both efficiency and product quality, enabling the production of novel materials, including high-performance cotton fiber fragments and nanostructured cellulose products. They integrate these biological methods with green solvents or mild chemical pretreatments to enhance dissolution, improve fiber separation in blended textiles, and increase overall process efficiency. Together, these approaches offer promising, more sustainable alternatives to conventional recycling, though challenges remain in scaling, cost optimization, and maintaining material quality (see fig. 1). The authors of [11] emphasize the need for hybrid models combining these methods to address their individual limitations, such as integrating technological sorting for mechanical recycling or developing non-toxic green solvents for chemical recycling.

3. FIBER AND YARN PERFORMANCE

3.1 Fiber Properties

Recycling methods strongly shape the properties and performance of recycled fibers. Mechanical recycling, which relies on shredding, grinding, or repeated extrusion, typically shortens fibers and degrades their strength, because fibers are broken by shear and impact during processing, as presented by the authors of [14],[15]. In many fiber-reinforced composites and textile systems, higher screw speeds, higher fiber volume contents, and aggressive size-reduction steps are all linked to more severe fiber length reduction and loss of mechanical properties [16]. This is why mechanically recycled textile fibers and composite reinforcements often need blending with virgin fibers or are downcycled into lower-value products. By contrast, chemical or solvent-based recycling of fiber-reinforced polymers and textiles can preserve or restore the underlying polymer or cellulose structure, enabling the production of more uniform, high-quality recycled fibers. In carbon-fiber systems, solvolysis or optimized pyrolysis can remove the matrix while largely retaining fiber stiffness and much of the tensile strength, especially when followed by appropriate surface sizing, so the recovered fibers approach virgin performance [17]. Reviews of textile waste management similarly note that polymer recycling by melting or dissolving, as well as chemical depolymerization of synthetics, tends to yield recycled materials with more consistent quality than purely mechanical routes, albeit at higher energy and process complexity [18].

Because recycling routes and parameters so strongly affect fiber length, strength, fineness, and surface condition, the properties of recycled fibers are inherently variable. Studies across glass, carbon, natural, and textile fibers emphasize that careful control of recycling conditions (temperature, screw speed, number of cycles, repulping/refining severity) and thoughtful selection of feedstock and additives are essential to obtain reproducible properties and ensure reliable performance in downstream applications such as yarns, nonwovens, or structural composites [18], [14].

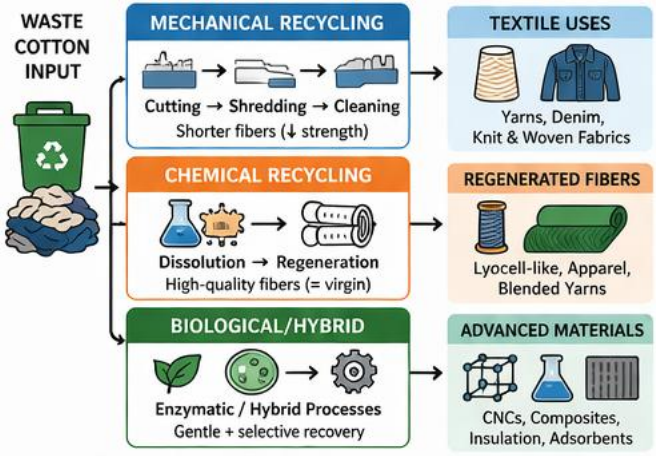

***Fig. 1**: Recycling pathways and applications*

3.2 Yarn and Fabric Performance

The integration of recycled cotton fibers into yarns and fabrics is a key strategy for advancing sustainability in the textile industry, but it requires careful blending to maintain product quality. Research consistently demonstrates that blends containing up to 25–30% recycled cotton can be used in ring-spun yarns without significant loss of performance, making them suitable for mainstream applications such as knitwear and woven apparel [5],[19]. At the fabric level, studies show that textiles made with recycled cotton can achieve comparable abrasion resistance, drape, and comfort to those made from virgin cotton, especially when optimal spinning methods and finishing processes are employed [20]. These findings highlight the potential for recycled cotton to be widely adopted in apparel manufacturing, provided that blending ratios and processing techniques are optimized.

4. APPLICATIONS OF RECYCLED COTTON

4.1 Textile Applications

Recycled cotton is now used across many textile product types, from everyday knitwear to denim and nonwovens. Its shorter, more variable fibres are managed through blending, spinning, and finishing strategies that allow functional and aesthetic performance comparable to virgin cotton in many cases. Knit tops such as T-shirts and polos can be effectively produced using ring-spun 30 Ne yarns that incorporate up to approximately 25–30% recycled cotton derived from both pre- and post-consumer waste. Fabrics made from blends of recycled cotton and recycled polyester (r-PET), for example in a 60/40 ratio, demonstrate bursting strength and pilling resistance comparable to those of standard commercial T-shirt materials [21].

When appropriate finishing processes are applied, knitted fabrics containing even higher proportions of recycled cotton up to 80% can achieve satisfactory performance in terms of bursting strength, abrasion resistance, and pilling. This is particularly effective when compact yarns are used in combination with optimized wet finishing techniques such as bio-polishing and controlled stripping and dyeing [20]. Additionally, single-jersey knitted fabrics developed from recycled denim waste, using ring-spun blends with ratios as high as 75/25 recycled to virgin fibres, have shown promising results in both tensile strength and abrasion resistance, making them a viable option for durable knitwear applications [22]. Denim fabrics, both in warp and weft directions, can successfully incorporate rotor-spun yarns with high levels of recycled cotton, making them suitable for large-scale commercial weaving. In the case of stretch denim, elastic core-spun yarns can include up to 60% recycled cotton while still maintaining adequate strength, elongation, and compatibility with high-speed loom operations [21].

For handloom applications, rotor yarns containing up to 75% recycled cotton have demonstrated no significant decline in key performance characteristics such as pilling resistance, abrasion durability, or air permeability, even in plain and twill woven structures [23]. More broadly, mechanically recycled cotton is widely utilized in general woven fabrics and home textiles, particularly in the form of coarser rotor-spun yarns in the 10–20 Ne range. These yarns are well-suited for products such as denim, towels, and various home furnishing materials, where durability and texture are essential.

4.2 Nonwoven and Insulation Materials

Nonwoven fabrics made from recycled cotton are widely studied for use in thermal and acoustic insulation, especially in buildings and technical clothing, where fiber length and uniformity are less critical than in yarn-spun textiles. Research shows these materials can match or approach the performance of conventional synthetic insulators while adding moisture management and sustainability benefits.

Recycled cotton, often blended with polyester from post-consumer garment waste, has proven by the authors of [24] to be highly effective in the production of nonwoven insulation materials for buildings. Technologies such as chemical bonding and air-laid processing enable the formation of lightweight, porous structures with excellent sound-absorbing capabilities. These nonwovens can achieve sound absorption coefficients exceeding 70% across a broad frequency range (125 - 4000 Hz), making them particularly suitable for interior acoustic applications such as wall linings, ceilings, and partition systems. Importantly, their acoustic performance remains stable even under conditions of elevated humidity, which is a critical factor in real-world building environments [25]. From a thermal perspective, insulation panels and boards manufactured from textile waste, including significant proportions of recycled cotton—demonstrate thermal conductivity values typically in the range of 0.034 to 0.05 W/m·K. These values are comparable to those of widely used conventional insulation materials such as mineral wool and polymeric foams, indicating that recycled textile-based solutions can serve as viable, sustainable alternatives in building envelopes [26]. Additionally, post-consumer cotton fibers can be utilized in loose-fill insulation or incorporated into nonwoven mats. These forms exhibit similar thermal conductivity ranges, with their performance influenced primarily by environmental conditions such as temperature and humidity, while fiber orientation has a relatively minor effect. This makes them versatile for various installation methods, including cavity wall insulation and attic applications [25].

Insulation materials derived from recycled cotton not only contribute to waste reduction and circular economy goals but also offer competitive thermal and acoustic performance, supporting their growing adoption in sustainable construction practices.

4.3 Advanced materials

Recycled cotton is increasingly transformed from textile waste into advanced materials rather than just lower-value textiles. The authors of [27],[28] focus on extracting cellulose nanocrystals (CNCs) or nanofibrils from post-consumer garments, blended fabrics, and cotton process waste, using acid hydrolysis, deep eutectic solvents, or NaOH/urea systems. These nano-cellulose materials offer high crystallinity, aspect ratio, and surface area, making them attractive for nanocomposites, electronics packaging, and functional films. CNCs from cotton waste have been used to reinforce poly(vinyl alcohol), PLA, methylcellulose, and polypropylene, giving large gains in tensile strength, modulus, and sometimes impact resistance, with potential uses in automotive and construction components, flexible films, and lightweight foams or nanopapers for electronic or packaging applications [29]. Surface-sulfated or citrated CNCs from waste cotton further improve flame resistance or transparency, enabling electronic packaging and conductive film possibilities. Beyond structural nanocomposites, recycled-cotton-derived cellulose is explored as adsorbents, biofuel precursors, and environmental materials. Activated or surface-modified cotton waste and CNCs show high adsorption capacity for dyes, heavy metals, oils and other recalcitrant pollutants in water, and can form improved membranes or aerogels for wastewater treatment. [30]

5. CONCLUSIONS

The recycling of cotton fibers constitutes a fundamental component in the transition toward a circular and sustainable textile industry. Mechanical recycling is the most established and cost-effective method for reintegrating cotton waste into textiles and nonwovens, albeit with fiber degradation, whereas chemical and emerging biological processes enable recovery of high-purity cellulose, producing regenerated fibers with properties comparable to or exceeding those of virgin cotton. The development of hybrid recycling systems, integrating mechanical, chemical, and biotechnological processes, further enhances process efficiency and material quality, contributing to the advancement of closed-loop recycling models.

Despite the challenges associated with variability in feedstock, process scalability, and economic viability, recent research highlights significant progress in improving the performance of recycled fibers and expanding their end-use potential. In particular, the valorization of cotton waste into high-value products such as nanocellulose, composites, and functional materials underscores the broader industrial relevance of recycling strategies beyond conventional textile applications.

REFERENCES

[1] B. Ütebay, P. Çelik, and A. Çay, *"Effects of cotton textile waste properties on recycled fibre quality,"* J. Cleaner Prod., vol. 222, pp. 29–35, 2019.

[2] S. Wang and S. Salmon, *"Progress toward circularity of polyester and cotton textiles,"* Sustain. Chem., vol. 3, pp. 376–403, 2022.

[3] Y. Arafat and A. J. Uddin, *"Recycled fibers from pre- and post-consumer textile waste as blend constituents in manufacturing 100% cotton yarns in ring spinning: A sustainable and eco-friendly approach,"* Heliyon, vol. 8, e11275, 2022.

[4] G. Pamuk and E. Z. Yıldız, *"Physical properties of plain and twill woven fabrics produced from carded and recycled cotton yarn,"* Pamukkale Univ. Muh. Bilim. Derg., vol. 28, no. 7, pp. 1030–1035, 2022.

[5] T. Azevedo *et al.*, *"Reinforcing cotton recycled fibers for the production of high-quality textile structures,"* Polymers, vol. 17, p. 1392, 2025.

[6] I. Schlapp-Hackl *et al.*, *"From postconsumer cotton towels to new cotton textile fibers,"* J. Appl. Polym. Sci., vol. 141, e55460, 2024.

[7] B. B. de Brito et al., *"Regenerated cellulose filaments from the recycling of textile cotton waste using ionic liquids,"* ACS Omega, vol. 10, no. 19, pp. 19983–19991, 2025.

[8] J. Ma et al., *"Advancements in component separation through chemical methods for recycled polyester/cotton blended textiles,"* Cellulose, vol. 31, pp. 9543–9563, 2024.

[9] K. Choudhury, M. Tsianou, and P. Alexandridis, *"Recycling of blended fabrics for a circular economy of textiles: Separation of cotton, polyester, and elastane fibers,"* Sustainability, vol. 16, p. 6206, 2024.

[10] J. Ghosh et al., *"Chemical valorization of textile waste: Advancing sustainable recycling for a circular economy,"* ACS Omega, vol. 10, no. 12, pp. 11697–11722, 2025.

[11] T. Grover et al., *"Sustainable strategies for the valorization of cotton and cotton blended waste: Pathways to circular economy,"* Cellulose, vol. 32, pp. 4077–4100, 2025.

[12] M. Vehviläinen et al., *"Sustainable continuous process for cellulosic regenerated fibers,"* Chem. Fibers Int., vol. 70, pp. 128–130, 2020.

[13] I. E. Lanz, E. Laborda, C. Chaine, and M. Blecua, *"A mapping of textile waste recycling technologies in Europe and Spain,"* Textiles, vol. 4, pp. 359–390, 2024.

[14] S. MohammadKarimi et al., *"Investig. of the fiber length and the mechanical properties of waste recycled from continuous glass fiber-reinforced polypropylene,"* Recycling, 2023.

[15] R. Gonçalves, A. Martinho, and J. Oliveira, *"Recycling of reinforced glass fibers waste: Current status,"* Materials, vol. 15, 2022.

[16] A. Abbas et al., *"Serviceability and washing durability of recycled polyester, wool, and acrylic: Sustainability concerns and microfiber leaching,"* Ind. Crops Prod., 2025.

[17] D. Semitekolos et al., *"Performance restoration of chemically recycled carbon fibres through surface modification with sizing,"* Polymers, vol. 17, 2024.

[18] M. Abbas-Abadi et al., *"Advancing textile waste recycling: Challenges and opportunities across polymer and non-polymer fiber types,"* Polymers, vol. 17, 2025.

[19] M. Motin et al., *"Investigating the ideal combination of virgin cotton fibre length with recycled fibre for better yarn quality,"* Textile & Leather Review, 2024.

[20] B. Utebay, P. Çelik, and A. Çay, *"Effects of finishing processes on physical properties of knitted fabrics produced by recycled cotton fibers,"* J. Cleaner Prod., 2024.

[21] Y. Arafat and A. Uddin, *"Recycled fibers from pre- and post-consumer textile waste as blend constituents in manufacturing 100% cotton yarns in ring spinning,"* Heliyon, vol. 8, 2022.

[22] E. Kärkkäinen et al., *"Characterisation of fibre mechanical recycled cotton denim fibres and the effects of their properties on yarns and knits,"* Recycling, 2025.

[23] A. Uddin and P. Roy, *"Transforming melange fabric waste into mélange yarn employing compact, Siro, and compact-Siro spinning,"* Cleaner Waste Syst., 2024.

[24] S. Sakthivel et al., *"Thermal and sound insulation properties of recycled cotton/polyester chemical bonded nonwovens,"* J. Eng. Fibers Fabr., vol. 15, 2020.

[25] A. Angelotti et al., *"Thermal conductivity assessment of cotton fibers from apparel recycling for building insulation,"* Energy Build., 2024.

[26] M. Wazna et al., *"Development, characterization and thermal performance of insulating nonwoven fabrics made from textile waste,"* J. Ind. Text., vol. 48, pp. 1167–1183, 2019.

[27] S. Rizal et al., *„Cotton wastes functionalized biomaterials from micro to nano: A cleaner approach for a sustainable environmental application"*, Polymers, vol. 13, 2021.

[28] S. Mohamed et al., *„Recycling waste cotton cloths for the isolation of cellulose nanocrystals: A sustainable approach",* Polymers, vol. 13, 2021.

[29] P. Srichola et al., *„Recycling of nanocellulose from polyester–cotton textile waste for modification of film composites"*, Polymers, vol. 15, 2023.

[30] A. Işıtan et al., *„Sustainable production of microcrystalline and nanocrystalline cellulose from textile waste using HCl and NaOH/urea treatment",* Polymers, vol. 17, 2024.

ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

MORPHOLOGICAL AND PHYSICAL-CHEMICAL INVESTIGATION OF MICROWAVE TRANSMISSION LINES COATED ON TEXTILES

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Abstract: *Textile structures for flexible microstrip transmission lines play a significant role in the development of wearable articles, as they connect the textile antenna with the wearable transceiver. Such articles are currently developed to monitor physiological parameters of humans with medical or sports applications. Our paper proposes two types of coated transmission lines on a textile substrate, one using silver coating and the other a carbon-based coating, with two geometrical dimensions. Their designed functionality is to act as band pass filters at the resonant frequency of 900 MHz, in order to deliver maximum power to a wearable antenna. The four coated transmission lines were prepared via screen printing on the dielectric substrate, while a conductive knitted fabric was sewn on the back side to act as ground plane. The transmission lines were characterized regarding their morphological and physical-chemical properties, in order to investigate the electrical conductivity and continuity of the coated transmission lines, as well as their adhesion onto the textile substrate. For this investigation scanning electron microscopy, X-ray energy-dispersive spectrometry and Fourier-transform infrared spectroscopy in the band of 4000-400 cm^{-1} were employed. The results of the morphological investigation proved good conductivity and continuity of the transmission lines, while the physical-chemical investigation showed the chemical elements of the coated microwave transmission lines. The reflection loss (also known as input reflection coefficient, return loss, S11), of the transmission lines was measured via a vector network analyzer. Simulation results and measurement results show broad agreement, thus proving their functionality.*

Key words: *distributed elements, flexible microwave circuits, conductive coatings, band pass filters, microwave transmission lines*

1. INTRODUCTION

Microwave transmission lines integrated into textile fabrics provide the connection between the transceiver and the textile antenna [1]. Several manufacturing technologies are available, such as embroidery of metallic yarns, or coating with conductive pastes [2-3]. The coating of transmission lines however, sets some challenges regarding adhesion onto the textile substrate, the quality of electrical conductivity and the continuity of the electrical signal transmission [4]. A resonant circuit is needed in order for the textile transmission line to deliver maximum power to the textile antenna at a certain frequency [5, 7-8]. Our scientific contribution presents several variants of textile microstrip transmission lines coated on a textile substrate, acting as band pass filters with destination GSM communication (900 MHz). This paper describes an investigation of the morphological and physical-chemical analysis of the coated transmission lines with silver and carbon paste on a textile dielectric substrate.

2. MATERIALS AND METHODS

2.1 The dielectric substrate

The textile substrate was chosen for its suitable physical-mechanical and electrical properties and as well for its heat curing resistance: it is a woven fabric with 70% Kermel (polyamide-imide) and 30% viscose fibres [6].

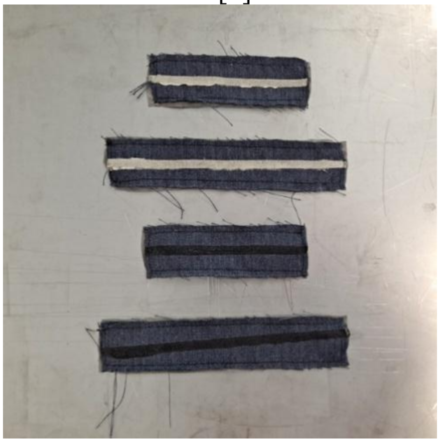


Fig. 1: *The four samples acting as microwave filters*

This woven fabric was screen printed with two types of conductive paste, namely silver paste from Sigma Aldrich (Ag 60% + AgCl 40%) and carbon paste from BareConductive. A knitted fabric with 10 Ωsq resistance was sewn on the back side of the dielectric woven fabric as ground plane, in order to achieve a micro strip textile structure. According to the simulation, two geometrical dimensions for the transmission lines were selected to be screen printed on the substrate with band pass filter functionality: 4 mm × 100 mm transmission line and 4 mm × 150 mm transmission line (Fig. 1).

The four resulting samples were cured in oven at 80ºC for 30 minutes and the knitted fabric was attached afterwards by sewing on the back side as ground plane (electrical return path).

3. RESULTS

3.1. SEM analysis of the conductive coatings

Scanning electron microscopy (SEM) was used to analyze the morphology of the impregnated conductive inks as follows. A FEI Quanta 200 microscope was operated at 15 kV, 130 Pa pressure in low vacuum mode, large field detector and a working distance around 10 mm. The SEM images with 100× and 3000× magnifications were acquired for the textile substrate, for silver coating and carbon coating for 10 and 15 cm lengths (Figs. 2-11).

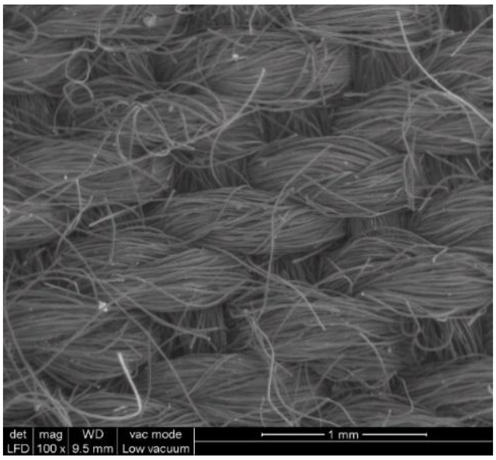


***Fig. 2**: SEM image of textile substrate (100×)*

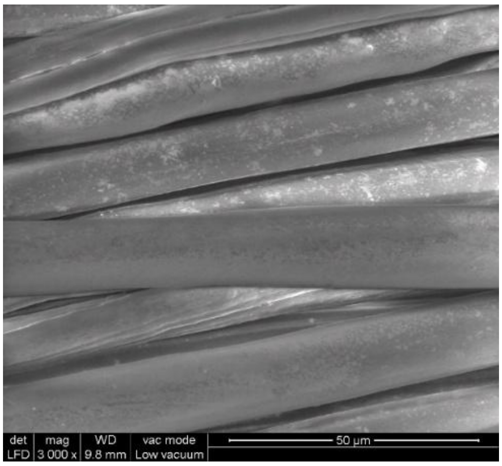


***Fig. 3**: SEM image of textile substrate (3000×)*

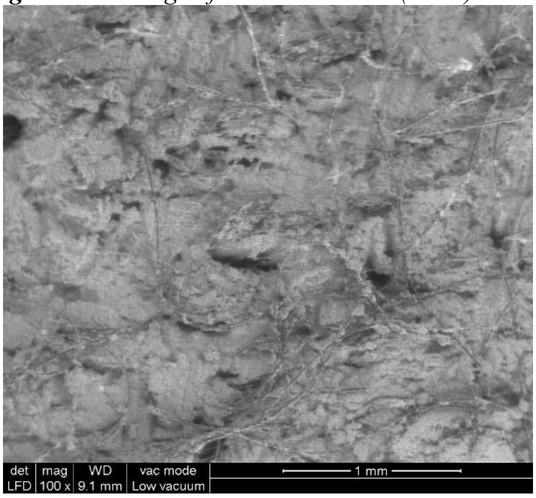


***Fig. 4**: SEM image of Ag 10 cm length (100×)*

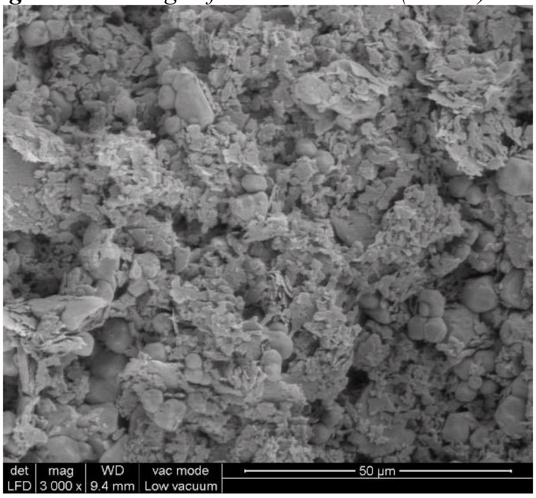


***Fig. 5**: SEM image of Ag 10 cm length (3000×)*

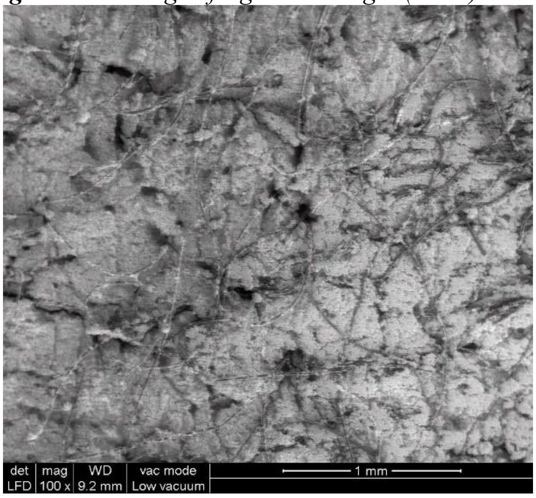


***Fig. 6**: SEM image of Ag 15 cm length (100×)*

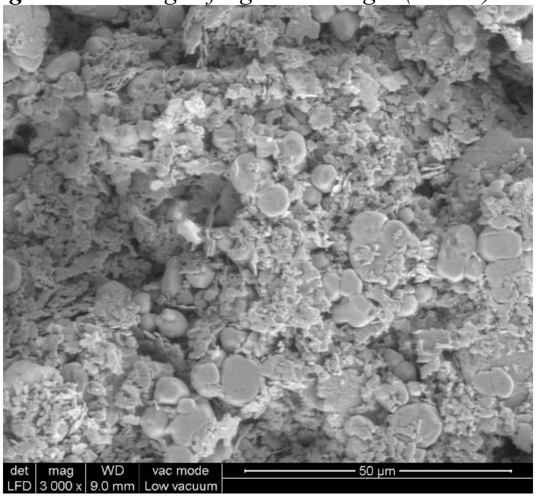


***Fig. 7**: SEM image of Ag 15 cm length (3000×)*

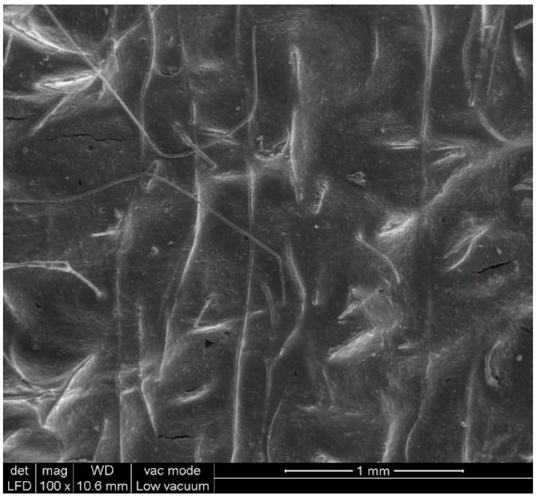


Fig. 8*: SEM image of C 10 cm length (100×)*

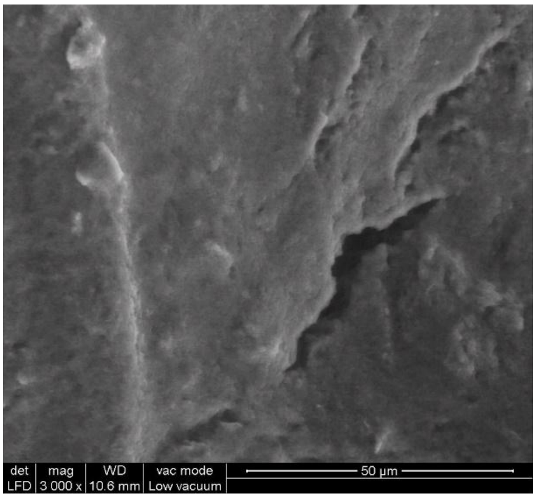


Fig. 9*: SEM image of C 10 cm length (3000×)*

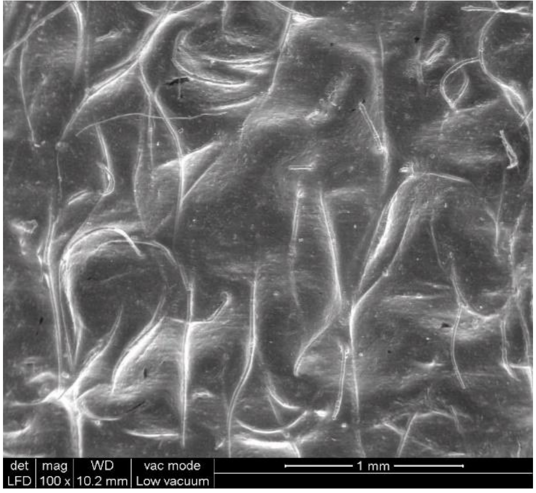


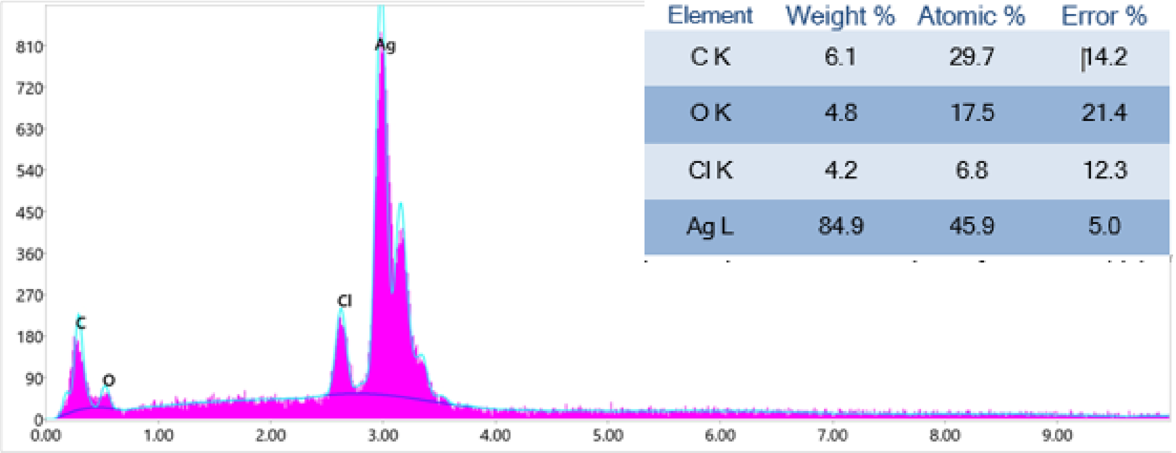
Fig. 10*: SEM image of C 15 cm length (100×)*

Fig. 11*: SEM image of C 15 cm length (3000×)*

The surface micro-structure of the silver coating presents some discontinuous features but having their regions in high electrical contact. This leads to adequate conductivity of the deposited layer, and sufficient mechanical strength, due to the high internal binding surface between these regions. The micro-structure of the carbon-based coating presents a better continues aspect, which provides a high conductivity and also a high mechanical resistance.

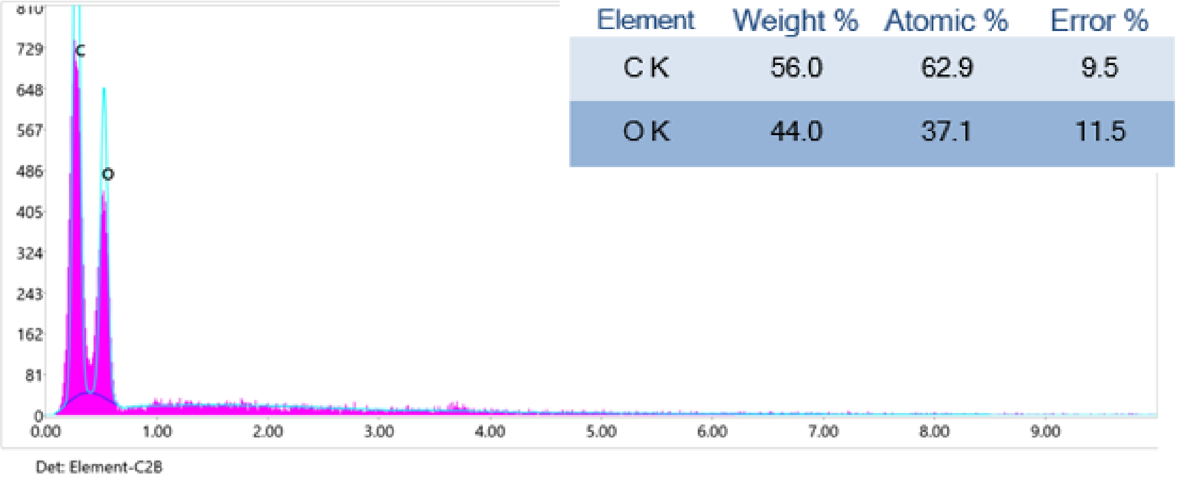
3.2. EDX analysis of the conductive coatings

X-ray energy-dispersive spectrometry (EDX) was performed to measure the chemical elements concentrations in the deposited conductive coatings, using an Ametek EDX Element instrument. The acquired spectra and percent concentration values are presented in Figs. 12 and 13.



Element	Weight %	Atomic %	Error %
C K	6.1	29.7	14.2
O K	4.8	17.5	21.4
Cl K	4.2	6.8	12.3
Ag L	84.9	45.9	5.0

Fig. 12: *EDX spectrum of Ag 10 cm length*



Element	Weight %	Atomic %	Error %
C K	56.0	62.9	9.5
O K	44.0	37.1	11.5

Fig. 13: *EDX spectrum of C 10 cm length*

The elemental composition of the silver paste indicates the presence of silver chloride in an organic matrix (composed of carbon and oxygen compounds) that disperses the silver salt, allowing the silver ions to interconnect and form a flexible, conductive network at the atomic level. In contrast, the elemental composition of the carbon paste reflects the presence of carbon, as well as the oxygen contained in its organic additives.

3.3. FT-IR analysis of the conductive coatings

The identification of chemical compounds in samples was made by Fourier-transform infrared spectroscopy (FT-IR) in the range of 4000-400 cm^{-1} in the attenuated total reflectance mode with a diamond crystal, using a Thermo Scientific Nicolet iS50 instrument. The spectra of 10 cm silver and carbon conductive films are shown in Figs. 14 and 15.

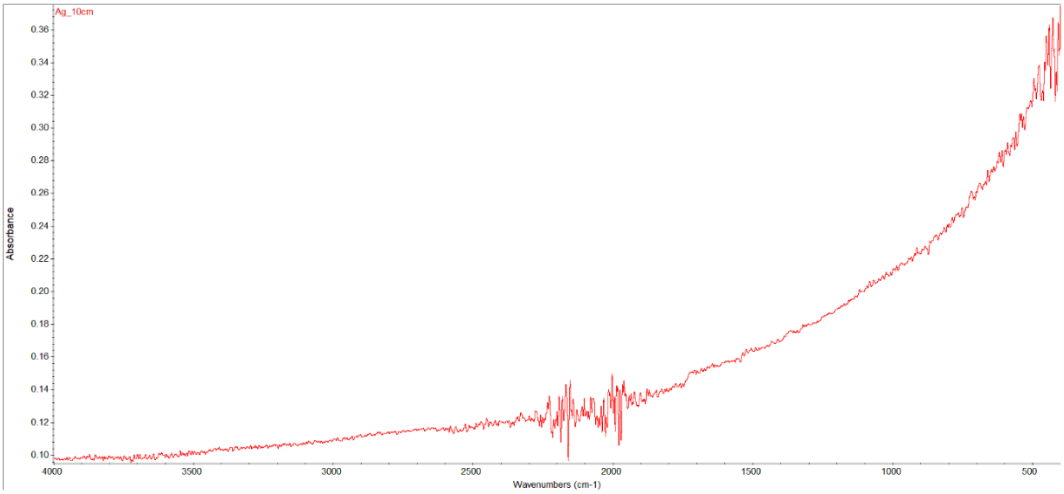


***Fig. 14**: FT-IR spectrum of Ag 10 cm length*

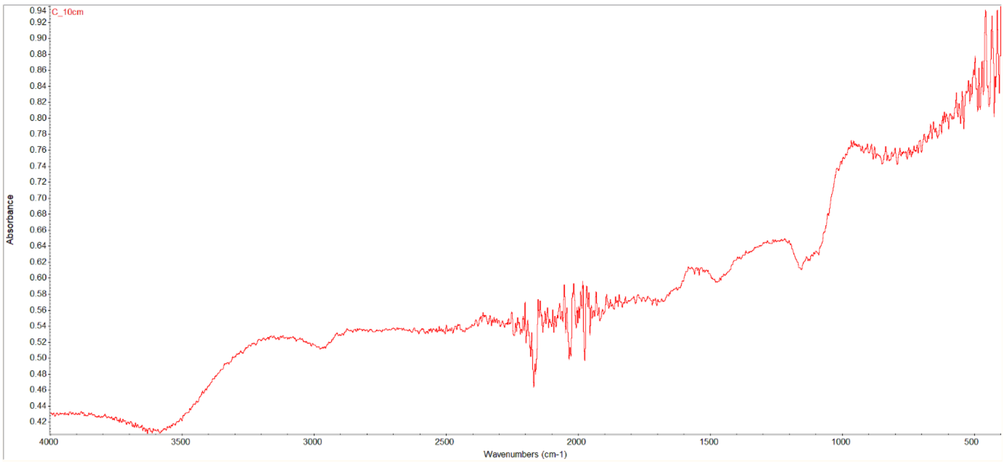


***Fig. 15**: FT-IR spectrum of C 10 cm length*

FT-IR analyses of the carbon paste show that the carbon-carbon bond peaks of the carbon structures appearing in the mid-infrared band (1500–1000 cm^{-1}) from molecular vibrational transitions, a band that is absent in the case of silver paste due to the presence of silver-chloride ionic bonds instead of covalent carbon-carbon.

3.4. Electric microwave simulation and measurements

The manufactured transmission lines were simulated in microwave frequency range 100-2000 MHz, via the software SONNET LITE, in order to prove the band pass filter functionality. The 100 x4 mm transmission line had a resonant frequency at 1100 MHz, while the 150 x 4 mm line had resonant frequencies at 700 MHz and 1400 MHz. The resonant frequency differed from the initial simulation target of 900 MHz, after introducing the substrate dielectric parameters. These simulation results were validated by vector network analyzer (VNA) measurements on the four coated samples. The PocketVNA 4G vector network analyzer attached to a laptop, with the related software was used in this regard (Fig. 16).

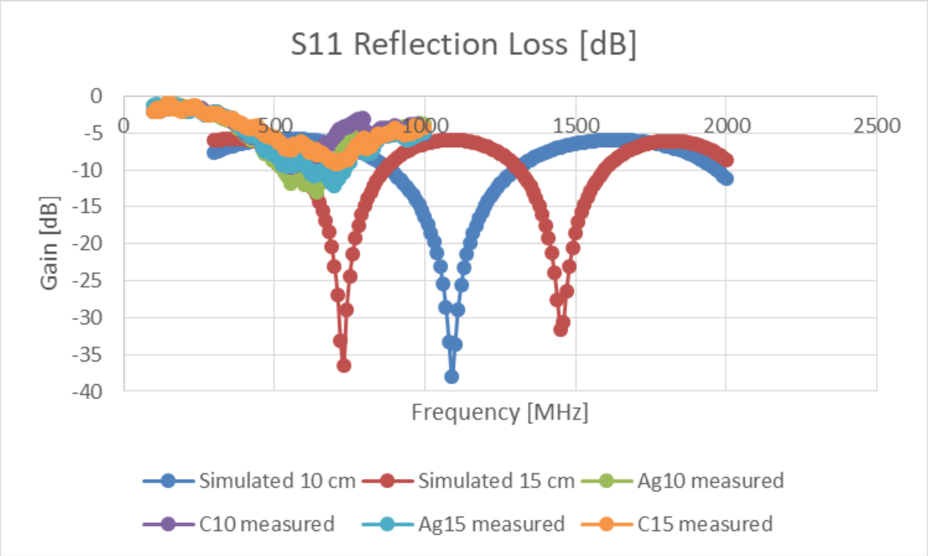


Fig. 16*: Simulated and measured results for the four transmission lines*

The measurements with the VNA were conducted in the frequency range 100-1000 MHz, as calibration results proved to be more stable in this frequency range.

4. DISCUSSION

The morphological investigations revealed that the surface of silver conductive coating is discontinued, containing very compacted granules which are enough in electrical contact to assure the electrical conductivity. The surface of C conductive coating is continuous, a fact which leads to a good electrical conductivity. The chemical investigations reveal the silver and the carbonic content of pastes, the oxides and other C-O organic compounds that are present in the paste matrixes and the C-C structures from carbonic paste (1500-1000 cm^{-1} band).

On the other hand, the measured reflection loss (S11) of the manufactured transmission lines broadly coincides with the simulation values (Fig. 16). This is mainly due to two reasons:

- the electric conductivity of the simulation was set to 10^7 S/m, while the manufactured transmission lines have 10^3-10^5 S/m, with a shift of the Gain in dB;
- the measured parameters of the dielectric textile substrate (relative electric permittivity and tangent delta) [6], may differ and hence the resonant frequency shifts.

However, in case of the 15 cm transmission lines, the measurement has same resonant frequency as the simulation.

5. CONCLUSIONS

The aim of this research was to provide flexible microwave transmission lines to deliver maximum power to wearable antennas. The resonant frequency was initially designed for 900 MHz (GSM communication), however after updating the simulation with the current physical parameters of the dielectric substrates, the resonant S11 frequency of the 100 mm line and 150 mm line shifted to 1100 MHz and 700 MHz. Specific aim of this paper was to analyze, from a morphological point of view (SEM), and from a physical-chemical perspective (EDX, FT-IR), the quality of the transmission lines on the dielectric textile substrate prepared by coating with silver and carbon pastes. Envisaged analysis was directed to the electric conductivity and signal continuity, as well as adhesion of the conductive paste onto the textile substrate. The SEM analysis presents some discontinuous features of the transmission lines, and regions in high electrical contact. The EDX analysis showed the presence of silver chloride in the case of the silver paste, and carbon and oxygen, from the organic additives, in the carbon paste. The FT-IR analysis of the carbon paste shows the carbon-carbon bonds of carbonic structures manifested in the 1500-1000 cm^{-1} middle-infrared band of vibrational molecular transitions, which were absent from the silver paste due to silver-chloride ionic bonding rather than carbon-carbon bonding.

The proposed textile structure for the flexible microstrip transmission lines generally meets its designed functionality. The measured values of the reflection loss S11 shifted when compared to the simulated values in Gain and resonant frequency, due to differences in the electric conductivity of the traces and in the electric parameters of the dielectric textile substrate. Future work envisages a better correlation of the design and simulation of the band pass with respect to physical and electrical parameters.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Ł. Januszkiewicz and I. Nowak, *"Knitted Microwave Transmission Line for Wearable Electronics",* Appl. Sci. 2024, 14(23), 10798. https://doi.org/10.3390/app142310798

[2] R. Salvado et al., "*Textile materials for the design of wearable antennas: A survey*", Sensors 2012, 12(11), 15841–15857. https://doi.10.3390/s121115841

[3] M. Rafiq et al., "*A review on the manufacturing techniques for textile based antennas*", J. Eng. Fibers Fabr., vol. 19, pp. 1–18. https://doi.org/10.1177/15589250241226585

[4] V. Marterer et al., "*Wearable textile antennas: investigation on material variants, fabrication methods, design and application*", Fash. Text. (2024) vol. 11, 9. https://doi.org/10.1186/s40691-023-00369-1

[5] P. Salonen et al., "*Effect of textile materials on wearable antenna performance: A case study of GPS antennas*", *IEEE Antennas and Propagation Society Symposium, 2004.* Monterey, CA, USA, vol. 1, pp. 459–462, 2004. http://doi.org/10.1109/APS.2004.1329673

[6] I. R. Radulescu et al., "*Conductive textile transmission lines for microwave frequency filters*", Annals of The University of Oradea Fascicle of Textiles, Leatherwork, vol. 2, pp. 71–78 2025.

[7] R. V. Caramaliu, A. Vasile and I. Bacis, "*Wearable vital parameters monitoring system*", Proc. SPIE 9258, Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies VII, 92580R (20 February 2015). https://doi.org/10.1117/12.2070041

[8] I. R. Rădulescu et al., "*Conductive textile structures and their contribution to electromagnetic shielding effectiveness*", Industria Textila, 71(5), pp. 432–437, 2020. http://doi.org/10.35530/IT.071.05.1783

ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

COMPARATIVE ASSESSMENT OF PLA, PHA AND NATURAL CELLULOSIC FIBERS IN SUSTAINABLE TEXTILE APPLICATIONS

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Abstract: *The textile industry is under increasing pressure to reduce dependence on petroleum-based fibers and to adopt materials with lower environmental impact. Among the most promising alternatives are polylactic acid (PLA), polyhydroxyalkanoates (PHA), and natural fibers, each offering distinct benefits and limitations for sustainable textile applications. PLA is a bio-based polymer that is relatively easy to process and already used in some textile and nonwoven products, but its biodegradation is often limited to controlled industrial conditions. PHA is a microbial polyester with strong biodegradation potential and high sustainability appeal, yet its commercial adoption remains constrained by high production costs and processing challenges. Natural fibers such as hemp, flax, cotton, and jute are renewable and widely used in textiles, offering comfort, breathability, and established manufacturing routes, although they often require treatment or blending to overcome variability and moisture sensitivity. This short review compares these three material families in terms of origin, biodegradability, processability, mechanical performance, cost, and textile suitability. The analysis shows that no single fiber can satisfy all sustainability and performance requirements. Instead, future sustainable textile systems will likely depend on material selection according to application, blending strategies, and improved end-of-life management.*

Key words: *PLA, PHA, natural fibers, sustainable textiles, biodegradable polymers, bio-based materials*

1. INTRODUCTION

Sustainable textile development has become a major research direction because conventional synthetic fibers are tied to fossil resources and waste problems. Conventional synthetic fibers, which are predominantly derived from petroleum, are associated with substantial greenhouse gas emissions, resource depletion, and persistent waste in the environment [1], [2]. Lifecycle studies indicate that the production of these fibers is energy-intensive and strongly linked to fossil-based supply chains, while their limited biodegradability can result in long-term accumulation in ecosystems [3]. These environmental drawbacks are further accentuated by the global context of energy and raw-material insecurity, including volatility in oil markets and disruptions affecting strategic transport corridors, such as the Strait of Hormuz, nowadays. Such conditions highlight the vulnerability of petroleum-based supply chains and reinforce the need for renewable, bio-based alternatives in textile manufacturing.

Within this context, bio-based polymers and natural cellulosic fibers have received increasing attention as possible substitutes for conventional textile materials. Among them, polylactic acid (PLA), polyhydroxyalkanoates (PHA), and natural fibers such as cotton, flax, hemp, and jute represent three particularly relevant categories for comparative analysis because they differ in technological maturity, biodegradability, cost profile, and textile performance [4, 5]. PLA and PHA are bio-based polyesters with distinct processing and degradation characteristics, while natural fibers are long-established renewable materials that continue to play a central role in sustainable-textile research [4]. The objective of this paper is to compare these three material families in relation to their origin, processing, properties, environmental performance, and textile suitability, and to identify their main advantages and limitations for future sustainable textile systems.

2. MATERIALS AND METHODS

This paper was developed as a short narrative review based on recent literature addressing sustainable fibers for textile applications. The comparison focuses on three material families (PLA, PHA, and natural fibers), selected because they represent distinct but complementary approaches to reducing the fossil-based content of textiles. The review criteria included raw-material origin, fiber-processing routes, mechanical and thermal characteristics, biodegradability, end-of-life considerations, industrial maturity, and representative textile applications.

Sources included review papers, technical overviews, and sector-specific analyses concerning textile processing, biodegradable polymers, and natural-fiber performance along with the use of these materials in apparel, nonwovens, home textiles, and technical textiles. A particular attention was also given to reported constraints linked to cost, moisture sensitivity, hydrolytic degradation, or limited infrastructure for composting and recycling.

The resulting synthesis is qualitative and comparative in nature and is intended to provide an academically grounded overview suitable for a short review article format.

2.1 PLA / PHA, as biodegradable polymers

PLA / PHA are part of the main class of biodegradable polymers [6], as shown in **Fig 1**.

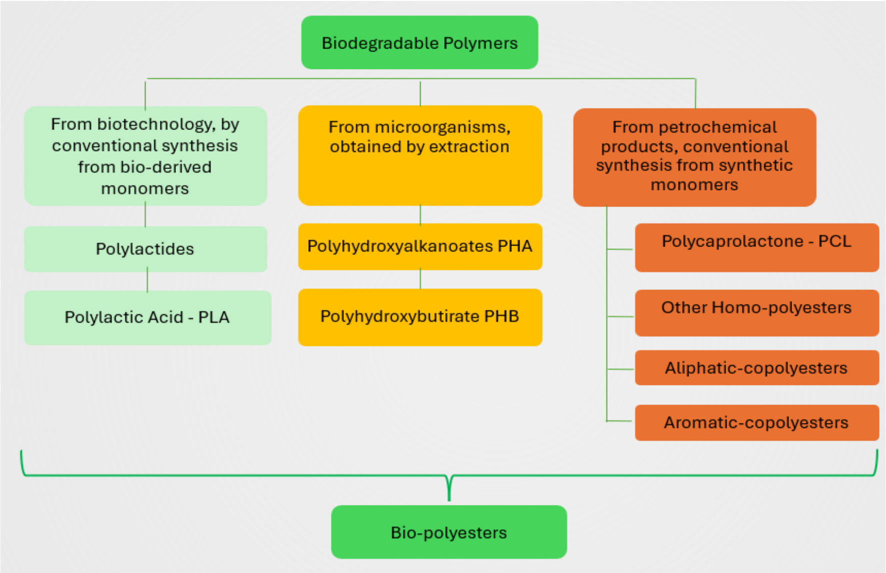
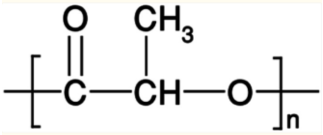


***Fig. 1**: Main biodegradable polymers*

Bio-based polymers could be obtained from microbial production, such as PHA, or by producing bio-based monomers through fermentation and conventional chemistry followed by polymerization, such as PLA. There are also polymers that are prepared from petrochemical products (synthetic monomers, such as polycaprolactone, PCL). [6 Averous, 2012]

2.2 PLA for textiles

PLA is a bio-based and biodegradable polymer produced from renewable plant-based feedstocks, such as corn starch or sugar cane, which makes it a prominent alternative to petroleum-based polyesters, used in the textile industry [4]. The raw material used in the synthesis of PLA is the high purity monomer, lactide [4]. Chemical formula is stated in **Fig. 2** [6].



$$\left[-\overset{\overset{\displaystyle O}{\|}}{C}-\overset{\overset{\displaystyle CH_3}{|}}{C}H-O- \right]_n$$

Fig. 2*: The chemical structure of PLA [6]*

The PLA family includes poly(l-lactide) (PLLA), poly(d-lactide) (PDLA), poly(dl-lactide) (PDLLA), poly(meso-lactide), and copolymers obtained from the monomers [4]. Based on the stereochemistry of the polymer structure, PLA can be semicrystalline or amorphous, which provides the PLA fibers with specific properties, as increased durability, while the purity of lactic acid stereo-copolymers affects the physical properties of PLA, depending on the applied production process [4]. PLA fibers are typically produced via melt spinning, either as continuous filaments or as staple fibers, and can be integrated into conventional spinning, knitting, and weaving lines without major process changes [7]. This relative process compatibility has supported its introduction into apparel blends, home-textile products, and disposable or semi-durable nonwoven articles. **Fig. 3** shows PLA short fibers and filaments produced by Shenzen Esun Industrial Group.

Fig. 3*: PLA short fibers and filaments [8]*

With respect to performance, PLA fibers exhibit useful tensile strength, acceptable dimensional stability, low pilling tendency, and a smooth, soft handle surface which enhances comfort in next-to-skin products such as sportswear, underwear, and children's clothing [9]. PLA also offers moderate moisture-wicking and reasonable breathability, which can be further improved by texturing, fiber cross-section design, or blending with cellulosic fibers [10]. However, several limitations remain significant. PLA exhibits lower thermal resistance than polyethylene terephthalate (PET), with a relatively low glass-transition temperature and susceptibility to deformation during high-temperature processing, finishing, or ironing [9,10]. In addition, PLA is sensitive to hydrolytic degradation under conditions of moisture, elevated temperature, or alkaline treatment, which can constrain dyeing and wet processing.

From an environmental point of view, PLA is frequently described as biodegradable and industrially compostable, although its effective degradation generally depends on controlled conditions rather than unmanaged natural environments [9].

In summary, PLA is a technologically mature and relatively versatile bio-based fiber that can be processed with conventional textile machinery and offers advantages in renewability and compostability. However, its thermal sensitivity, hydrolytic degradation, and dependence on industrial end-of-life infrastructure imply that its deployment should be carefully aligned with specific textile applications and value-chain capabilities.

2.3 PHAs for textiles

Polyhydroxyalkanoates (PHAs) are a class of intracellular biopolymers synthesized by various bacteria, where they serve as carbon and energy storage in the form of granules [11]. These biopolymers are produced through fermentation of renewable carbon resources, including sugars, plant oils, and agricultural residues [12]. Structurally, PHAs consist of hydroxyalkanoate (HA) monomer units arranged into polymer chains formed during bacterial fermentation [12]. Chemical structure is presented in **Fig. 4.**

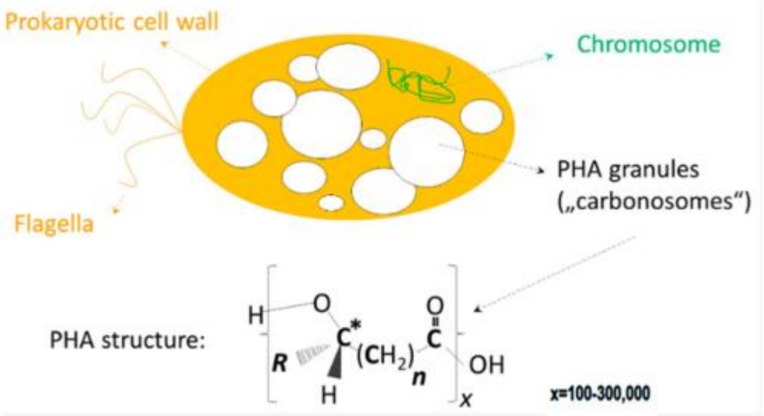


Fig. 4*: The chemical structure of PHA [11]*

PHAs can be converted into textile fibers mainly through melt spinning or solution-based techniques (such as wet, dry, or electrospinning), often with modifications like copolymerization or blending to improve processability and mechanical performance [11]. Melt spinning is the closest to conventional synthetic fiber production. The PHA (e.g., PHB or PHBV) is melted and extruded through spinnerets, then drawn to orient the polymer chains [13]. PHA’s principal attraction in the textile sector lies in their biodegradability profile, since PHA materials have been reported to degrade in soil, water, marine environments, and industrial composting systems under suitable conditions [12]. This characteristic provides a substantial conceptual advantage for textile products designed within circular-economy or low-persistence in ecosystems. Depending on formulation, PHA materials can exhibit behavior ranging from relatively rigid to more elastomeric, which creates opportunities for diverse textile uses, including biodegradable wipes, agricultural textiles, selected medical or hygiene materials, protective layers, and niche fashion products where biodegradability is prioritized [14]. **Fig. 5** presents variants of staple PHA fibers, in paralell with fillaments.

***Fig. 5**: The chemical structure of PHA [15,16]*

PHAs are often blended with other polymers (PLA, PCL) to improve spinnability, flexibility, and durability. This is currently one of the most practical approaches for textile applications [14]. PHA fibers are reported to be lightweight, mechanically robust, and breathable, with good comfort properties for clothing and personal protective applications.

Despite these advantages, PHA fibers still face significant challenges. Production costs are higher than those of conventional synthetics due to complex fermentation and downstream processing requirements, and industrial scale PHA manufacturing remains limited globally [4]. Thermal and mechanical behavior can be less predictable than that of PLA or PET, and long term performance under repeated washing and mechanical stress has not yet been extensively documented in open literature [4].

2.4 Natural cellulosic fibers in textiles

Natural fibers, such as cotton, flax, hemp, jute, are widely regarded as sustainable alternatives to synthetic fibers because they are derived from renewable biological sources and are generally biodegradable at end of life. These fibers are typically extracted from plant stems, seeds, bast layers, and can be processed into yarns and fabrics using well established spinning, weaving, and knitting technologies. Natural fibers are valued for their low thermal conductivity and good thermal insulation, which makes them suitable for protective clothing and other purpose-related textiles.

The specific properties of natural fibers vary substantially according to botanical origin, cultivation conditions, harvesting method, and subsequent treatment [17]. Bast fibers such as flax and hemp can offer relatively high stiffness and strength, whereas cotton is typically associated with softness and wear comfort. Natural fibers also present hydrophilic behavior and significant moisture regain, which can improve thermophysiological comfort but may also result in dimensional instability or property changes under humid conditions [17].

On the other hand, natural fibers display several limitations that affect their widespread deployment as unique components in high performance textiles. Variability in fiber diameter, length, and strength between batches can complicate quality control and fabric consistency. Sensitivity to moisture and biological degradation, especially in humid environments, can reduce durability unless fibers are chemically treated.

3. RESULTS AND DISCUSSIONS

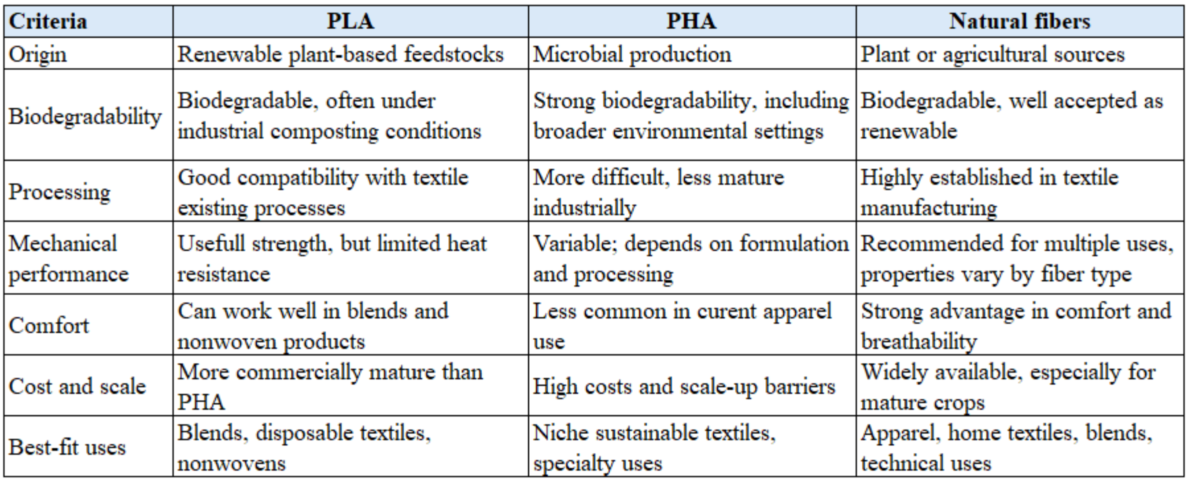
3.1 Comparative assessment

PLA, PHA, and natural cellulosic fibers each occupy a distinct niche in the landscape of sustainable textile materials, and their relative strengths and weaknesses become clearer when examined side by side. From a production and process perspective, PLA is the most mature among the bio based options, with fibers that can be integrated into standard spinning, knitting, and weaving lines without major modifications. PLA’s mechanical properties are broadly comparable to those of conventional polyester, yet its lower thermal stability and susceptibility to hydrolytic degradation limit its suitability for high temperature processing and long term durability under moisture stress. In contrast, PHA offers superior biodegradability in a wider range of environments, including soil, water, and marine settings, which makes it attractive for circular economy oriented textiles, but its production cost structure and scale-up challenges restrict its current deployment to niche, high value products.

Natural fibers, such as cotton, flax, hemp, and jute, provide a renewable and biodegradable base material with well established comfort and thermal insulation properties, and they can be processed on existing textile equipment with minimal capital investment. However, their mechanical performance and quality can vary with cultivation conditions and post harvest treatments, and many require additional processing to improve moisture resistance, strength, and dyeing behavior. In practical terms, PLA is particularly suitable for blends, disposable textiles, and technical nonwovens where end of life management can be controlled, while PHA is currently better positioned for niche biodegradable products and specialized applications where environmental degradation is a primary design objective.

3.2 Stuctured comparison

Fig. 6 offers a structured comparison which includes the main characteristics of PLA, PHA, and natural fibers in terms of origin, biodegradability, processability, mechanical performance, and typical textile applications.



Criteria	PLA	PHA	Natural fibers
Origin	Renewable plant-based feedstocks	Microbial production	Plant or agricultural sources
Biodegradability	Biodegradable, often under industrial composting conditions	Strong biodegradability, including broader environmental settings	Biodegradable, well accepted as renewable
Processing	Good compatibility with textile existing processes	More difficult, less mature industrially	Highly established in textile manufacturing
Mechanical performance	Usefull strength, but limited heat resistance	Variable; depends on formulation and processing	Recommended for multiple uses, properties vary by fiber type
Comfort	Can work well in blends and nonwoven products	Less common in curent apparel use	Strong advantage in comfort and breathability
Cost and scale	More commercially mature than PHA	High costs and scale-up barriers	Widely available, especially for mature crops
Best-fit uses	Blends, disposable textiles, nonwovens	Niche sustainable textiles, specialty uses	Apparel, home textiles, blends, technical uses

Fig. 6*: A structured comparison of PLA, PHA and natural cellulosic fibers*

The structured summary highlights the trade-offs between these three material families:

PLA's relatively high industrial maturity and processability, PHA's strong biodegradability but limited economic and technological readiness, and the comfort and renewal potential of natural fibers balanced against their variability and moisture-sensitivity. By presenting these attributes side by side, the table supports the discussion of appropriate fiber selection for different types of sustainable textile products.

4. CONCLUSIONS

This review has highlighted that PLA, PHA and natural fibers each contribute in different ways to the development of sustainable textile systems. PLA represents a relatively mature bio based polymer with good processability and mechanical properties comparable to conventional polyester, making it suitable for apparel blends, disposable textiles, and technical nonwovens, when paired with controlled end of life strategies, such as industrial composting or collection based recycling. PHA, although less economically viable at present, offers enhanced biodegradability under diverse environmental conditions and is particularly promising for niche, high value textiles, where biodegradability is a primary design criterion. Natural cellulosic fibers, including cotton, flax, hemp, jute, and others, remain the most versatile option for apparel, because they combine renewability, biodegradability, comfort, and industrial familiarity, even if they require optimization for performance, consistency and durability.

Taken together, these materials suggest that the most effective solution toward more sustainable textiles lies not in choosing a single "best" fiber, but in strategically combining complementary materials. Blends and hybrid structures that integrate PLA or PHA with natural fibers can balance performance, comfort, and environmental footprint while reducing dependence on fossil based resources.

In the light of the authors'contribution to the literature, the comparison table offers a concise, structured overview that synthesizes key properties and application profiles of PLA, PHA, and natural fibers, reinforcing the paper's argument that no single fiber type is universally optimal for application-driven material selection in sustainable textile design.

Future textile systems are likely to depend on hybrid material combinations, improved fiber engineering, better composting and recycling infrastructure, and more rigorous lifecycle assessment, in order to balance environmental objectives with real manufacturing and consumer requirements.

REFERENCES

[1] R. P. Singh, S. Mishra, A. P. Das, "*Synthetic microfibers: Pollution toxicity and remediation*", in Chemosphere, Vol. 257, October 2020, 127199, https://doi.org/10.1016/j.chemosphere.2020.127199

[2] E. R. S. Kraetzig, L.V. Avila, A.L. Salvia, R.S. Bichueti, M.A. Schvartz, "*An analysis of practices implemented within the textile sector to reduce greenhouse gas emissions*," Navus-Revista De Gestao E Tecnologia, vol. 14, 2024, DOI10.22279/navus.v14.1899

[3] P. Tekin, H. Alici, T. Demirdelen, "*A Life Cycle Analysis of a Polyester-Wool Blended Fabric and Associated Carbon Emissions in the Textile Industry*," Energies, vol. 17, Jan. 2024.

[4] A. Z. Naser, I. Deiab, B.M. Darras, "*Poly(lactic acid) (PLA) and polyhydroxyalkanoates (PHAs), green alternatives to petroleum-based plastics: a review*," in RSC Adv., 2021, 11(28), pp. 17151-17196. doi: 10.1039/d1ra02390j. PMID: 35479695; PMCID: PMC9033233

[5] S. Sayam, "*Natural fibers in sustainable materials: extraction technologies, fiber modification, and performance-sustainability relationships*", RSC Adv. Feb. 2026, 16(12):10495-10537. doi: 10.1039/d5ra09029f. PMID: 41737458; PMCID: PMC12926875.

[6] L. Avérous and E. Pollet, "*Environmental Silicate Nano-Biocomposites*", Springer-Verlag London, 1st ed., 2012, ISBN 978-1-4471-4108-2 (eBook)

[7] V. Gupta, "*Melt-Spinning Processes. Manufactured Fibre Technology*"; Springer, 1997; pp 67−97. DOI: 10.1007/978-94-011- 5854-1_4.

[8] https://www.esungroup.net/news/understanding-polylactic-acid-pla-fiber-properties-and-applications/

[9] A. Z. Naser, I. Deiab, F. Defersha, S. Yang, "*Expanding poly (lactic acid)(PLA) and polyhydroxyalkanoates (PHAs) applications: A review on modifications and effects*". Polymers 2021, 13 (23), 4271

[10] D.P. Raja, K. Ravichandran, V. Rangaraj, T. Panchal, and B. Dasan, "*Poly(lactic acid) fibers, yarns and fabrics: manufacturing, properties and applications*," Textile Progress, 2023, vol. 55, no. 1, pp. 1–60

[11] M. Koller, "*Biodegradable and Biocompatible Polyhydroxyalkanoates (PHA): Auspicious Microbial Macromolecules for Pharmaceutical and Therapeutic Applications*", Molecules, 2018, 23(2), 362; https://doi.org/10.3390/molecules23020362

[12] J. Sehlin and N. Hashemi, "*Biodegradable Polyhydroxyalkanoate Fibers in Sustainable Textiles*", ACS Sustainable Resource Management, 2025, vol.2, pp. 876-879

[13] A. Koeppel, C. Holland, "*Progress and trends in artificial silk spinning: a systematic review*". ACS Biomaterials Science & Engineering, 2017, 3 (3), pp. 226−237

[14] T. Iwata, T. Tanaka, "*Manufacturing of PHA as Fibers. Plastics from bacteria: natural functions and applications*", 2010, vol. 14, pp. 257−282

[15] https://www.neonliontech.com/bio-based-pha-staple-fibers-marine-degradation-home-compostable/

[16] https://pha-sourcing.com/applications/textile/

[17] T. Islam, M. Hossain, & S. Covington, "*Natural Fibers Towards Fashion Sustainability: A Review of Raw Materials, Production, Application, and Perspective*", Journal of Natural Fibers, 2025, 22(1). https://doi.org/10.1080/15440478.2025.2462218

[16] T. Iwata, T. Tanaka, "*Manufacturing of PHA as Fibers. Plastics from bacteria: natural functions and applications*", 2010, vol. 14, pp. 257−282

ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

THE FASHION INDUSTRY IN MOLDOVA IN THE CONTEXT OF ALIGNMENT WITH EUROPEAN UNION TRENDS AND PROSPECTS FOR INCREASING COMPETITIVENESS AND SUSTAINABLE DEVELOPMENT

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Abstract: *The fashion industry is among the most dynamic economic sectors worldwide, but also one of the most exposed to environmental and social pressures due to intensive resource use, short production cycles, and complex global value chains. In the European Union, these challenges have triggered a profound transformation of the fashion industry, driven by policies promoting sustainability, circular economy principles, digitalization, and extended producer responsibility. As an economic partner closely integrated into European markets, the Republic of Moldova is directly influenced by these structural changes.*

This article analyzes the alignment of the fashion industry in the Republic of Moldova with key European Union trends and examines the prospects for increasing competitiveness while ensuring sustainable development. The study highlights the structural characteristics of the Moldovan fashion industry, which remains predominantly based on C&M and CMT production models. Although these models have facilitated integration into European value chains, they have also constrained domestic value added and limited functional upgrading.

At the same time, recent trends indicate a gradual shift toward higher value-added activities. An increasing number of small and medium-sized enterprises have initiated production under their own brands, mainly targeting the domestic market. The analysis shows that sustainability, digitalization, eco-design, and circular economy practices can act as strategic drivers of competitiveness rather than merely compliance requirements. Strengthening innovation capacity and human capital emerges as essential for the long-term sustainable integration of the Moldovan fashion industry into European markets.

Key words: *fashion industry, competitiveness, sustainability, value chain, digitalization, circular economy.*

1. INTRODUCTION

The fashion industry is among the most dynamic but also most pressured economic sectors globally, characterized by short production cycles, intense competition, and significant environmental impact. For small and medium-sized enterprises (SMEs) in the European Union and the Republic of Moldova, competitive challenges are intensified by increasingly stringent requirements regarding sustainability, traceability, and social responsibility along the value chain. In this context, integrating competitiveness with sustainable development becomes not merely a strategic option, but an essential condition for maintaining and strengthening market position.

The sustainable development approach is particularly relevant for the fashion industry, a sector traditionally associated with intensive resource consumption, waste generation, and social pressures related to working conditions.

From a competitiveness perspective, Michael E. Porter emphasizes that sustainable competitive advantage does not derive from short-term cost reductions, but from productivity, innovation, and continuous improvement capability [1]. Applied to SMEs in the fashion industry, this vision highlights the importance of investments in design, efficient production technologies, supply chain management, and differentiation through value-added, including sustainability criteria.

For fashion enterprises in the European Union, the transition toward sustainable business models is accelerated by European policies promoting the circular economy, environmental impact reduction, and social responsibility. In this framework, competitiveness is no longer assessed exclusively through immediate economic performance, but through firms' ability to create long-term value for customers, employees, and communities. The World Economic Forum emphasizes that sustainable prosperity is determined by an integrated set of factors including effective institutions, innovation, human capital, and the responsible use of natural resources [2].

For fashion enterprises in the Republic of Moldova, the challenge of sustainable competitiveness is twofold. On the one hand, firms must respond to European market requirements, including quality and sustainability standards. On the other hand, they operate in an economic context characterized by limited financial and technological resources. Thus, sustainable competitiveness can be defined as the ability of organizations and economies to achieve economic performance while simultaneously preserving social and natural capital. [3]

2. EUROPEAN TRENDS IN THE FASHION INDUSTRY

2.1 Sustainability as a new industrial paradigm

Over the past two decades, the fashion industry has entered a profound process of structural reconfiguration, driven by growing recognition of the significant negative environmental and social impacts of the traditional fast fashion model. The dominant linear model, based on the logic "produce–consume–discard", has led to overproduction, intensive use of natural resources, and the generation of substantial volumes of textile waste, becoming incompatible with global sustainable development objectives. [4]

In response to these challenges, sustainability increasingly asserts itself as a new industrial paradigm, steering the fashion sector toward principles inspired by the circular economy. This paradigm entails designing products to be durable, repairable, and recyclable, keeping materials in use for longer periods, and minimizing waste generation throughout the product life cycle. [5]

At the European Union level, this shift is institutionally supported by the EU Strategy for Sustainable and Circular Textiles, which aims at the structural transformation of the textile industry by 2030. The strategy stipulates that textile products placed on the European market should be more durable, contain a higher share of recycled materials, and be accompanied by effective mechanisms for collection, reuse, and recycling.[6] In this context, sustainability is no longer perceived as an external constraint, but as an essential criterion of competitiveness and industrial adaptability.

One of the central dimensions of the new paradigm is extending the lifespan of clothing products. Studies show that prolonging the use of a garment significantly reduces its carbon footprint and the resource consumption associated with producing new items. Consequently, business models based on repair, reuse, resale, and rental are gaining increasing importance, particularly for SMEs in the fashion industry, which can more rapidly adopt such flexible solutions [7].

The transition toward sustainability also entails cultural and organizational change within fashion firms. This includes the adoption of eco-design, greater transparency in supply chains, and the assumption of extended producer responsibility throughout the textile product life cycle. For

SMEs, this approach may generate competitive advantages through differentiation, the development of a responsible brand image, and facilitated access to European markets.[8]

To assess the level of sustainability within the fashion industry in the Republic of Moldova, a survey was conducted among 20 enterprises operating in the sector and representing different business models, including service provision for European clients and production and commercialization under own brands.[8]

The findings of the survey enabled a comparative analysis between sustainability-related trends and policy orientations at the EU level and the current state of sustainability practices in the Republic of Moldova (Table 1).

Tabele 1. *Dominant trends in the fashion industry: European Union and Republic of Moldova*

Dimension	European Union	Republic of Moldova
Production model	Transition from fast fashion to sustainability. Durable and circular textiles	~76% production in lohn regime; ~24% own-brand production; early transition toward sustainability
Role of sustainability	Regulatory obligation	Incipient implementation
Digitalization	3D design, Digital Product Passport	3D design, low level
Value chains	Controlled supplier integration, nearshoring	Peripheral position
Competitiveness	Innovation and branding, quality and compliance	Manufacturing quality, cost competitiveness

Source: Compiled by the author based on [6] and [8].

This comparative overview highlights the structural gaps between the Republic of Moldova and the main EU markets, justifying the accelerated implementation by the APIUS association of the Action Plan to Ensure Sustainability for the Textile Industry in the Republic of Moldova. [8]

2.2 The European Union as a normative actor in the fashion industry

The EU Strategy for Sustainable and Circular Textiles establishes as a strategic objective a paradigm shift by 2030 from the linear model of production and consumption toward a systemic model aimed at maintaining the value of products, materials, and resources in the economy for as long as possible. Within this framework, circular-oriented design becomes an essential tool for reducing primary resource consumption and limiting textile waste generation.

At the same time, the EU strategy integrates the principle of extended producer responsibility (EPR), through which economic actors in the fashion industry are called upon to assume greater responsibility for the impact of their products throughout the entire life cycle, including post-consumer stages. The implementation of EPR mechanisms stimulates waste prevention, separate collection, reuse, and textile recycling, thereby contributing to reduced environmental pressure and internalization of the social and ecological costs of production.

By combining the circular economy with extended producer responsibility, the EU strategy seeks not only to reduce the environmental and social impact of the textile industry, but also to create a competitive framework in which sustainability becomes a determining factor for access to and performance on the European market. [6].

To translate the objectives of the EU Strategy for Sustainable and Circular Textiles into concrete economic practices, the European Union has introduced a series of public policy instruments that directly influence production, reporting, and textile product management. These measures significantly affect external suppliers to the European market, including enterprises in the

Republic of Moldova, which must adapt their processes and standards to remain competitive and eligible on the EU market.

Based on the surveyed enterprises’ responses and the current state of the fashion industry in the Republic of Moldova, the analysis outlines the expected impact of EU policy instruments on the sector. The results show how these measures may affect sustainability practices, strategic orientation, and compliance capacity of Moldovan fashion enterprises, shaping the industry’s future development (Table 2).

Tabele 2. *EU public policy instruments and implications for the fashion industry in the Republic of Moldova*

EU instruments	**Main objective**	**Implications for Moldova**
EU Textile Strategy	Circular economy	Industrial modernization
Extended Producer Responsibility (EPR)	Textile waste management	Increased compliance costs
Digital Product Passport	Traceability	Need for digitalization
European Green Deal	Climate neutrality	Gradual adaptation of standards

Source: Compiled by the author based on [6], [8] .

The table shows that EU policies generate both constraints and opportunities for the development of Moldova’s light industry.

3. THE REPUBLIC OF MOLDOVA IN THE FASHION INDUSTRY VALUE CHAIN

3.1 The current structural model

The fashion industry is one of the important branches of the manufacturing industry in the Republic of Moldova and of the national economy as a whole. [10] In 2024, it accounted for approximately 13% of the total number of enterprises in manufacturing, over 20% of total employment, and nearly 8% of turnover. The sector is strongly export-oriented, accounting for about 9.6% of total national exports.

Despite being among the country’s top five exporters, the industry is predominantly oriented toward export manufacturing operations under C&M and CMT regimes. This positioning limits the value-added created at the national level. The degree of Moldova’s integration into the European fashion value chain is illustrated in Figure 1.

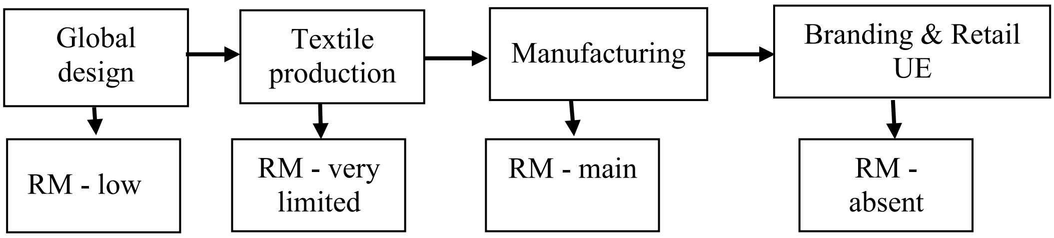

Fig. 1. *Positioning of the Republic of Moldova in the fashion industry value chain*
Source: Compiled by the author.

Figure 1 highlights the concentration of activities in Moldova at low value-added stages and the need to expand participation toward higher stages of the value chain.

Aligning Moldova's fashion industry with European trends involves a structural transition from cost-based competitiveness (C&M and CMT models) toward a value-added and innovation-oriented model. This requires the implementation of in-house design and the development of own brands as resilient and competitive business models.

To strengthen competitiveness, Moldova's light industry must overcome a purely cost-based model and shift toward higher value-added activities, such as own product development, design, and local branding. Over the past five years, the share of production manufactured and sold under own brands on the domestic market increased by two percentage points. Although growth is relatively slow, it indicates a clear trend toward higher value-added products. It should also be noted that some enterprises sell own-brand products on external markets through e-commerce.

The structure of production and its distribution by market is shown in Figure 2.

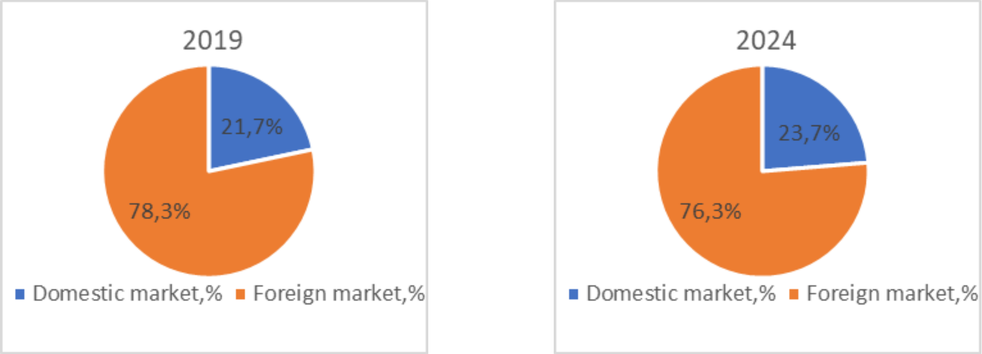

Fig.2. *Evolution of the structure of manufactured and marketed production by sales markets*
Source: Compiled by the author based on [11].

In addition to implementing high value-added products to enhance competitiveness, fashion enterprises in Moldova need innovation, digitalization, and circular economy practices. Technological investment and professional skills development are essential conditions for this transition. The adoption of energy-efficient technologies, use of sustainable materials, and respect for social standards can increase the sector's attractiveness for European investors and partners.

For the Republic of Moldova, adapting to new EU market requirements is no longer optional, but an essential condition for maintaining competitiveness. With APIUS Association joining EURATEX, Moldova's fashion enterprises will be guided in aligning with European policies and capitalizing on opportunities created by new trends. Consequently, the fashion industry can evolve toward a sustainable and resilient long-term model.

5. CONCLUSIONS

The analysis reveals that the predominant reliance of fashion industry enterprises in the Republic of Moldova on C&M and CMT production models significantly constrains value creation and positions the sector at the periphery of European value chains. This structural dependence is likely to hinder the alignment process with European Union trends, which are increasingly oriented toward sustainability, circular economy principles, and digitalization.

To overcome this situation, it is recommended to accelerate the implementation of the Action Plan 2023–2027 for the implementation of the sustainability roadmap for the light industry in the Republic of Moldova [8]. This plan prioritizes several key strategic directions, including: increasing the production and commercialization of garments under own brands to enable diversification and a shift toward higher value-added products; retechnologization of the industry and the adoption of innovation; digital transformation of production and management processes;

implementation of sustainable and circular textiles; and alignment with standards compatible with the requirements of the European market.

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REFERENCES

[1] M. E. Porter and Claas van der Linde, "*Toward a New Conception of the Environment-Competitiveness Relationship*," Journal of Economic Perspectives, vol. 9, nr.4, pp. pp. 97-118, Autumn, 1995. [Online]. Available: https://www.jstor.org/stable/2138392

[2] A., Balkytė & M., Tvaronavičienė. *Perception of competitiveness in the context of sustainable development: Facets of "sustainable competitiveness".* Journal of Business Economics and Management, 11(2), pp. 341–365, 2010. [Online]. Available: https://journals.vilniustech.lt/index.php/JBEM/article/view/5858/5100

[3] C., Williment, "*Why WEF is Urging Change in Sustainability, Finance and Tech*," Sustainability Magazine, 9 septembrie 2025. [Online]. Available: https://sustainabilitymag.com/news/why-wef-is-urging-change-in-sustainability-finance-and-tech

[4] M., Gheorghița, *Contribuția angajamentului social și de mediu la sustenabilitatea întreprinderilor din industria ușoară și implementarea economiei circulare*, Conferința "Creativitate. Tehnologie. Marketing" IV, Chişinău, Moldova, 31 martie 2023, pp. 17-22. [Online]. Available: https://ibn.idsi.md/vizualizare_articol/191758

[5] M., Gheorghița, C., Crucerescu, *Alignong the clothing manufacturing industry of the Republic of Moldova with the sustainable future of fashion,* The USV Annals of Economics and Public Administration, Vol. 25 No. 1(41), 2025, pp. 7-17. [Online]. Available: https://annalsfeaa.usv.ro/index.php/annals/article/view/2915/3957

[6] Strategia UE pentru textile sustenabile și circulare. Bruxelles, 30.3.2022. COM(2022) 141 final. [Online]. Available: https://eur-lex.europa.eu/legal-content/RO/TXT/HTML/?uri=CELEX:52022DC0141

[7] E., D'Itria, & R., Aus, *Circular fashion: Evolving practices in a changing industry*, Sustainability: Science, Practice and Policy, Vol. 19, no. 1, 2023. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/15487733.2023.2220592#abstract

[8] D., Vantyghem, M., Gheorghița, D., Allo, D., Zavec. *Viitorul sustenabil al industriei de modă din Republica Moldova*. Chisinau, 2024. [Online]. Available: https://apius.md/2024/06/10/viitorul-sustenabil-al-industriei-de-moda-al-republicii-moldova/

[9] Beyond circular fashion. A new business model for the fashion industry. Report, Zeriwasteeurope, 2023. [Online]. Available: https://zerowasteeurope.eu/wp-content/uploads/2023/01/Jan23-ZWE_Beyond-Circular-Fashion_-Report.pdf

[10] M., Gheorghita, D. Nistor, *Strategic vosion for recovery of Moldova's fashion Indistry after Covid-19.* Annals of the University of Oradea, Fascicle of textiles, leatherwork, Volumul 22, 2021, pp. 107-112. [Online]. Available: https://ibn.idsi.md/vizualizare_articol/186752

[11] Banca de date statistice. [Online]. Available: https://statbank.statistica.md/PxWeb/pxweb/ro/40%20Statistica%20economica/40%20Statistica%20economica__14%20IND__IND020/IND020300.px/?rxid=b2ff27d7-0b96-43c9-934b-42e1a2a9a774

ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

CLASSIFICATION AND EVALUATION OF MATERNITY CLOTHING USING GEOMETRIC INDICES AND MACHINE LEARNING

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Abstract: *Maternity apparel constitutes a specific domain within fashion design, necessitating consideration of the intricate physiological and psychological requirements of expectant mothers. The objective of this research is to formulate a systematic classification system for maternity garments, predicated on functional and aesthetic attributes, geometric indices, and machine learning methodologies. A comprehensive analysis was conducted on 32 distinct clothing types and 10 categories of frequently utilized garments; furthermore, 24 geometric indices were extracted from each silhouette to quantify shape, proportions, compactness, and structural features. Feature selection techniques, including FSRNCA, RReliefF, and SFCPP, were employed to ascertain the most pertinent geometric parameters for classification purposes. To categorize clothing into five functional-aesthetic groups, four machine learning algorithms were used: k-nearest neighbors (k-NN), decision tree, ensemble model, and support vector machine (SVM) with an ECOC strategy. The ensemble model achieved the highest classification accuracy, reaching 100%, which showed its strong reliability even with small and diverse datasets. The results were validated through expert evaluation by specialists in fashion design, functional apparel, and maternity clothing. This research builds upon current methodologies by combining geometric and semantic attributes, thereby presenting a holistic approach to the assessment and classification of maternity clothing. Moreover, the suggested framework opens avenues for future advancements, such as the integration of three-dimensional body models, personalized garment suggestions tailored to individual body shapes, and intelligent systems designed for the adaptive design of maternity apparel. Consequently, this study enhances comfort, functionality, and aesthetic appeal within the realm of maternity wear, ultimately supporting the well-being and self-assurance of pregnant women across the entirety of their pregnancy.*

Keywords: *Functional design, Geometric features, Feature extraction, Machine learning, Classification accuracy, Personalization*

1. INTRODUCTION

Clothing design is primarily determined by shape, color, and material, with maternity clothing incorporating contour, construction, and the textiles used [1]. Shapes are important for the style and aesthetics of clothing, with the most commonly used types being A, H, X, T, O, and S [2]. Additional configurations such as “tunic” and “hourglass” expand the classification [3]. These proportions and design solutions correspond to women’s bodies during pregnancy [4]. Contour can highlight or conceal features of the human body [5]. According to Zou et al. [6], the development of fashion design requires international collaboration, multilingual platforms, and innovative technologies that integrate historical and digital perspectives. Research on contours in fashion covers their recognition, cultural significance, and practical application in pregnant women. Jiang et al. [7] developed a method for intelligent recognition of trouser contours using DeepLabV3+, improving accuracy and classification, although with limitations in the variety of poses and clothing. What these studies have in common is more accurate recognition, cultural interpretation, and personalized application of visual configurations in contemporary fashion design. Research on contours in fashion design can be summarized as technologically applied and theoretically cultural.

Technological-applied research focuses on automated contour recognition, classification, and optimization using modern digital methods. Zhang et al. [8] used fuzzy C-means and keypoint positioning algorithms to measure A-shapes in traditional Chinese costumes. Tsuru et al. [9] applied statistical methods such as principal component analysis and cluster analysis to group dresses, while Nie et al. [10] used variance analysis to quantify the factors influencing X-shapes. Lee et al. [11] analyzed over 1,300 images of wedding dresses, classifying their elements as bodices, sleeves, and skirts, which helps designers create fashionable and sought-after models. The presented research focuses on precision, personalization, and efficiency in clothing design and evaluation, primarily in relation to online shopping and digital fashion.

Theoretical-cultural studies encompass classification systems, historical and cultural interpretations of garment outlines, and qualitative methods of analysis. Kazlacheva [12, 13] proposes a detailed classification based on fit, geometric shapes, letter designations, and visual analogies, noting that there is no complete overlap between different classification systems. Hadijah et al. [14] use observation, interviews, and documentation to study the structural details of dresses but are not supported by numerical evidence or statistical analyses that would make them objectively verifiable. Radieva [15] examines the proportions of the lower part of garments at Christian Dior and Cristobal Balenciaga using correspondence analysis, focusing on the influence of design decisions on the overall visual appearance. Indrie et al. [16] complement this line of research by introducing a new classification of combined configurations and applying principal component analysis to more accurately classify garments. These studies prove the cultural, aesthetic, and social value of the outlines of clothing, considering them not only as visual forms but also as carriers of identity, style, and historical heritage.

Pregnancy is a period of significant physiological changes that affect the contours and visual perception of the female body. These transformations lead to a dynamic evolution of characteristic body proportions, which has direct implications for the design and functionality of garments designed for pregnant women.

Figure 1 presents typical contours observed in pregnant women, which are classified by visual categories such as A-, H-, O-, T-, and X-shaped configurations.

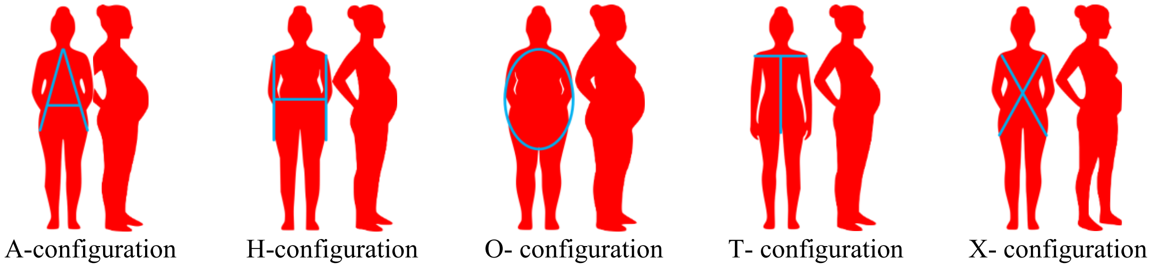

A-configuration H-configuration O- configuration T- configuration X- configuration

Fig. 1: *Visual body configurations during pregnancy*

These categories often overlap with established body types in fashion theory, including pear-shaped, hourglass, apple-shaped, and rectangle-shaped [17]. The A-shaped configuration is associated with wider hips and narrow shoulders, characteristic of early pregnancy, when the pelvic region begins to widen [18]. The H-shaped proportions, with evenly distributed lines, often transform into an O-shaped structure in the later stages of pregnancy due to central volume accumulation [19]. The T-shaped configuration, although less common, is observed in women with an athletic build and may undergo visual changes as gestation progresses [20]. The X-shaped construction, resembling an hourglass, is more stable in early pregnancy but gradually changes as the abdomen grows [21]. The transformations presented are important for the creation of adaptive and aesthetic garments that meet the needs of pregnant women at different stages of gestation. The choice of clothing during pregnancy is a complex process that combines physiological needs and psychosocial factors, reflecting the identity, emotional state, and social role of the woman. Leading criteria in the choice of clothes are comfort, softness of fabrics, and their ability to adapt to body changes.

Figure 2 presents basic outerwear that pregnant women prefer, among which are blouses, shirts, tunics, cardigans, sweaters, sweatshirts, jackets, coats, and blazers, as well as specialized corsets and bustiers. Blouses, shirts, and tunics are usually made of soft and elastic fabrics that provide freedom of movement and easy adaptation to the growing belly and are often distinguished by pleated or loose cuts, creating visual balance and comfort [22]. Cardigans, sweaters, and sweatshirts provide warmth and layering, which is important during hormonal changes that affect body temperature, while also creating a sense of comfort and protection, which is psychologically significant for the pregnant woman [23]. Jackets and coats, as outerwear, are designed with additional space in the abdominal area and more often include adjustable elements, fulfilling not only a thermal but also a social function, emphasizing the identity of the expectant mother [24]. The jacket and blazer, although less commonly worn, find application in professional environments, adapting through elastic panels or a loose fit, allowing the woman to maintain her professional role and self-confidence [25]. Corsets and bustiers, traditionally associated with body shaping, are used with caution during pregnancy, with medical recommendations limiting their use unless specifically designed to support the back or pelvis, and in some cases corrective belts are used to relieve back pain, but not for aesthetic purposes [26].

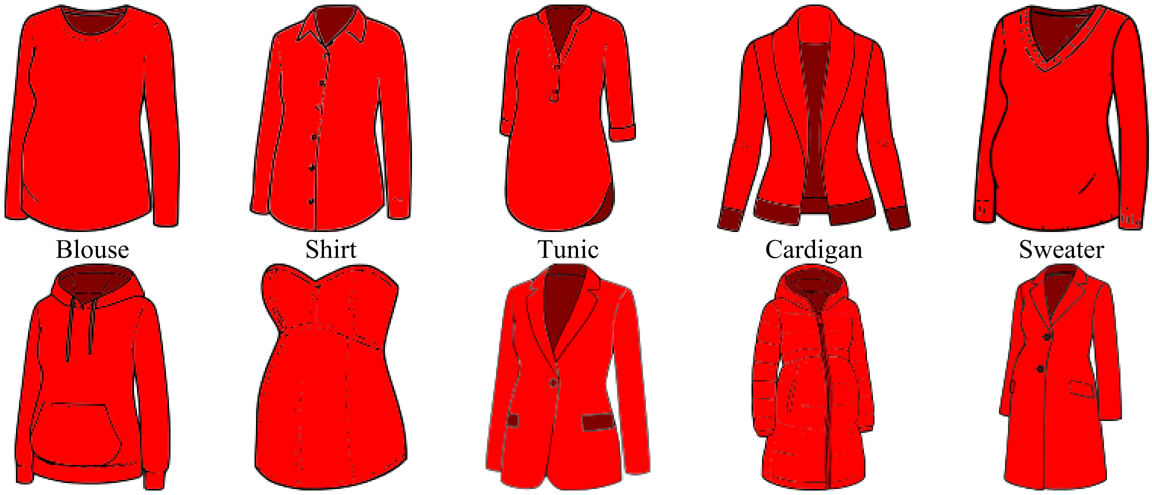

Blouse Shirt Tunic Cardigan Sweater
Sweatshirt Corset Jacket Jacket Coat

Fig. 2*: Clothes more often worn by pregnant women*

Pregnancy is a period of intense physical and emotional changes that require clothing that combines comfort, adaptability, and aesthetics. Maternity clothing influences how a woman perceives her body and feels at different stages of pregnancy. Figure 3 shows the main maternity clothing categories, which are grouped into five categories.

These categories include comfortable and loose cuts such as oversized and cape, adaptive constructions such as wraps and lace-up models, visually balancing designs with pleats and accents around the bust, stable and supportive solutions such as straight and padded structures, and upper construction elements such as sleeves, straps, and polos.

Choosing the right maternity clothing ensures both the physical comfort and psychological well-being of the pregnant woman [4, 17, 27, 28]. Maternity clothes suitable for the entire period of pregnancy combine comfort, adaptability, and visual balance, with the most functional being loose and adjustable shapes. These are A-shaped, trapezoidal, oversized, wrap clothing ("hug me"), as well as models with ties, buttons, or zippers, which provide space in the abdominal area and adapt to the changing dimensions of the body. These designs do not restrict movements, assist thermoregulation, and are also applicable during the breastfeeding period. Maternity clothes with visual accents, such as pleats, gathers, and emphasized lines under or above the bust – create aesthetic harmony and increase the woman's confidence by distracting attention from the areas with the greatest changes. More structural shapes of maternity clothes, such as straight and box, can offer stability and support in the second and third trimesters. Suitable for the entire period of pregnancy are those garments that provide flexibility, comfort, and adaptation, without compromising the personal style and self-esteem of the expectant mother.

The review of available literature sources shows that research is mainly focused on visual classification, cultural interpretation, and automated recognition, but to a lesser extent they take into account the specific physiological and psychological needs of the pregnant woman. There is a lack of an integrated approach that combines aesthetics, functionality, and quantitative assessment of clothing related to pregnancy. This necessitates the development of a systematic methodology for the classification and assessment of clothing for pregnant women, which would reflect the real requirements of this consumer segment and support the creation of adaptive and comfortable design.

***Fig. 3**: Clothes for pregnant women*

The aim of this work is to systematize the classification of clothing for pregnant women, based on functional and aesthetic criteria, geometric indices, and machine learning algorithms. It is necessary to identify appropriate clothing that meets the physiological and psychological needs of women during pregnancy and after childbirth.

2. MATERIAL AND METHODS

The classification of maternity clothing includes coded designations, grouping by functional and aesthetic criteria, and evaluation with geometric indices. Feature selection and machine learning methods were used to determine the informativeness and accuracy of the classification. Table 1 shows the designations of maternity clothing. Each garment is designated by a code (CS1–CS32) and a short name reflecting its design features and decorative elements.

***Table 1**: Designations of clothing for pregnant women*

№	Name	№	Name	№	Name	№	Name
CS1	A-line	**CS9**	Box	**CS17**	Underbust	**CS25**	With belt
CS2	Asymmetrical	**CS10**	Pleated	**CS18**	Padded	**CS26**	With straps
CS3	Strapless	**CS11**	Above Bust	**CS19**	Sleeve	**CS27**	With sleeves
CS4	Bomber	**CS12**	Cloak	**CS20**	Straight	**CS28**	With front zipper
CS5	Ruffles and Drapery	**CS13**	Unlined	**CS21**	Wrap	**CS29**	Free

CS6	Double Breasted	**CS14**	Oversized	**CS22**	Slim	**CS30**	Short
CS7	Vest-Dress	**CS15**	Peplum	**CS23**	Hourglass	**CS31**	Trapezoidal
CS8	Corset	**CS16**	Slim-Fit	**CS24**	Tie-front	**CS32**	Extended

Table 2 shows the designations of garments more often worn by pregnant women. The suitability of these garments for pregnant women, such as blouses, tunics, vests, and coats, is explained by their ability to adapt to anatomical changes during pregnancy, providing comfort, freedom of movement, and ease of dressing. On the other hand, corsets and tight-fitting clothes are less used, as they restrict movement, do not allow expansion of the volume around the abdomen, and can cause discomfort or even pain.

***Table 2**: Clothing designations more often worn by pregnant women*

№	**Name**	**№**	**Name**
A1	Blouses	**A6**	Sweatshirts
A2	Shirts	**A7**	Corsets
A3	Tunics	**A8**	Jackets
A4	Vests	**A9**	Jackets
A5	Sweaters	**A10**	Coats

The criteria described in Table 3 were used to group maternity clothing. These criteria were used to classify garments according to their functionality and aesthetics from a pregnancy perspective. Each group (G1–G5) reflects a specific aspect of design—from physical comfort and adaptability to body changes to visual balance, structural support, and stability in the upper body. A brief description of each group, typical construction and decorative elements, as well as the main function that the given criterion performs in supporting the needs of a woman during the different stages of pregnancy and postpartum, is provided.

***Table 3**: Criteria for grouping clothing for pregnant women*

№	**Criteria**	**Description**	**Typical elements**	**Main function**
G1	Comfort and freedom	Space and movement	Loose fit, oversized, capes, cardigans, bombers	Physical comfort and thermoregulation in the 2nd and 3rd trimesters
G2	Adaptability	Adjustment to body changes	Wrap cuts, ties, buttons, zippers, belts	Flexibility during pregnancy and postpartum (incl. breastfeeding)
G3	Visual balance	Harmony and aesthetic deviation	Asymmetry, ruffles, pleats, under/over bust accents	Supports a woman's self-esteem, diverts attention from areas of change
G4	Structural support	Support and visual design	Corset and straight shapes, box silhouette, belts, lining	Posture support
G5	Upper structure	Upper comfort and stability	Straps, sleeves, polo collars	Provides comfort, style and stability in the chest and neck area

The typical garments for pregnant women were grouped by three specialists in the subject area independently of each other. They have diverse but complementary professional experience in the field of fashion design, with a focus on adaptive and functional design, medicine, and the trade of maternity clothing.

A total of 24 coefficients per object in an image were used [29]. The coefficients (K1-K24) can be grouped according to the geometric and metric characteristics they describe. Groups K1, K3, K4, K5, K6, and K15 include coefficients related to the ratio between the perimeter (P) and the area (A) of the figure, which is an indicator of compactness and deviation from the ideal shape. Groups K2, K10, K16, K18, and K20 contain coefficients based on the ratio between the major and minor axes of the garments (D and d), expressed as dimensionless ratios. Groups K7, K9, K11, K12, and K14 describe differences and ratios between D and d, using combined or transformed relationships, including roots and polynomials. Groups K13, K19, K21, K23, and K24 describe the relationship between diameters and perimeter, estimating external density or extensibility. Finally, K22 uses volume (V) together with diameters, thus presenting a sufficiently detailed assessment of clothing.

The geometrical clothing coefficients (indices) have the form:

$$K_1=\frac{P^2}{A} \quad \textbf{(1)}$$

$$K_2=\frac{D}{d}.100,\% \quad \textbf{(2)}$$

$$K_3=\frac{P^2}{4\pi A} \quad \textbf{(3)}$$

$$K_4=\frac{1}{K_3} \quad \textbf{(4)}$$

$$K_5=\frac{A}{A_{ideal}} \quad \textbf{(5)}$$

$$K_6=\frac{A}{A_{mr}} \quad \textbf{(6)}$$

$$K_7=\left(\sqrt{\frac{D}{2}}+\sqrt{\frac{d}{2}}\right)\frac{\sqrt{\frac{D}{2}}}{d}-1 \quad \textbf{(7)}$$

$$K_8=\frac{\frac{d}{2}}{\frac{D}{2}} \quad \textbf{(8)}$$

$$K_9=\left(\frac{D}{2}-\frac{d}{2}\right)\frac{D}{d^2} \quad \textbf{(9)}$$

$$K_{10}=\frac{d}{D}-1 \quad \textbf{(10)}$$

$$K_{11}=\frac{\left(\frac{D}{2}-\frac{d}{2}\right)}{d} \quad \textbf{(11)}$$

$$K_{12}=\frac{D-d}{D} \quad \textbf{(12)}$$

$$K_{13}=\frac{dD}{2}-1 \quad \textbf{(13)}$$

$$K_{14}=\frac{(D+2)(d+2)}{2D^2(-dD+D+2)} \quad \textbf{(14)}$$

$$K_{15}=\frac{P^2}{4\pi A}-1 \quad \textbf{(15)}$$

$$K_{16}=\frac{d}{D} \quad \textbf{(16)}$$

$$K_{17}=\frac{D}{d}-1 \quad \textbf{(17)}$$

$$K_{18}=\frac{D}{d} \quad \textbf{(18)}$$

$$K_{19}=\frac{dD}{2} \quad \textbf{(19)}$$

$$K_{20}=\frac{D-d}{2d} \quad \textbf{(20)}$$

$$K_{21}=\frac{P}{D} \quad \textbf{(21)}$$

$$V=\frac{4}{3}\pi\frac{D}{2}\left(\frac{d}{2}\right)^2 \qquad K_{22}=\frac{3V}{4\pi Dd^2} \quad \textbf{(22)}$$

$$K_{23}=\frac{P}{D-P} \quad \textbf{(23)}$$

$$K_{24}=\frac{D}{D-P} \quad \textbf{(24)}$$

where d is the minor axis of the garment; D is the major axis of the garment; P is the perimeter; A is the area; A_{ideal} is the ideal area calculated along the major and minor axes of the garment; Amr is the area of the rectangle enclosing the garment; V is the volume calculated along the major and minor axes.

The informativeness of the clothing indices for pregnant women was determined using the FSRNCA, RreliefF, and SFCPP selection methods. FSRNCA (Feature Selection for Classification and Regression by Neighboring Component Analysis). This method identifies the most appropriate clothing indices obtained in such a way as to minimize the prediction error [30]. RReliefF is used for feature selection in regression tasks. It evaluates the importance of features based on their ability to distinguish data that are close to each other [31]. This algorithm is suitable for assessing the significance of features for distance-based models. SFCPP (Selection of Features with Comparable Predictive Power). A feature selection method that identifies features with similar predictive power while reducing data redundancy [32]. Informative indices are those that have weighting coefficients with a value above 0,6 [33].

To group the maternity clothes into the five proposed groups, based on their shape indices, the following classification methods were used: k-NN, Decision Tree, Ensemble method and SVM. The k-nearest neighbor (k-NN) method is not complex, but it is a sufficiently effective classifier that classifies an object according to the set of its k-nearest neighbors in the feature space. It is suitable for small to moderate-sized data sets, where a long training process is not required [34]. The decision tree is a widely used method due to its interpretability, ability to process both numerical and categorical data, and sufficiently good efficiency for moderate-sized data sets. It represents a hierarchical structure, which facilitates the visualization of the classification process [35]. The ensemble method combines multiple weak classifiers (e.g. decision trees) into a single strong model, improving accuracy and robustness on small and noisy datasets. The method reduces variance through techniques such as Bagging and Boosting. Especially for more complex class boundaries, ensemble models have significantly better performance compared to single classifiers [36]. Multiclass SVM with ECOC strategy. The fitcecoc function in MATLAB implements the Error-Correcting Output Codes (ECOC) approach for multiclass classification by binarizing the problem and using binary classifiers as SVMs. The method is efficient on a large number of classes and shows reasonably good robustness against noise [37].

The classification accuracy is estimated by the following formula:

$$Accuracy=\frac{TP+TN}{TP+TN+FP+FN}\times 100,\% \quad \textbf{(25)}$$

where TP (True Positive) The model correctly predicts a positive class; TN (True Negative) The model correctly predicts a negative class; FP (False Positive) The model incorrectly predicts a positive class; FN (False Negative) The model incorrectly predicts a negative class; TP+TN are the correctly classified data; FP+FN are the incorrectly classified data.

12. RESULTS

An analysis was made of the possibility of combining garments more often worn by pregnant women and the types of garments into which they can be made. Table 4 presents the average ratings of three specialists in the subject area, on a scale from 1 to 5. "0" marks the combinations of clothes that, according to the specialists, are not recommended for wearing by pregnant women. According to the results presented by the specialists in the subject area, the lower ratings for some of the combinations of clothes for pregnant women are due to several factors. Combinations with low ratings (e.g., CS3, CS8, CS16, CS23, CS30) refer to clothes that are not suitable during pregnancy, as they restrict movement, tighten the body, or are not functional. For example, corsets (CS8) or tight-fitting clothes would be extremely uncomfortable and unhealthy for the growing belly. Lower scores for other combinations (e.g., CS4, CS6) may be explained by decreasing comfort during different stages of pregnancy, where clothes that were suitable at the beginning become impractical later. At the same time, high scores (5) for combinations such as CS1, CS2, CS5, CS9, and CS10 are given to versatile and comfortable garments, such as A-line loose tunics, expandable shirts, or oversized sweaters, which provide space and comfort throughout the pregnancy.

A grouping of maternity clothing was made by three specialists in the subject area. The results are presented in table 5. In all cases, the specialists have the same opinion about the groups in which the clothing falls, except for GS11, which according to two of the specialists falls into group G3, and according to the third, falls into group G5. This clothing is placed in group G3.

The groups into which maternity clothing is distributed were used as the basis for the selection of informative indices. The results of this selection are shown in Figure 4. Table 6 presents the selected clothing indices for pregnant women. Using the FSRNCA method, 9 indices were selected, which have weight coefficient values above 0.6. Using the RreliefF method, 7 of them are informative. Using the SFCPP method, the most were selected compared to the other methods – a total of 10 clothing indices.

The misclassified data are shown in red and bold. In this method, the best results compared to the others are achieved by the ensemble model, which classifies all garments correctly—100% accuracy. SVM also performs stably with fewer errors, while Decision Tree and especially k-NN show significantly lower accuracy. kNN allows 17 errors, making it the weakest model. The results show that the FSRNCA-selected garment indices can be used effectively when processed with ensemble approaches, but not so much with simpler models such as k-NN.

***Table 4**: Averaged assessments of specialists in the subject area regarding possibilities for combining clothing more often worn by pregnant women and the types of clothing.*

Clothes Types of clothes	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
CS1	5	5	5	2	4	2	0	3	5	2
CS2	5	5	5	3	4	1	0	1	2	1
CS3	0	0	0	0	0	0	0	0	0	0
CS4	0	0	0	0	0	0	0	0	3	2
CS5	5	4	5	3	4	1	0	3	3	1
CS6	1	2	0	0	0	0	0	3	3	3
CS7	0	0	3	3	0	0	0	0	0	0
CS8	0	0	0	0	0	0	0	0	0	0
CS9	5	5	5	3	4	3	2	3	4	4
CS10	5	5	5	3	4	2	0	3	3	1
CS11	5	5	5	2	2	2	0	3	3	1
CS12	0	0	0	0	0	0	0	0	3	3
CS13	5	5	5	3	4	3	0	3	3	3
CS14	5	5	5	3	4	3	2	3	3	3
CS15	2	2	3	0	0	0	0	0	0	0
CS16	0	0	0	0	0	0	0	0	0	0
CS17	5	5	5	2	2	2	0	3	3	1
CS18	0	0	0	0	0	0	0	0	3	3
CS19	3	0	0	0	3	1	0	0	0	0
CS20	5	5	4	3	4	3	2	3	3	3
CS21	5	5	5	2	3	2	0	3	3	2
CS22	1	1	0	0	2	2	0	0	0	0
CS23	0	0	0	0	0	0	0	0	0	0
CS24	5	5	5	2	3	2	3	3	3	3
CS25	3	3	3	3	2	2	2	3	3	3
CS26	2	0	2	0	0	0	0	0	0	0
CS27	5	5	5	3	4	3	2	3	3	3
CS28	5	5	5	2	3	2	0	3	3	3
CS29	5	5	5	3	4	3	0	3	3	3
CS30	0	0	0	0	0	0	0	0	0	0
CS31	5	5	5	2	3	3	0	3	3	1
CS32	5	5	5	3	4	3	0	3	3	3

***Table 5**: Grouping of maternity clothing by specialists*

Clothes	S1	S2	S3	Total	Clothes	S1	S2	S3	Total
CS1	1	1	1	**1**	CS17	3	3	3	**3**
CS2	3	3	3	**3**	CS18	4	4	4	**4**
CS3	5	5	5	**5**	CS19	5	5	5	**5**
CS4	1	1	1	**1**	CS20	4	4	4	**4**
CS5	3	3	3	**3**	CS21	2	2	2	**2**
CS6	2	2	2	**2**	CS22	5	5	5	**5**
CS7	1	1	1	**1**	CS23	4	4	4	**4**
CS8	4	4	4	**4**	CS24	2	2	2	**2**
CS9	1	1	1	**1**	CS25	2	2	2	**2**
CS10	3	3	3	**3**	CS26	5	5	5	**5**
CS11	3	3	5	**3**	CS27	5	5	5	**5**
CS12	1	1	1	**1**	CS28	2	2	2	**2**
CS13	1	1	1	**1**	CS29	1	1	1	**1**
CS14	1	1	1	**1**	CS30	3	3	3	**3**
CS15	3	3	3	**3**	CS31	1	1	1	**1**
CS16	5	5	5	**5**	CS32	1	1	1	**1**
CSx-characteristic maternity clothing; Sx-specialist number									

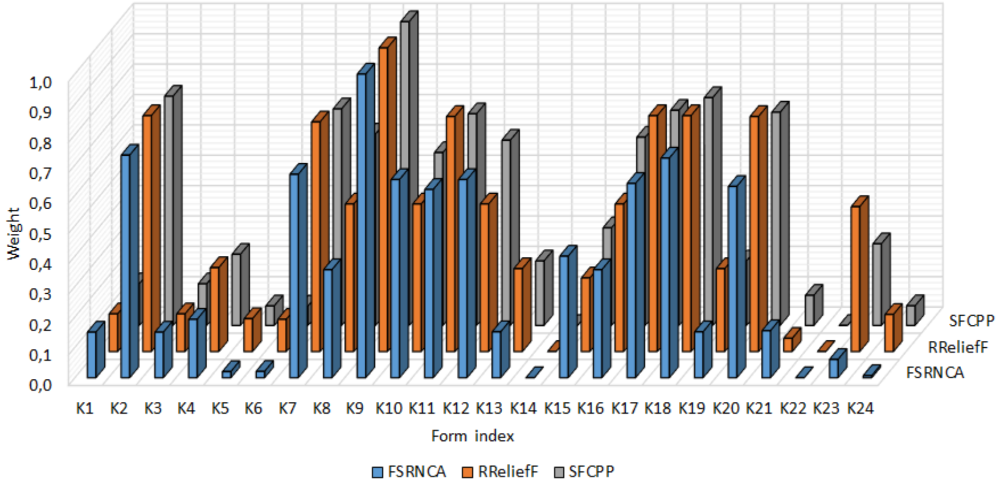


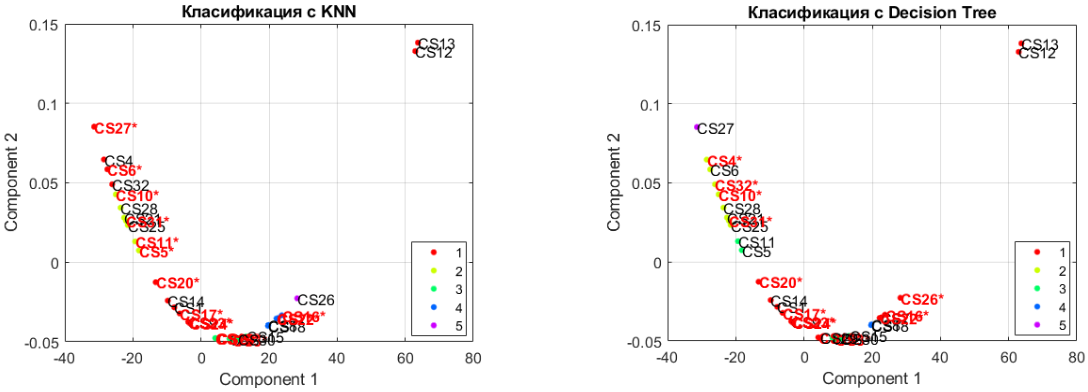
***Fig. 4**. Results of clothing geometrical index selection for typical maternity clothing*

***Table 6**: Selected clothing geometrical indices relative to typical maternity clothing items*

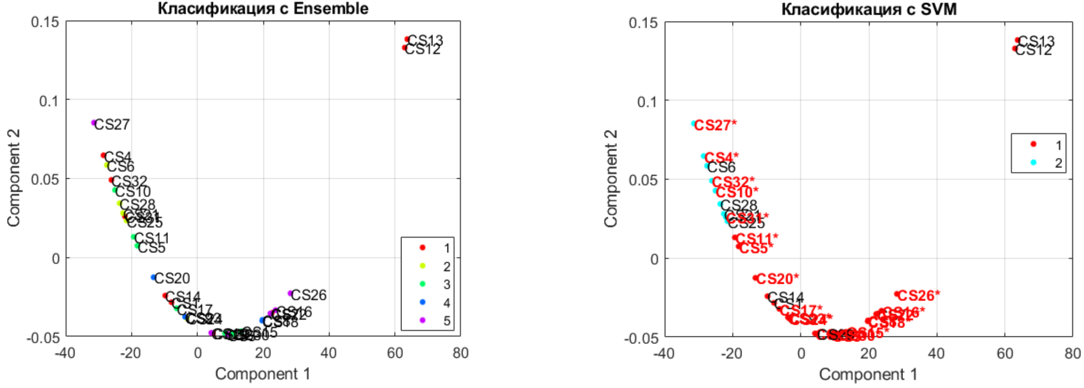
Index Method	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12
FSRNCA		+					+		+	+	+	+
RReliefF		+					+		+		+	
SFCPP		+					+	+	+		+	+

Index Method	K13	K14	K15	K16	K17	K18	K19	K20	K21	K22	K23	K24
FSRNCA					+	+		+				
RReliefF					+	+		+				
SFCPP				+	+	+		+				

Figure 5 presents the results of classification by a vector of indices selected with the FSRNCA method.



a) k-NN b) DT

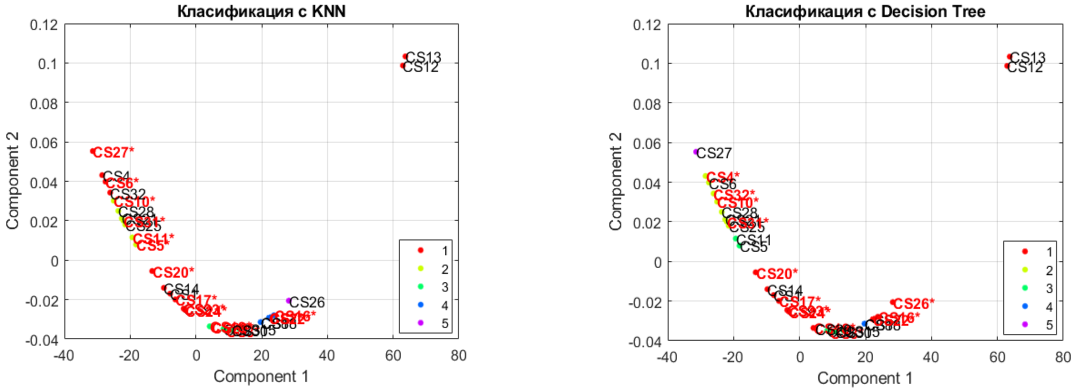


c) E d) SVM

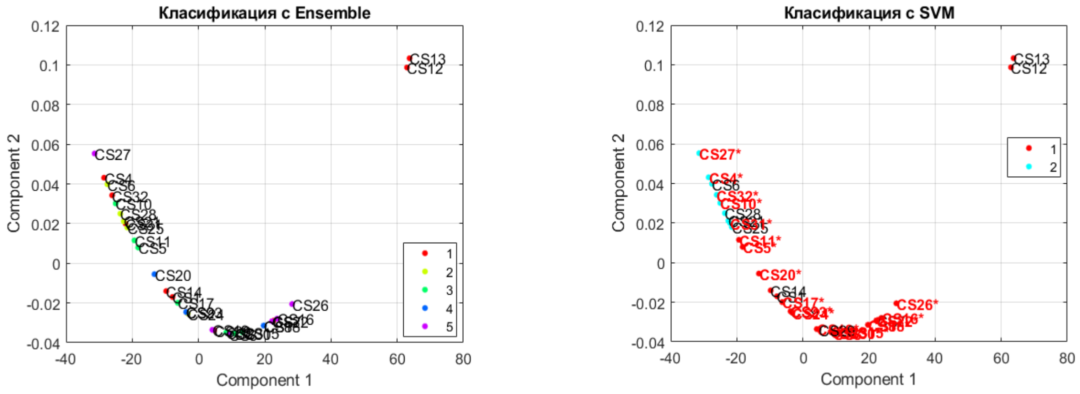
***Fig. 5**: Classification results of clothing geometrical indices selected with FSRNCA method*
k-NN (k-nearest neighbors); DT-decision tree; E-(Ensemble) Ensemble method; SVM-support vector method

Figure 6 presents the results of classification by a vector of indices selected with the RReliefF method. Again, the ensemble model stands out with a sufficiently efficient classification – 100% accuracy. SVM and Decision Tree show similar results, with a moderate number of errors, while k-NN again performs the worst. Although RReliefF manages to extract relevant features, its efficiency strongly depends on the chosen classifier. Ensemble methods make the best use of the selected features, while kNN remains sensitive to noise and class proximity.

Figure 7 presents the results of classification by a vector of indices selected using the SFCPP method. The results using indices selected using SFCPP coincide with those from RReliefF, which suggests that the selected features lead to a similar differentiation between classes. The ensemble model again demonstrates sufficiently effective classification, while SVM and Decision Tree are of moderate accuracy, and k-NN has the most errors. This shows that SFCPP is a reliable method for index selection, but effective results are achieved only with more complex models that can capture nonlinear dependencies between the data.

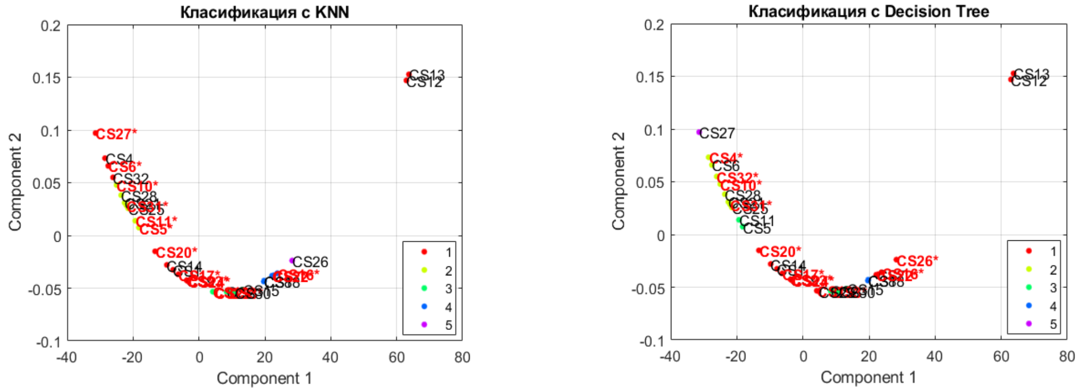


a) k-NN b) DT

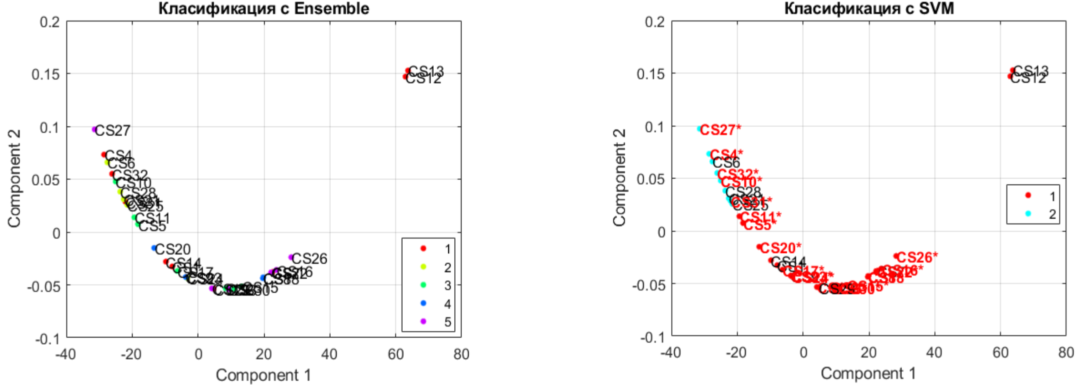


c) E d) SVM

Fig. 6*: Classification results of clothing geometrical indices selected with the method RreliefF*
k-NN-k-nearest neighbors; DT-decision tree; E-(Ensemble) Ensemble method; SVM-support vector method



a) k-NN b) DT



c) E d) SVM

Fig. *7: Classification results by clothing geometrical indices selected with SFCPP method*
k-NN-k-nearest neighbors; DT-decision tree; E-(Ensemble) Ensemble method; SVM-support vector method

Table 7 presents the results of the data clustering, depending on the method for selecting garment indices and the classifier used. The presented results show that the ensemble model (E) achieves the highest accuracy when using indices selected by all three selection methods, classifying all garments correctly. SVM also demonstrates stable results, with a moderate number of misclassified garments, while Decision Tree and especially kNN allow significantly more incorrect classifications. Regardless of the method for selecting garment indices, k-NN shows the lowest efficiency due to being more sensitive to the choice of features and the structure of the data.

***Table** 7: Results of grouping maternity clothing using classifiers*

Clothes	**Selction method**	FSRNCA				RReliefF				SFCPP			
	Classifier **Real group**	kNN	DT	E	SVM	kNN	DT	E	SVM	kNN	DT	E	SVM
CS1	**1**	1	1	1	1	1	1	1	1	1	1	1	1
CS2	**3**	3	3	3	1	3	3	3	1	3	3	3	1
CS3	**5**	3	3	5	1	3	3	5	1	3	3	5	1
CS4	**1**	1	2	1	2	1	2	1	2	1	2	1	2
CS5	**3**	2	3	3	1	2	3	3	1	2	3	3	1
CS6	**2**	1	2	2	2	1	2	2	2	1	2	2	2
CS7	**1**	4	1	1	1	4	1	1	1	4	1	1	1
CS8	**4**	4	4	4	1	4	4	4	1	4	4	4	1
CS9	**1**	1	1	1	1	1	1	1	1	1	1	1	1
CS10	**3**	2	2	3	2	2	2	3	2	2	2	3	2
CS11	**3**	2	3	3	1	2	3	3	1	2	3	3	1
CS12	**1**	1	1	1	1	1	1	1	1	1	1	1	1
CS13	**1**	1	1	1	1	1	1	1	1	1	1	1	1
CS14	**1**	1	1	1	1	1	1	1	1	1	1	1	1
CS15	**3**	3	3	3	1	3	3	3	1	3	3	3	1
CS16	**5**	4	1	5	1	4	1	5	1	4	1	5	1
CS17	**3**	1	1	3	1	1	1	3	1	1	1	3	1
CS18	**4**	4	4	4	1	4	4	4	1	4	4	4	1

***Table** 7: Continued…*

Clothes	**Selction method**	FSRNCA				RReliefF				SFCPP			
	Classifier **Real group**	kNN	DT	E	SVM	kNN	DT	E	SVM	kNN	DT	E	SVM
CS19	**5**	3	1	5	1	3	1	5	1	3	1	5	1
CS20	**4**	1	1	4	1	1	1	4	1	1	1	4	1
CS21	**2**	2	2	2	2	2	2	2	2	2	2	2	2
CS22	**5**	4	1	5	1	4	1	5	1	4	1	5	1
CS23	**4**	1	1	4	1	1	1	4	1	1	1	4	1
CS24	**2**	1	1	2	1	1	1	2	1	1	1	2	1
CS25	**2**	2	2	2	2	2	2	2	2	2	2	2	2
CS26	**5**	5	1	5	1	5	1	5	1	5	1	5	1
CS27	**5**	1	5	5	2	1	5	5	2	1	5	5	2
CS28	**2**	2	2	2	2	2	2	2	2	2	2	2	2
CS29	**1**	3	1	1	1	3	1	1	1	3	1	1	1
CS30	**3**	3	3	3	1	3	3	3	1	3	3	3	1
CS31	**1**	2	2	1	2	2	2	1	2	2	2	1	2
CS32	**1**	1	2	1	2	1	2	1	2	1	2	1	2

Figure 8 shows the classification accuracy, depending on the method for selecting informative indices of clothing and the classifier used. The results show that the ensemble model (E) achieves 100% accuracy for all selection methods, while kNN and SVM perform significantly worse — with 50% and 34% accuracy, respectively. Decision Tree shows moderate efficiency with 59% accuracy. The figure clearly illustrates that the choice of classifier has a greater impact on the accuracy of clustering than the specific method for feature selection, since the results are identical for all three techniques.

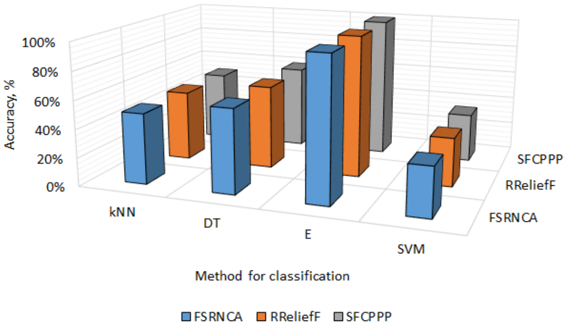


***Fig. 8**: Accuracy of classification of typical maternity clothing*

The analysis of the compatibility between the types of garments preferred by pregnant women, in which they can be made, shows clear dependencies between functionality, stage of pregnancy, and visual structure of the garment. Combinations with high scores (e.g., CS1, CS2, CS5, CS9, CS10) have versatility and adaptability, offering comfort and freedom of movement throughout the gestation period. Combinations with low or zero scores (e.g., CS3, CS8, CS16, CS23, CS30) are characterized by limited functionality, inappropriate constructions, or excessive tightness, making them inappropriate for pregnant women.

The grouping of maternity clothing by experts shows a high degree of consistency, which proves the reliability of visual classification, except for single cases such as CS11, where there is a discrepancy in the opinions of the evaluators. The selection of informative indices of clothing by three different methods (FSRNCA, RReliefF, SFCPP) shows that the most effective results are achieved when using an ensemble model that classifies all garments correctly, regardless of the method for selecting shape indices.

This proves the effectiveness of ensemble approaches—their ability to capture complex, nonlinear dependencies between features. The k-NN method offers the lowest accuracy and high sensitivity to the structure of the data, which makes it unsuitable for tasks with high visual and semantic variability. The accuracy of classification depends more on the model chosen for this purpose than on the specific feature selection method. Ensemble models stand out as reliable when processing visual data of maternity clothing, while simpler algorithms such as k-NN require further optimization or replacement with more robust solutions.

4. DISCUSSION

Unlike theoretical and cultural studies [12, 13, 14, 15], which focus on visual and historical aspects of clothing outlines, the present study combines visual analysis with quantitative geometric indices, which allows for an objective classification and comparison between garments and types of clothing suitable for pregnant women.

This paper further develops the conclusions of Shamsaei et al. [23] and Sun et al. [4] by proposing a structured classification of maternity clothing, taking into account the adaptability, comfort, and aesthetics needed during different stages of pregnancy. The assessments of experts and numerical analyses in the paper objectively show which garments correspond to the needs of the pregnant woman.

This paper uses three methods for selecting informative garment indices (FSRNCA, RReliefF, SFCPP), which build on the approaches of Zhang et al. [8] and Tsuru et al. [9], providing higher informativeness and reducing data redundancy. This leads to more efficient classification and better interpretation of the results.

Compared to Jiang et al. [7], which uses DeepLabV3+ for visual configuration recognition, the present study applies ensemble models that achieve 100% accuracy in classifying maternity clothing. This leads to an improvement in the reliability of the model and its applicability to real data.

While most cited sources consider silhouettes in a general fashion context, the present study focuses entirely on the needs of the pregnant woman. Criteria such as adaptability, comfort, visual balance, and structural support are included, which reflect the real requirements of this specific consumer segment.

5. CONCLUSION

In this work, a structured classification of maternity clothing was made, based on five defined criteria, which cover functionality and aesthetics. Each garment was analyzed using 24 geometric indices, and their informativeness was assessed using three feature selection methods. By applying machine learning algorithms, a sufficiently high accuracy in the classification was achieved (100% in the ensemble method).

From the study of the available literature, it was found that structural elements such as ties, buttons, and zippers contribute to the flexibility of the clothing and facilitate its use both during pregnancy and after childbirth.

It has been proven that certain garments, such as A-shaped, oversized, trapezoidal, and wrap, provide the highest level of comfort and adaptability during the different stages of pregnancy.

Existing theoretical models were supplemented by the introduction of geometric indices of garments, which allow for an objective classification of and assessment of their functionality.

It was found that ensemble machine learning models achieve the highest accuracy in garment classification compared to the other methods, including k-NN, DT, and SVM, making them a reliable tool for analysis.

The integration of geometric indices into digital tools would support the automated assessment of maternity clothing, as well as provide additional validity of the results. The development of adaptive and multifunctional garments, suitable for both pregnancy and the postpartum period, would meet the need for sustainable and personalized design.

REFERENCES

[1] M. Pavlova, "Development of boutique denim clothing by the 'upcycling' method," E3S Web Conf., vol. 327, 03002, 2021.

[2] S. Stangerup, P. Caye-Thomasen, M. Tos, and J. Thomsen, "The natural history of vestibular schwannoma," Otol. Neurotol., vol. 27, no. 4, pp. 547–552, 2006.

[3] Japan Fashion Education Promotion Association, Fashion Sales 3, Fashion Sales Capability Examination Grade 3 Grade Official Text. Japan Fashion Education Promotion Association, 2018, pp. 102–105.

[4] Y. Sun and Z. D. Md Nor, "Research on design elements of maternity wear based on the physiological and psychological needs of pregnant women: A narrative review," Int. J. Heritage, Art Multimedia, vol. 6, no. 19, pp. 1–12, 2023.

[5] L. Peters, "You are what you wear: how plus-size fashion figures in fat identity formation," Fashion Theory, vol. 18, pp. 45–71, 2014.

[6] Y. Zou, S. Pintong, T. Shen, and D.-B. Luh, "Evaluation and trend of fashion design research: visualization analysis based on CiteSpace," Fash. Text., vol. 9, p. 45, 2022.

[7] X. Jiang, Z. Chen, C. Chi, S. Sha, and J. Zhang, "Research on intelligent recognition of trouser silhouettes based on label optimization," J. Eng. Fiber Fabr., vol. 18, pp. 1–9, 2023. doi: 10.1177/15589250231168950

[8] J. Zhang, J. Wang, L. Xing, and H. Liang, "Automatic measurement of traditional Chinese costume from its silhouette through fuzzy c-means clustering method," J. Eng. Fiber Fabr., vol. 15, 2020.

[9] T. Tsuru, M. Sugahara, and H. Nishimura, "A classification method for silhouettes of various clothes," in Proc. ISASE 2019, Fashion Design & Business, 2019, pp. 1–4, Submission No. C000033.

[10] Q. X. Nie, Y. Li, and X. G. Wang, "Analysis on influencing factors of X-shape dress silhouette based on eye-tracking technology," J. Phys. Conf. Ser., vol. 1848, 012123, 2021. doi: 10.1088/1742-6596/1848/1/012123

[11] S. Lee and S. Kwon, "Dress design analysis and pattern making techniques for increasing the efficiency of dress production," Hum. Ecol. Res., vol. 61, pp. 53–71, 2023. doi: 10.6115/her.2023.005

[12] Z. Kazlacheva, "Silhouettes in the ladies outer garments," Tekstil Obleklo, vol. 9, pp. 8–11, 2007.

[13] Z. Kazlacheva, "Silhouettes of lady's elastomeric clothing," Tekstil i Obleklo, vol. 58, no. 1, pp. 12–15, 2010.

[14] I. Hadijah, E. Prahastuti, and A. D. Astuti, "Analysis of dress pattern of body fitting without waist dart on chiffon fabrics," in Advances in Social Science, Education and Humanities Research, Proc. 2nd Int. Conf. Vocational Education and Training (ICOVET 2018), Fashion Technology Dept., Universitas Negeri Malang, vol. 242, pp. 85–91, 2018.

[15] K. Radieva, "An investigation of shaping in design of Christian Dior and Cristobal Balenciaga," IOP Conf. Ser. Mater. Sci. Eng., vol. 1031, 012025, 2021.

[16] L. Indrie, J. Ilieva, P. Dineva, Z. Kazlacheva, Z. Zlatev, and A. Sturza, “A study of types of silhouettes in women’s clothing,” Industria Textila, vol. 76, no. 1, pp. 19–30, 2025. doi: 10.35530/IT.076.01.2024139

[17] S. Grogan, Body image: Understanding body dissatisfaction in men, women and children, 3rd ed. London: Routledge, 2016. doi: 10.4324/9781315683926

[18] Z. Sohrabi, A. Kazemi, Z. Farajzadegan, and M. Janighorban, “Body perception in pregnant women: A qualitative study,” BMC Pregnancy Childbirth, vol. 23, Art. 165, 2023.

[19] E. B. Salzer, J. F. F. Meireles, A. F. Â. Toledo, M. R. de Siqueira, M. E. C. Ferreira, and C. M. Neves, “Body image assessment tools in pregnant women: A systematic review,” Int. J. Environ. Res. Public Health, vol. 20, no. 3, p. 2258, 2023.

[20] T. F. Cash and L. Smolak, Body image: A handbook of science, practice, and prevention, 2nd ed. New York, NY: Guilford Press, 2011.

[21] F. Sterlacci, “Wedge, column, pear and hourglass: 4 body types to know,” University of Fashion Blog, 2017. Available: https://www.universityoffashion.com/blog/wedge-column-pear-hourglass-four-body-types-know. . Accessed: Aug. 3, 2025.

[22] S. S. Ricci, Essentials of maternity, newborn, and women’s health nursing, 4th ed. Philadelphia, PA: Lippincott Williams and Wilkins, 2025.

[23] A. Shamsaei, A. Kazemi, H. Enteshary-Najafabadi, and N. Khosropour Borujeni, “Essential criteria for designing healthy maternity wear: A narrative review,” Iran. J. Nurs. Midwifery Res., vol. 27, no. 6, pp. 492–495, 2022.

[24] M. Nash, Dressing and Maternity Fashion, in Making ‘Postmodern’ Mothers, pp. 84–130. Palgrave Macmillan, 2012. doi: 10.1057/9781137292155_6

[25] J. P. Ogle and K. E. Tyner, “The role of maternity dress consumption in shaping the self and identity during the liminal transition of pregnancy,” J. Consum. Cult., vol. 13, no. 1, pp. 119–139, 2013.

[26] C. Quintero Rodríguez and O. Troynikov, “The effect of maternity support garments on alleviation of pains and discomforts during pregnancy: A systematic review,” J. Pregnancy, Article ID 2163790, 2019. doi: 10.1155/2019/2163790

[27] A. Jaiswal, “Smart motherhood wear: A solution to the problem of maternity wear,” Int. J. Home Sci., vol. 8, no. 1, pp. 278–281, 2022.

[28] M. S. Rasel and J. Sarkar, “Maternity clothing: A comprehensive review,” Dept. Textile Eng., KUET, Bangladesh, 2017. Available: https://www.researchgate.net/publication/320443178_Maternity_Clothing_A_comprehensive_Review

[29] I. Mytiai and A. Matsyura, “Mathematical interpretation of artificial ovoids and avian egg shapes (part I),” Regul. Mech. Biosyst., vol. 10, pp. 92–102, 2019.

[30] FSRNCA, “Feature selection using neighborhood component analysis for regression,” MathWorks, Online. Available: https://www.mathworks.com/help/stats/fsrnca.html. . Accessed: Jul. 18, 2025.

[31] W. Wei, D. Wang, and J. Liang, “Accelerating ReliefF using information granulation,” Int. J. Mach. Learn. Cybern., vol. 13, pp. 29–38, 2022.

[32] SFCPP, “Select Subset of Features with Comparative Predictive Power,” MathWorks, Online. Available: https://www.mathworks.com/help/stats/feature-selection.html. . Accessed: Jul. 26, 2025.

[33] A. Farrell, G. Wan, S. Rush, J. Martin, J. Belant, A. Butler, and D. Godwin, “Machine learning of large-scale spatial distributions of wild turkeys with high-dimensional environmental data,” Ecol. Evol., pp. 1–12, 2019.

[34] T. Cover and P. Hart, “Nearest neighbor pattern classification,” IEEE Trans. Inf. Theory, vol. 13, no. 1, pp. 21–27, Jan. 1967. doi: 10.1109/TIT.1967.1053964

[35] J. R. Quinlan, “Induction of decision trees,” Mach. Learn., vol. 1, no. 1, pp. 81–106, 1986. doi: 10.1007/BF00116251

[36] T. G. Dietterich, “Ensemble methods in machine learning,” in Proc. Int. Workshop Multiple Classifier Systems, 2000, pp. 1–15. Springer. doi: 10.1007/3-540-45014-9_1

[37] T. G. Dietterich and G. Bakiri, “Solving multiclass learning problems via error-correcting output codes,” J. Artif. Intell. Res., vol. 2, pp. 263–286, 1995. doi: 10.1613/jair.105

ANNALS OF THE UNIVERSITY OF ORADEA
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EVALUATION OF PHYSICO-MECHANICAL AND ELECTRICAL PROPERTIES OF RING- AND ROTOR-SPUN COTTON/STAINLESS STEEL CONDUCTIVE YARNS

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Abstract: *Nowadays, conductive yarns are widely used in various applications due to their ability to conduct electricity while preserving the characteristics of conventional textiles. They are commonly integrated into fabrics for antistatic protective equipment, enabling the dissipation of electrical charges and reducing risks in sensitive settings. When metallic fibers are blended with other fibers to produce conductive yarns, two key questions arise: what is the minimum amount of metallic fiber required to achieve adequate electrical conductivity, and which spinning technology should be used to ensure an optimal balance between performance and cost? The objective of the study was to evaluate the effects of the spinning technique and the metallic fiber content on the performance of conductive yarns developed for charge dissipation in industrial settings. Conductive yarns of 37 tex were produced by ring and rotor spinning from two cotton–stainless steel fiber blends (96/4 and 81/19). Due to their compact structure, characterized by a high degree of fiber straightening and parallelization, ring-spun yarns exhibited higher strength, lower elongation at break, and lower linear resistivity compared to rotor-spun yarns. Conversely, as a result of fiber back-doubling in the rotor groove, rotor-spun yarns showed improved uniformity in both linear density and strength. Increasing the proportion of stainless steel fibers led to an increase in tensile strength, accompanied by a decrease in both yarn diameter and elongation at break. At the same time, the higher stainless steel content reduced the linear resistivity of the yarn, thereby enhancing its ability to dissipate electrical charges.*

Key words: *antistatic yarns, stainless steel fibers, cotton-metal fiber blends, ring spinning, rotor spinning, yarn resistivity*

1. INTRODUCTION

Electrostatic charges that build up on the surface of fabrics due to triboelectric charging can lead to the ignition of flammable substances in explosive atmospheres, damage to electronic components, or contamination of precision equipment in cleanrooms [1,2]. To prevent the buildup and discharge of static electricity, conductive materials are integrated into textiles to enable efficient dissipation of electrical charges [3,4].

One of the solutions to obtain textiles with antistatic properties is the use of conductive yarns. Currently, conductive yarns can be obtained through several methods: blending conductive fibers with conventional fibers, core-spun yarn technology (wrapping a conductive filament with a sheath of conventional fibers), twisting or plying conductive filaments with textile yarns, coating or plating conventional yarns with conductive materials, using intrinsically conductive polymers, and incorporating carbon nanotubes or graphene [5]. The choice of the method depends on the targeted conductivity level, mechanical performance, comfort, durability, manufacturing cost, and final application, such as antistatic textiles, sensors, smart textiles, or electromagnetic shielding materials [6, 7].

In this paper, conductive yarns from blends of natural fibers, such as cotton, with conductive fibers, such as stainless steel are analyzed. Combining the two types of fibers in a blend leads to the obtaining of textile materials that retain the hygroscopic properties, air and water permeability as well as the softness conferred by cotton, and at the same time ensure electrical conductivity and antistatic protection, properties conferred by metallic fiber. Ichim et al. analyzed the properties of 29.4 tex rotor yarns spun from cotton–stainless steel blends in different ratios (96/4, 92/8, and 88/12) and reported yarn linear resistivity values ranging from 2.02×10^{9} Ω/cm to 2.1×10^{3} Ω/cm.

Producing high-performance yarns from such blends requires a careful selection of the spinning technology. Ring spinning is one of the oldest and most widely used methods of yarn production, valued for the superior quality and strength of the finished product. In contrast, rotor spinning is a more modern method, characterized by higher production speed and lower operating costs, but often associated with lower yarn quality [8]. In this sense, the comparison between ring spinning and rotor spinning becomes essential, not only for optimizing the functional properties of the yarns, but also for balancing production costs according to the requirements of the final application.

The proportion of metallic fibers has a considerable impact on the mechanical characteristics of the yarn, such as tensile strength and elongation, while also influencing the aesthetic appearance, uniformity and behavior in the spinning process. A content that is too low may impair yarn performance, whereas excessive content can adversely affect hand, increase production costs, and reduce the processability of the blend.

The objective of this research was to evaluate the effect of spinning technology and metallic fiber content on the properties of yarns designed for antistatic protective equipment. This study investigates the physico-mechanical and electrical properties of 37 tex conductive yarns produced by ring and rotor spinning from two cotton/stainless steel fiber blends (96/4 and 81/19).

2. MATERIALS AND METHODS

The stainless steel fibers used in the experiments, provided by Hunan Huitong Advanced Materials Co., Ltd. (China), were characterized by the following properties: a length of 50 mm, a linear density of 390 mtex, a tenacity of 17.9 cN/tex, an elongation at break of 1%, and a density of 7.85 g/cm^{3}.

The cotton fibers, supplied by the Faculty of Industrial Design and Business Management (Romania), had the following characteristics: an average length of 27.3 mm, a linear density of 259 mtex, a tenacity of 9.6 cN/tex, an elongation at break of 6%, and a density of 1.52 g/cm^{3}.

The stainless steel fibers, in sliver form, were blended with cotton fibers during the first passage through the draw frame. To ensure a homogeneous distribution of the metal fibers within the sliver cross-section, three draw frame passages were carried out.

To obtain a blend of 81% cotton and 19% stainless steel, seven cotton slivers and one stainless steel sliver were fed into the first draw frame passage. In the subsequent passages, eight slivers of the cotton–stainless steel blend were processed.

To obtain a blend of 96% cotton and 4% stainless steel, seven cotton slivers and one stainless steel sliver were fed into the first draw frame passage. In the second passage, six cotton slivers and two slivers of the cotton–stainless steel blend were processed, while in the final passage, eight slivers of the blend were fed into the draw frame.

Yarns were spun with a twist multiplier of 112 using common practices in cotton spinning mills, employing both rotor spinning and ring spinning methods.

Yarn properties were evaluated under standard atmospheric conditions of 20 ± 2 °C and 65 ± 2% relative humidity. The linear density of the yarns was determined in accordance with the SR EN ISO 2060 standard. Tensile properties were measured using a Tinius Olsen H5 K-T tensile tester equipped with a 250 N load cell, following the EN ISO 2062 standard and using a gauge length of 500 mm. Twist measurements were carried out on a Mesdan twist tester in accordance with the EN ISO 2061 standard, using a clamping distance of 250 mm. The yarn diameter was measured using a Mesdan microscope fitted with a Leica objective and camera, with images captured at 4× magnification.

To determine yarn resistivity, the specimen, consisting of an insulating plate around which the test yarn was wound, was placed in contact with the bar electrodes of the measuring device. A known voltage was applied across the electrodes, and the electrical resistance of the specimen was measured with an accuracy of ±20% using the voltmeter–ammeter method (STAS 11014-88). The measured electrical resistance was then used to calculate the linear resistivity of the yarn.

3. RESULTS AND DISCUSSION

The properties of rotor- and ring-spun yarns with a linear density of 37 tex (Nm 27), manufactured from cotton/stainless steel fiber blends in proportions of 96/4 and 81/19, are shown in Table 1.

Table 1: *Yarn properties*

Properties	**A1: 96/4 cotton/stainless steel**		**A2: 81/19 cotton/stainless steel**	
	Ring-spun yarn	**Rotor-spun yarn**	**Ring-spun yarn**	**Rotor-spun yarn**
Linear density, [tex]	37.08	36.32	37.58	36.04
CV of linear density, [%]	2.69	1.48	2.17	1.18
Diameter, [μm]	0.306	0.311	0.293	0.298
Twist, [tpm]	578.80	579.2	578.40	580.8
Breaking force, [cN]	374.1	234.2	431	340.7
CV of breaking force, [%]	11.89	9.92	10.26	8.30
Elongation at break, [%]	5.81	6.69	5.41	7.27
Linear resistivity, [Ω/cm]	1.03 x 10^9	1.9 x 10^9	728.2	1392.8

The average values of the yarn linear density fall within the variation limits permitted by the standard for a yarn with a nominal linear density of 37 tex, namely between 35.6 tex and 38 tex. The coefficient of variation (CV) of the linear density is higher for the ring-spun yarn than for the rotor-spun yarn, regardless of the blend. This can be explained by the fact that, in ring spinning, variations in the mass per unit length of the fed roving are transmitted directly to the yarn. In contrast, in rotor spinning, the fibers in the fed sliver are individualized by the action of the opening roller and transported separately to the rotor. Within the rotor, the fibers undergo random redistribution and blending as they are deposited in the collection groove. This process of fiber separation and blending helps to even out the strand formed in the rotor, thereby reducing the effect of fluctuations in the fed sliver [8,9]. Increasing the proportion of metal fibers in the yarn leads to a reduction in linear density irregularity, as stainless steel fibers exhibit more uniform linear density than cotton fibers.

For both blends, the diameter of the rotor-spun yarn is slightly greater than that of the ring-spun yarn, even though the rotor-spun yarns are marginally finer. As the proportion of stainless steel fibers increases, the yarn diameter decreases, which can be explained by the smaller thickness of steel fibers compared to cotton fibers. However, the diameter differences between the yarn variants are small.

Fig. 1 shows the microscopic appearance of 81/19 cotton–stainless steel yarns. The ring-spun yarn exhibits a smooth, compact structure, with fibers that are highly straightened and parallelized, arranged in concentric helical layers with Z twist. In contrast, the rotor-spun yarn displays a structure composed of two distinct layers. The core consists of fibers twisted in the Z direction, while the outer layer is formed either by fibers wrapped nearly perpendicularly around the core, creating so-called "belts," or by fibers with both S and Z twist directions that envelop the core in a net-like manner. Fig. 1b also highlights the presence of free loops—formed by fibers whose both ends are embedded within the yarn mass—in the rotor-spun yarn structure. This distinct structural configuration results in greater bulkiness compared to conventional ring-spun yarn [9,10].


a b

***Fig. 1**: Longitudinal view of the yarns (magnification 4x)*
a) ring-spun yarn, b) rotor-spun yarn

Table 1 shows that the breaking force of conventionally spun yarns is higher than that of rotor-spun yarns, regardless of the blend variant. In contrast, rotor-spun yarns exhibit lower variability in strength compared to the variation in breaking force observed in conventional yarns. This characteristic of rotor-spun yarns ensures a reduced number of breaks during subsequent processing stages, resulting in higher efficiency in weaving and knitting operations [11].

For yarns produced using the same spinning method, an increase in the proportion of metal fibers leads to higher breaking force and lower variability in breaking force.

The ring-spun yarn exhibits a lower elongation at break compared to the rotor-spun yarn. In the case of ring-spun yarn, an increase in the proportion of metal fibers results in a decrease in elongation at break.

Figure 2 shows the force–elongation curves for ring-spun and rotor-spun yarns with a nominal linear density of 37 tex, produced from blends of 96% cotton and 4% stainless steel (A1), and 81% cotton and 19% stainless steel (A2), respectively.

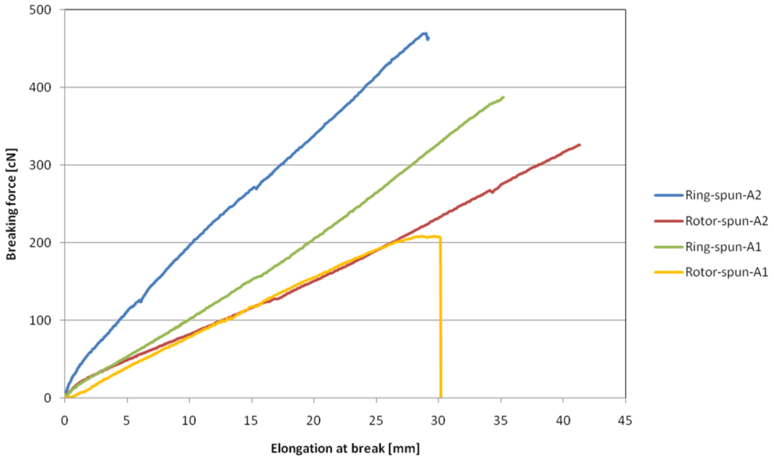

Fig. 2: *Force-elongation curves*

The force–elongation curves of the ring-spun yarns have a steeper slope than those of the rotor-spun yarns, indicating that the ring-spun yarns are stiffer and have a higher modulus of elasticity. This means that, at the same elongation, a higher tensile force is required for the ring-spun yarn, confirming that it is less elastic than the rotor-spun yarn.

From Table 1, it can be observed that the linear resistivity of the conventional yarn is approximately twice as low as that of the rotor-spun yarn. Therefore, the conventional yarn offers less resistance to the passage of electric current, conducts electricity more easily, and generates lower energy losses in the form of heat.

Linear resistivity depends on the internal structure of the yarn, the contact between fibers, the distribution of conductive fibers, as well as the density and homogeneity of the yarn. The conventional yarn is more compact, with straightened and parallel fibers arranged in helical layers, whereas the rotor-spun yarn is more voluminous, with fibers in the outer layer arranged in a more disordered manner. Since the contact surface between fibers is larger in the conventional yarn, its electrical conductivity is higher, resulting in lower linear resistivity.

In ring spinning, due to the higher tension applied during yarn formation, the metal fibers are better integrated among the cotton fibers, reducing the likelihood of fiber protrusion and improving both durability and conductive stability. However, the process is slower, more expensive, and may require equipment adaptations to process stainless steel fibers effectively, as these are more rigid and abrasive than natural fibers.

In comparison, rotor spinning is faster and more economical. However, the manner in which fibers are incorporated into the yarn—characterized by the fact that, during twisting, only one end of the fiber is bound into the yarn while the other remains free—results in a more random fiber orientation. Consequently, stainless steel fibers may be unevenly distributed, which can negatively affect the conductive efficiency and stability of the yarn during use.

For the same spinning technology, increasing the proportion of metal fibers leads to a decrease in yarn linear resistivity, and therefore to improved performance in dissipating electrical charges.

For a textile material to be used in antistatic protective clothing, its surface resistance must be lower than $2.5 \times 10^9\ \Omega$ [12]. The linear resistivity values of all the analyzed yarns indicate their suitability for antistatic applications. However, since this requirement refers specifically to surface resistance, further investigation is needed to assess the behavior of fabrics produced from these yarns.

4. CONCLUSIONS

The experimental research aimed to investigate the influence of the spinning technology and the proportion of metallic fibers on the properties of yarns intended for antistatic protective equipment.

Owing to their compact structure, in which the fibers exhibit a high degree of straightening and parallelization, ring-spun yarns showed higher strength, lower elongation at break, and lower linear resistivity than rotor-spun yarns. On the other hand, due to the back-doubling of fibers in the rotor groove, rotor-spun yarns exhibited greater evenness in linear density and strength.

An increase in the proportion of stainless steel fibers led to higher tensile strength, while both yarn diameter and elongation at break decreased. At the same time, the rise in stainless steel content reduced the yarn linear resistivity, enhancing its capacity to dissipate electrical charges.

In the current industrial context, any technological choice must be evaluated not only in terms of technical performance, but also in terms of economic efficiency. Ring spinning produces yarns with superior properties but involves higher production costs. In contrast, rotor spinning enables faster and more cost-effective production.

The choice of spinning method should be based on a well-balanced cost–performance ratio: where performance requirements are high, a higher price for superior yarn can be justified; conversely, for high-volume applications with moderate requirements, a technology that optimizes costs without significantly compromising functionality is preferable.

REFERENCES

[1] M. Ichim, I. Arnăutu, D. Cașcaval, E.S. Băcăiță, M.R. Zvonaru, “*Properties of Stainless Steel/Cotton Blended Rotor Spun Yarns for Antistatic Applications*”, in Proceedings of the 9th International Symposium "Technical Textiles - Present and Future" - Edition 2025, Paradigm Publishing Services, pp. 38-43, 2026.

[2] G. Cilveli, A. Okur, V. Sular, “*Electrostatic Properties of Clothing Fabrics Suitable for Different End-Uses*”, Fibres and Textiles in Eastern Europe, 28, pp. 50-57, 2020.

[3] J. Lowell, J.E. McIntyre, “*Antistatic fibres in fabrics and carpets*”, Journal of Electrostatics, Vol. 4, no 3, p. 267-282, 1978.

[4] V. Safarova, J. Militký, “*A Study of Electrical Conductivity of Hybrid Yarns Containing Metal Fibers*”, Journal of materials science & engineering, 2, pp. 109-114, 2012.

[5] Y. Chen, J. Hart, M. Suh, K. Mathur, R. Yin, “*Electromechanical Characterization of Commercial Conductive Yarns for E-Textiles*”. Textiles, 3, 294-306, 2023.

[6] X. He, T. Li, J. Xu, S. Yuan, S. Fu, “*Multifunctional conductive yarns based on cotton integrated knitting fabric strain sensor for human motion monitoring*”, Industrial Crops and Products, Vol. 232, 121339, 2025.

[7] M.Y.H. Saty, I. Abdalla, B. Sarkodie, A. Farooq, A. Elhassan, Y. Wang, Z. Xu, “*Recent advances of preparing structure-enhanced conductive yarns to control their performance in potential applications*”, Textile Research Journal, 94(23-24):2835-2862, 2024.

[8] E. Heinz, *The Rieter Manual of Spinning,* Vol.5 - Rotor Spinning, Rieter Machine Works Ltd., 2014.

[9] G. Trommer, *Rotor Spinning*, Frankfurt pe Main, Deutscher Fachverlag, 1995.

[10] C. Sava, *Tehnologii neconvenționale în filatură*, Iași, Performantica, 2014.

[11] V. Gribincea, M. Chiriță, Gh. Antoniu, Tehnologii flexibile și neconvenționale în filatura de bumbac, Iași, Editura Satya, 1996.

[12] ***, Protective clothing – electrostatic properties – Part 5: Performance requirements [Online]. Available: https://www.xmtextiles.com/standards/en-1149/

ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

MEMBRANE TECHNOLOGIES, INNOVATIONS, AND FIELD APPLICATIONS IN THE TEXTILE AND LEATHER INDUSTRIES: A REVIEW

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Abstract: *The textile and leather industries are among the sectors with the highest environmental impact globally due to their intensive use of water and chemicals in production processes. In particular, wastewater generated from processes such as dyeing, scouring, and tanning is characterized by high chemical oxygen demand (COD), color intensity, salinity, and heavy metal content. The inadequacy of traditional treatment methods for recovering these complex wastewater streams has made membrane technologies a critical solution for sustainable resource management. This paper provides a comprehensive examination of recent developments, innovative material designs, and full-scale field applications of membrane filtration systems (MF, UF, NF, RO) in the textile and leather industries. While the study focuses on reactive dye and salt recovery in the textile sector, specific application areas in the leather industry—such as chromium (Cr^{3+}) recovery, fractional separation of calcareous wastewater, and the isolation of protein-based byproducts—are analyzed in light of the literature.*

One of the article's key focal points is current innovations in membrane technologies. In this context, the efficiency of thermal-supported systems—such as membrane distillation—is discussed, along with new-generation surfaces incorporating graphene oxide and metal-organic frameworks (MOFs), as well as nanocomposite membranes engineered with "anti-fouling" (fouling-resistant) properties. Additionally, strategic solution proposals and cleaning protocols to address membrane fouling caused by high oil and protein loads in leather wastewater are discussed. In conclusion, this study not only presents technical performance data but also evaluates the contribution of membrane-integrated processes to "Zero Liquid Discharge" (ZLD) targets and their alignment with the circular economy model from a techno-economic perspective. By identifying gaps in literature and future research trends, the aim is to provide a comprehensive guide for both academic and industry professionals.

Key words: *Membrane technologies, Textile wastewater, Leather industry, Resource recovery, Nanocomposite membranes, Circular economy, Zero liquid discharge.*

1. MEMBRANES

1.1. Membrane Technologies and Working Mechanisms

Membrane technology stands out as a transformative solution to the 21st century's global challenges, such as energy conservation, clean water supply, and environmental protection. In its most basic form, a membrane is a selective barrier or interface that separates two phases in contact and controls the exchange of mass and energy between them. Unlike traditional filtration systems, membranes can have a molecularly homogeneous (dense) or physically heterogeneous (porous) structure. These structures, whose thickness can vary from less than a micrometer to several millimeters, can be designed in solid or liquid, isotropic or anisotropic (asymmetric) forms. As illustrated in Figure 1, the advanced nanoporous membrane layer acts as a selective barrier, balancing high waterproofness with breathability, which is essential for the thermal comfort of technical textiles.

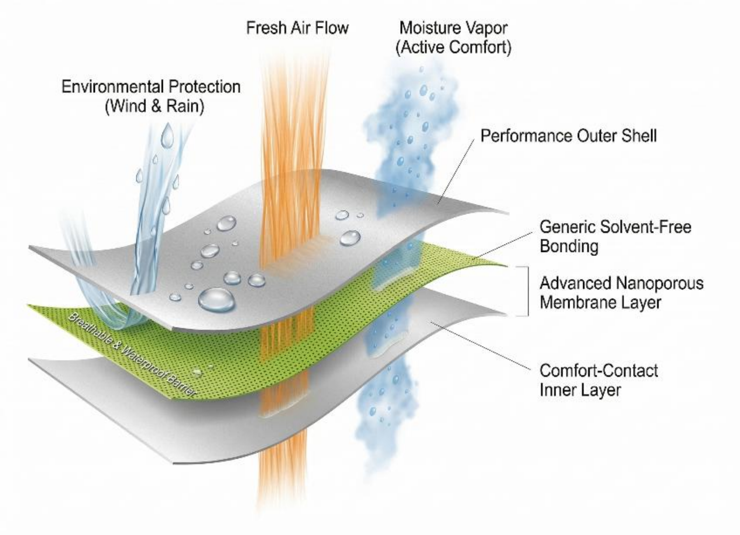


Fig.1. *General membrane illustration*

In membrane processes, separation performance is determined by the differences in the transport rates of the components within the membrane matrix. This transport process is explained by two basic mechanisms, depending on the driving forces acting within the system and on the morphological or chemical structure of the interface..

In the **"Pore-Flow / Sieving Model"**, which is dominant in porous membrane processes such as Microfiltration (MF) and Ultrafiltration (UF), separation is primarily based on the size exclusion principle; that is, whether particles can physically pass through the membrane pores is the determining factor. This convective transport is typically described by a modified form of Darcy’s Law:

$$Ji = K'ci\frac{dp}{dx} \quad \textbf{(1)}$$

where Ji is the flux, K' is the permeability coefficient, c_i is the concentration of component i, and dp/dx represents the pressure gradient.

On the other hand, in the **"Solution-Diffusion Model"**, which forms the basis of dense membrane processes such as Nanofiltration (NF), Reverse Osmosis (RO), Pervaporation, and Gas Separation, transport occurs by the dissolution of components on the membrane surface and their subsequent diffusion driven by a concentration gradient. In this model, separation success depends on the chemical affinity and molecular mobility of the components to the membrane material rather than their molecular size, governed by Fick's Law:

$$\mathrm{Ji} = \mathrm{Di}\frac{\mathrm{dci}}{\mathrm{dx}} \qquad \textbf{(2)}$$

In this expression, D_i represents the diffusion coefficient and dc_i/dx is the concentration gradient. The fundamental driving forces that trigger mass transport within the membrane, such as pressure, concentration, electrical potential, or temperature differences, create a "chemical potential gradient" that enables the selective transport of substances from one phase to another. The overall separation efficiency is quantified by the rejection coefficient (R), defined as:

$$R = \left(1 - \frac{cp}{cf}\right) * 100\% \qquad \textbf{(3)}$$

where c_p and c_f represent the solute concentrations in the permeate and feed streams, respectively.

1.2. Industrial Importance: Sustainability within the Framework of the "Green Deal" and Advantages of Membrane Technologies

The textile and leather sectors are well known for their immense global environmental footprint, primarily driven by their intensive use of freshwater and the continuous generation of highly polluted wastewater. The textile industry demands enormous volumes of water for sequential manufacturing processes such as bleaching, mercerization, dyeing, and finishing. Consequently, it discharges complex effluents characterized by high color intensity, elevated chemical oxygen demand (COD), extreme salinity, and non-biodegradable synthetic dyes [1]. Similarly, the leather tanning industry stands out as a major consumer of water and producer of waste, globally discharging heavy metals (e.g., chromium), toxic sludge, and millions of tons of common salt into water bodies annually [2]. In critical industrial zones worldwide, the unchecked discharge of untreated or partially treated industrial effluents has led to severe ecosystem degradation, groundwater and agricultural land contamination, and critical depletion of freshwater resources [3,4]. To mitigate this severe environmental crisis, the textile and leather industries are among the sectors with the largest global environmental footprint due to high water consumption and complex chemical use. In line with the European Parliament's "New Circular Economy Action Plan" and European Green Deal targets, membrane technology is recognized as the cornerstone of the "Process Intensification" strategy. This strategy transforms the leather and textile industry into a modern engineering structure by designing smaller, cleaner, and more energy-efficient production systems. The prediction that industrial water demand will increase by 400% by 2050 places membrane-based "green" separation processes at the center of the Green Deal targets in these sectors.

The role of membranes in this vision is built upon the pillars of energy efficiency, circular economy, and regulatory compliance. Membrane processes, unlike traditional thermal methods, can significantly reduce energy consumption through their "athermal" nature, which does not require phase change or chemical additives, and directly align with the United Nations' Clean Water (SDG 6) and Responsible Production (SDG 12) goals. Integrated membrane systems enable the recovery of 77% of water and the majority of chemicals, such as chromium, salt, and dyestuffs from textile and leather wastewaters, making the "Zero Liquid Discharge" (ZLD) and "Total Raw Material Utilization" concepts possible. In addition, revitalizing end-of-life membranes within the scope of a "second life" minimizes the system's total life-cycle cost and carbon footprint. The designation of Membrane Bioreactors (MBR) as the "Best Available Technique" (BAT) under EU directives makes this technology a technical necessity for Green Deal compliance.

Compared to traditional separation techniques commonly used in the leather and textile industries, such as distillation, evaporation, and chemical precipitation, membrane systems offer significant operational advantages. While most traditional methods require phase change for separation and consume large amounts of thermal energy, membrane processes operate at ambient temperature, reducing energy consumption by up to 18 times. While methods like chemical precipitation produce high-volume toxic sludges that are difficult to dispose of, membranes not only remove pollutants but also recover valuable raw materials with a purity that can be reintroduced into the production cycle. The modular structure and operational flexibility of membranes allow facility capacity to be easily increased without major construction, and they can be quickly integrated into existing production lines thanks to their small footprint. Functionally, membranes can separate similarly sized molecules that traditional filters cannot, with high selectivity, by exploiting differences in chemical affinity and diffusion rates. According to life cycle assessment (LCA) data, the low carbon footprint and the potential for recycling end-of-life modules make this technology the most competitive solution both economically and ecologically for the complex wastewater of the textile and leather industries.

Despite the significant advantages, industrial implementation of membrane technologies faces several technical and economic limitations. The primary challenge is membrane fouling, especially in the leather industry due to high protein and fat loads, which leads to a drastic decline in flux and requires frequent chemical cleaning. Furthermore, high operational costs (O&M) remain a concern for high-pressure systems like RO and NF, where electricity consumption for pumping constitutes a large portion of the budget. Lastly, the chemical and thermal stability of common polymeric membranes is limited; exposure to aggressive tanning agents or high-temperature textile effluents can cause material degradation, necessitating costly membrane replacements.

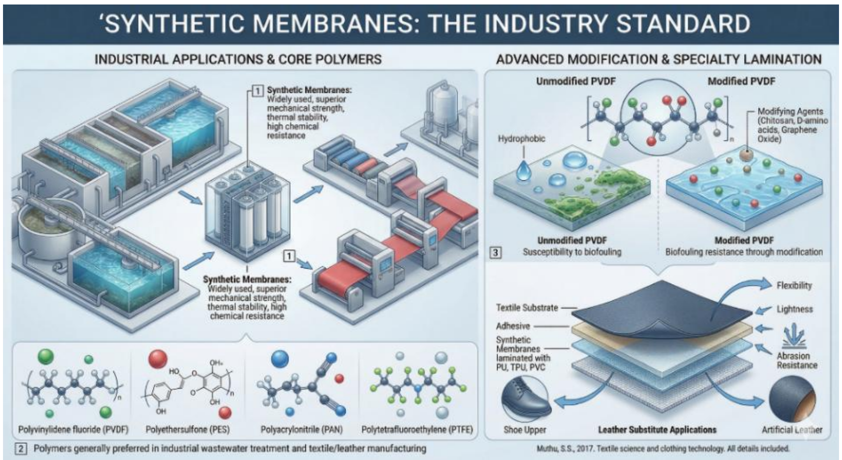
2. CLASSIFICATION OF MEMBRANES

Membranes can be designed in a wide variety of configurations to meet the specific requirements of industrial processes (e.g., high-pressure resistance, chemical fouling resistance, breathability, or selective permeability). Considering applications in the leather and textile industries and the growing sustainability focus, membrane technologies can be classified along three main axes: material type, morphological structure, and functional application areas.

2.1 Classification by Material: Synthetic and Natural/Biopolymeric Membranes

The most fundamental element determining membrane performance and lifespan is the main matrix used in its production.

- **Synthetic Membranes:** They are currently the most widely used membrane group due to their superior mechanical strength, thermal stability, and high chemical resistance [5]. Polymers such as Polyvinylidene fluoride (PVDF), Polyethersulfone (PES), Polyacrylonitrile (PAN), and Polytetrafluoroethylene (PTFE) are generally preferred in industrial wastewater treatment and textile/leather manufacturing [6]. Although PVDF stands out for its high chemical resistance and success in separation processes, its hydrophobic nature increases its susceptibility to biofouling, so it is often modified with agents such as chitosan, D-amino acids, or graphene oxide [7]. Furthermore, synthetic membranes laminated with Polyurethane (PU), Thermoplastic Polyurethane (TPU), and Polyvinyl Chloride (PVC), which are used as leather substitutes in shoe uppers and artificial-leather applications, have set an industry standard for their mechanical properties, such as flexibility, lightness, and abrasion resistance [8]. Figure 2 outlines the diverse core polymers used in synthetic membranes, highlighting their high mechanical and chemical stability which has established them as the current industry benchmark for textile effluent treatment.



Muthu, S.S., 2017. Textile science and clothing technology. All details included.

Fig.2. *General synthetic membranes diagram*

- **Natural and Biopolymeric Membranes (Green Membranes):** Within the framework of the Green Deal principles, biodegradable and biocompatible alternatives are rapidly gaining importance in order to reduce the environmental burden (toxicity and microplastic problems) of petrochemical-derived synthetics [9]. The leather and textile industries offer great potential to convert their waste (e.g., trimming waste) into valuable biopolymers. Collagen hydrolysates and gelatin obtained from leather waste via hydrolysis can be blended with polyvinyl alcohol (PVA) and chitosan to form environmentally friendly composite membrane films with high water-barrier properties [10]. Additionally, chitosan, a polysaccharide obtained from crustaceans (crab, shrimp) or fungi, and alginate, obtained from brown seaweeds, are used as highly efficient natural matrices for the removal of dyestuffs from textile wastewater, antimicrobial textile finishing processes, and the production of medical and wound-dressing textiles [11]. The transition toward bio-based polymers illustrated in Figure 3 emphasizes the potential of leather waste upcycling in creating biocompatible matrices that align with European Green Deal sustainability goals.

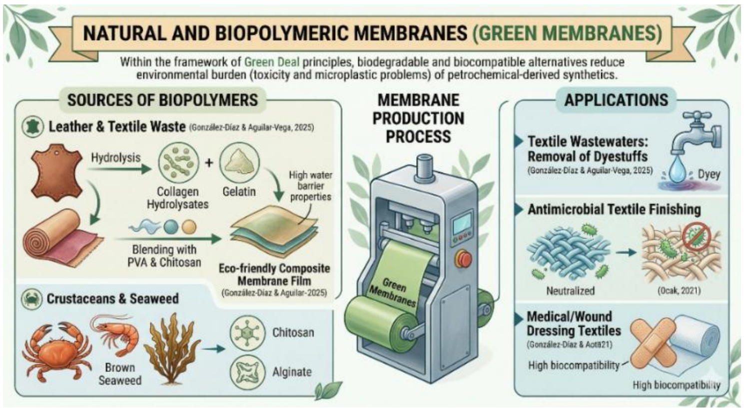
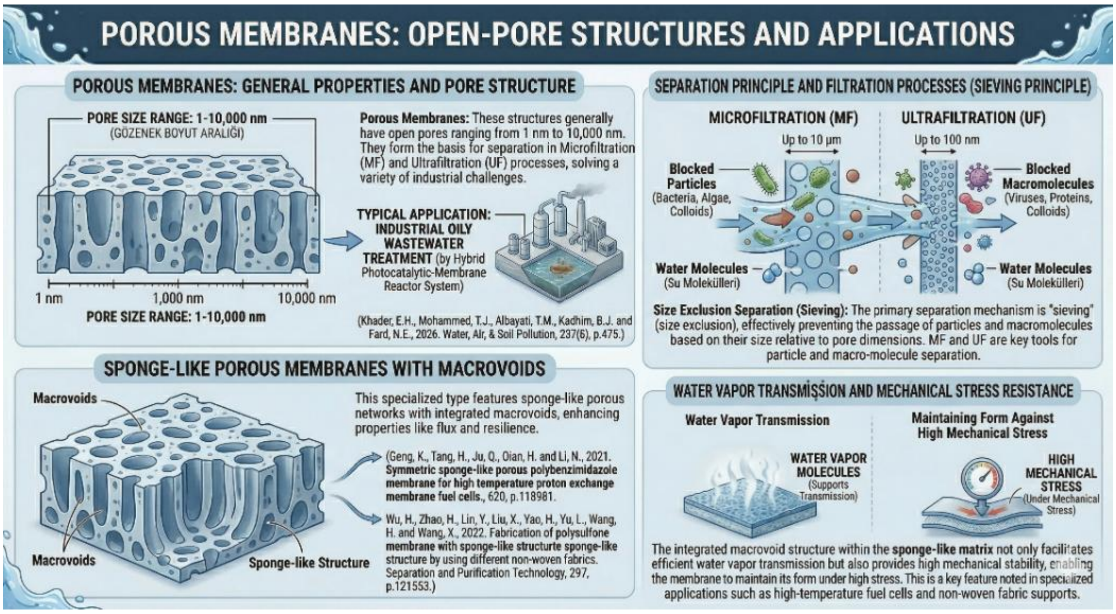


Fig.3. *General natural and biopolymeric membranes diagram*

2.2 Classification by Structure (Morphology): Porous, Dense, and Asymmetric Membranes

- The morphological structure of the membrane directly determines the transport mechanism (molecular diffusion or size exclusion). Primarily, these structures are classified into porous, dense, and asymmetric membranes. Porous membranes are structures generally having open pores ranging from 1 nm to 10,000 nm and are used in Microfiltration (MF) and Ultrafiltration (UF) processes [12]. They separate the passage of particles and macromolecules based on the "sieving" (size exclusion) principle. Sponge-like porous membranes with macrovoids can support water vapor transmission while maintaining their form against high mechanical stress [13,14]. As depicted in Figure 4, the open-pore structure of porous membranes facilitates particle separation through a sieving mechanism, providing an effective solution for pre-treating complex oily industrial wastewaters.



Porous Membranes: These structures generally have open pores ranging from 1 nm to 10,000 nm. They form the basis for separation in Microfiltration (MF) and Ultrafiltration (UF) processes, solving a variety of industrial challenges.

(Khader, E.H., Mohammed, T.J., Albayati, T.M., Kadhim, B.J. and Fard, N.E., 2026. Water, Air, & Soil Pollution, 237(6), p.475.)

Size Exclusion Separation (Sieving): The primary separation mechanism is "sieving" (size exclusion), effectively preventing the passage of particles and macromolecules based on their size relative to pore dimensions. MF and UF are key tools for particle and macro-molecule separation.

This specialized type features sponge-like porous networks with integrated macrovoids, enhancing properties like flux and resilience.

(Geng, K., Tang, H., Ju, Q., Oian, H. and Li, N., 2021. **Symmetric sponge-like porous polybenzimidazole membrane for high temperature proton exchange membrane fuel cells.**, 620, p.118981.

Wu, H., Zhao, H., Lin, Y., Liu, X., Yao, H., Yu, L., Wang, H. and Wang, X., 2022. Fabrication of polysulfone **membrane with sponge-like structurte sponge-like** structure by using different non-woven fabrics. Separation and Purification Technology, 297, p.121553.)

The integrated macrovoid structure within the **sponge-like matrix** not only facilitates efficient water vapor transmission but also provides high mechanical stability, enabling the membrane to maintain its form under high stress. This is a key feature noted in specialized applications such as high-temperature fuel cells and non-woven fabric supports.

Fig.4. *Porous membranes description in general*

On the other hand, dense, non-porous membranes are homogeneous layers with pore sizes below 1 nm, in which transport occurs via the "solution-diffusion" model [15, 16]. These structures enable nearly 100% removal of dissolved salts, heavy metals, and low-molecular-weight organic pollutants from the system under high pressure, particularly in Nanofiltration (NF) and Reverse Osmosis (RO) systems [17, 18]. The dense membrane structure and the corresponding solution-diffusion model detailed in Figure 5 illustrate the high-efficiency removal of dissolved pollutants, enabling the production of ultrapure process water.

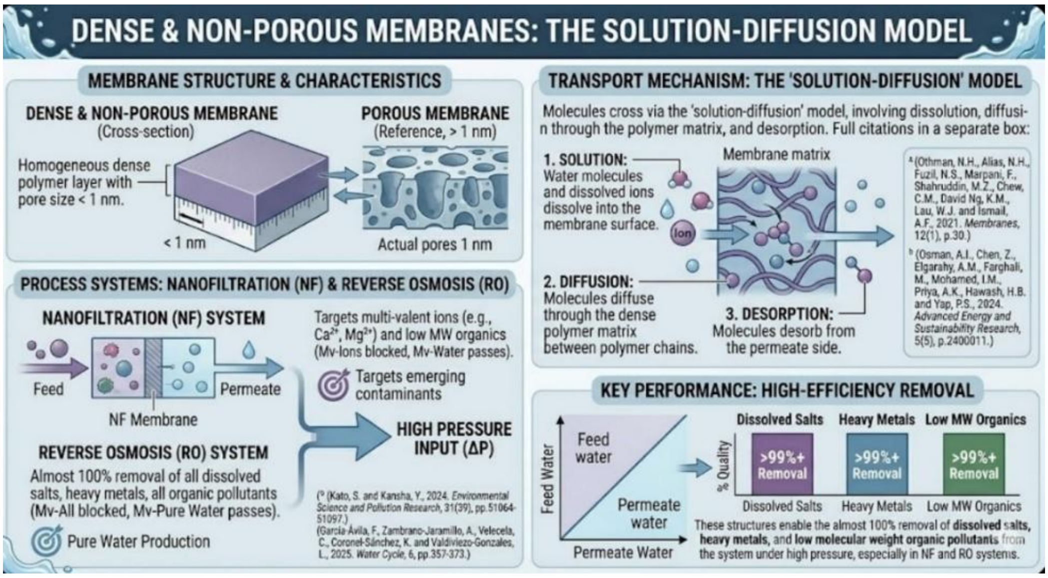


Fig.5. *Dense and non-porous membranes: general explanation*

Finally, forming the basis of industrial separation processes, asymmetric membranes consist of a pressure-resistant, very thin, dense, selective top layer (skin layer) and a thicker, sponge-like, porous bottom support (substrate) layer [19,20]. The fact that the pressure drop and the separation process occur only on this dense, sub-micron-thick surface minimizes fluid resistance. Thus, compared to traditional symmetric (uniform density throughout) membranes, both high selectivity and extraordinarily high permeability are achieved simultaneously [21, 22]. The morphology of asymmetric membranes shown in Figure 6 highlights the sub-micron skin layer where the actual separation occurs, emphasizing how this structure minimizes fluid resistance compared to symmetric versions.

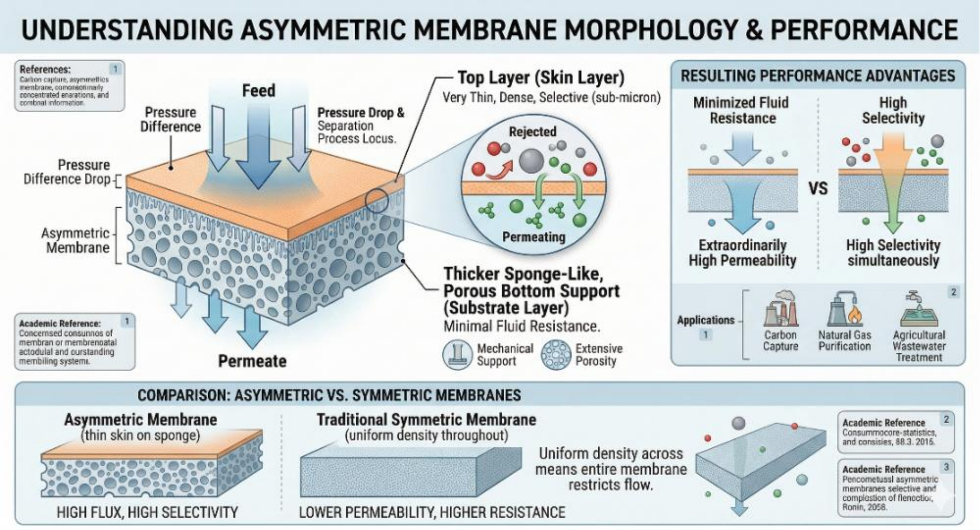


Fig.6. *Asymmetric membranes' general morphology and performance*

2.3 Classification by Function: Wastewater Treatment and Breathable/Waterproof Textiles

While membranes are classified solely by their driving forces in classical chemistry literature, in the textile and leather sectors, membrane design directly serves niche "functional" targets.

- **Wastewater Treatment & Resource Recovery:** This function is the integration of the circular economy and the Zero Liquid Discharge (ZLD) concept into the industry [23]. The removal of hazardous chromium and sulfur from leather tanning wastewater, and the selective separation of reactive/indigo dyes and salts in the textile industry for reuse (using NF and RO) are made possible by this specific function [24]. Specially designed hydrophobic and oleophobic functional membranes are tasked with treating complex oily industrial waters [25].
- **Breathable-Waterproof and Technical Functional Textiles:** This is a product-oriented function preferred in sportswear, military clothing, protective equipment, and footwear. While mechanically preventing the passage of liquid water droplets (or harmful microorganisms) from the outside environment, they offer excellent thermophysiological comfort by allowing sweat (water vapor) secreted from the human body to be expelled outwards through micro-pores or hydrophilic polymer chains via diffusion [26, 27, 28]. Today, PAN (Polyacrylonitrile) and cellulose-based membranes modified with melanin or nanoparticles synthesized from agricultural or marine wastes (pecan nutshells, coffee grounds, etc.) are equipped with extra technical functions such as antimicrobial and free radical scavenging (anti-aging), giving a new direction to the smart/protective textiles market [29].

2.4 Common Methods for Membrane Fabrication

The fabrication of high-performance membranes for leather and textile applications relies on several key industrial techniques:

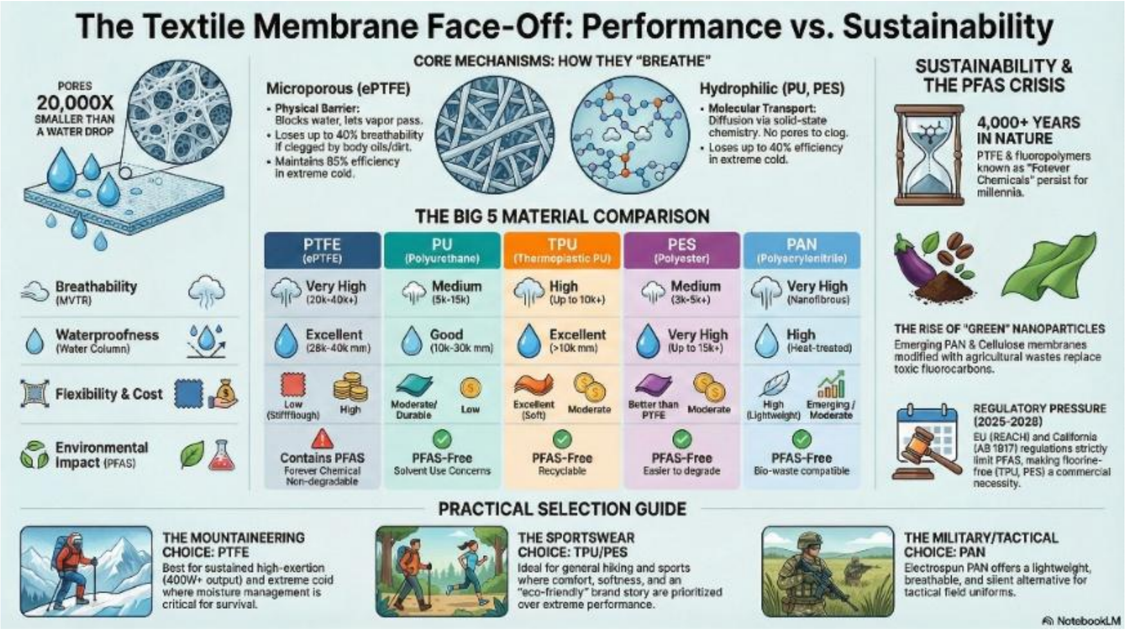
- **Phase Inversion:** This is the most common technique for producing asymmetric membranes. A homogeneous polymer solution is induced to separate into two phases: a solid polymer-rich phase that forms the membrane matrix and a liquid polymer-lean phase that creates the pores.
- **Electrospinning:** This technology uses an electric field to draw charged threads of polymer solutions into ultra-fine nanofibers. It is widely used to produce highly porous nanomembranes with exceptional surface area for protective clothing and advanced filtration.
- **Interfacial Polymerization:** Primarily used for thin-film composite (TFC) RO and NF membranes, this method involves a polymerization reaction at the interface of two immiscible solvents, resulting in an ultra-thin polyamide selective layer on a porous support.

3. APPLICATION AREAS IN THE TEXTILE AND LEATHER INDUSTRY

Membrane technologies, thanks to their structural diversity and high separation performances, play a critical role in the leather and textile industries, both in improving the performance of products reaching the end consumer and in ensuring the sustainability of industrial processes.

3.1. Functional Garments: The Use of Membranes in Thermal Comfort and Protective Clothing

In outerwear and protective technical textiles, membranes are the primary barriers that maintain breathability (water vapor permeability) while preventing the ingress of liquid water. Today, the market for functional apparel and smart textiles is dominated by five main polymer types, each offering distinct morphological structures, mechanical properties, and environmental profiles. The performance-sustainability face-off in Figure 7 highlights the technical superiority of conventional fluoropolymers alongside the urgent need for eco-friendly, PFAS-free alternatives in the tactical garments market.



Microporous (ePTFE)
- Physical Barrier: Blocks water, lets vapor pass.
- Loses up to 40% breathability if clegged by body oils/dirt.
- Maintains 85% efficiency in extreme cold.

Hydrophilic (PU, PES)
- Molecular Transport: Diffusion via solid-state chemistry. No pores to clog.
- Loses up to 40% efficiency in extreme cold.

	PTFE (ePTFE)	PU (Polyurethane)	TPU (Thermoplastic PU)	PES (Polyester)	PAN (Polyacrylonitrile)
Breathability (MVTR)	Very High (20k-40k+)	Medium (5k-15k)	High (Up to 10k+)	Medium (3k-5k+)	Very High (Nanofibrous)
Waterproofness (Water Column)	Excellent (28k-40k mm)	Good (10k-30k mm)	Excellent (>10k mm)	Very High (Up to 15k+)	High (Heat-treated)
Flexibility & Cost	Low (Stiff/Tough) High	Moderate/ Durable Low	Excellent (Soft) Moderate	Better than PTFE Moderate	High (Lightweight) Emerging / Moderate
Environmental Impact (PFAS)	⚠ Contains PFAS Forever Chemical Non-degradable	✓ PFAS-Free Solvent Use Concerns	✓ PFAS-Free Recyclable	✓ PFAS-Free Easier to degrade	✓ PFAS-Free Bio-waste compatible

4,000+ YEARS IN NATURE
PTFE & fluoropolymers known as "Fotever Chemicals" persist for millennia.

THE RISE OF "GREEN" NANOPARTICLES
Emerging PAN & Cellulose membranes modified with agricultural wastes replace toxic fluorocarbons.

REGULATORY PRESSURE (2025-2028)
EU (REACH) and California (AB 1817) regulations strictly limit PFAS, making floorine-free (TPU, PES) a commercial necessity.

THE MOUNTAINEERING CHOICE: PTFE
Best for sustained high-exertion (400W+ output) and extreme coid where moisture management is critical for survival.

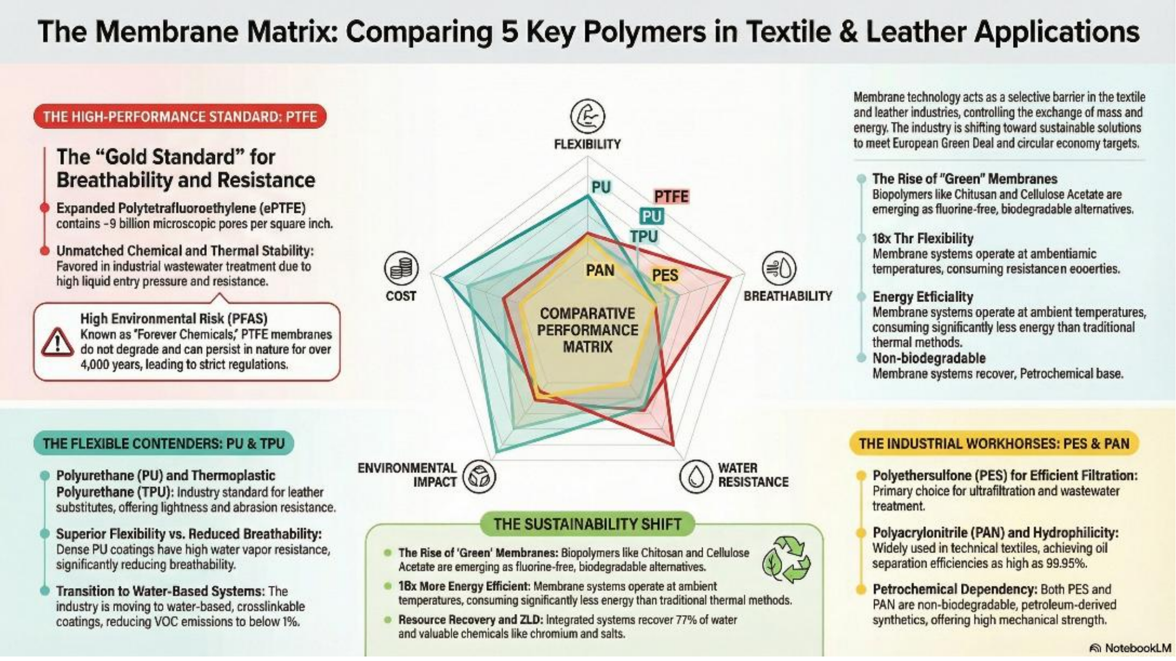
THE SPORTSWEAR CHOICE: TPU/PES
Ideal for general hiking and sports where comfort, softness, and an "eco-friendly" brand story are prioritized over extreme performance.

THE MILITARY/TACTICAL CHOICE: PAN
Electrospun PAN offers a lightweight, breathable, and silent alternative for tactical field uniforms.

Fig.7. *Comparison of surface morphologies and cross-sections of the five main textile membranes: PU, TPU, PES, PAN, and PTFE.*

- PTFE (Polytetrafluoroethylene): The gold standard in this field has been expanded polytetrafluoroethylene (ePTFE) membranes for many years. With a typical thickness of around 35 microns, ePTFE features a microporous structure containing billions of microscopic pores, providing extraordinarily high air permeability and water vapor transmission rates (WVTR) [30]. In comparative studies, PTFE consistently demonstrates the highest WVTR and air permeability among conventional textile membranes [31]. However, ePTFE is a synthetic fluoropolymer that degrades very slowly in nature and contributes to the severe environmental issue of "Forever Chemicals" (PFAS), prompting the industry to seek fluorine-free alternatives [32].
- PU and TPU (Polyurethane and Thermoplastic Polyurethane): As highly flexible and eco-friendly alternatives to PTFE, PU and TPU are typically applied as hydrophilic, non-porous (solid) membranes [33]. Because they lack visible micro-pores, moisture transport occurs via a solution-diffusion mechanism, in which water molecules bind to hydrophilic polymer chains and pass through to the other side. While their air permeability is significantly lower than that of microporous PTFE, they offer excellent elasticity, wind resistance, and wear resistance, making them highly suitable for activewear and artificial leather [34, 35, 36].
- PES (Polyethersulfone / Polyester): PES membranes offer a strong balance of performance and sustainability. In textile laminations, hydrophilic PES membranes (often around 15 microns thick) exhibit higher water vapor transmission rates than standard PU membranes, ranking just below PTFE. Additionally, PES membranes stand out with their exceptional thermal stability and mechanical strength. Unlike ePTFE, ester-based polymers degrade much faster and are easier to recycle, making them an eco-friendly option for outdoor applications [37, 38].

PAN (Polyacrylonitrile / Acrylic): PAN, containing a C≡N group, possesses excellent thermal and electrochemical stability along with relatively high hydrophilicity. It is particularly suitable for electrospinning, enabling the production of highly porous, ultra-thin nanofibrous membranes with superior air permeability. However, PAN inherently lacks mechanical strength and flexibility, so it is often blended with elastomeric materials (e.g., polyurethane) or used as a supporting layer to withstand the mechanical stress of functional garments [39, 40, 41]. The performance matrix presented in Figure 8 provides a multi-axial evaluation of key polymers, allowing for the strategic selection of membrane materials based on specific breathability, waterproofness, and environmental impact criteria.



The Membrane Matrix: Comparing 5 Key Polymers in Textile & Leather Applications

THE HIGH-PERFORMANCE STANDARD: PTFE

The "Gold Standard" for Breathability and Resistance

- **Expanded Polytetrafluoroethylene (ePTFE)** contains ~9 billion microscopic pores per square inch.
- **Unmatched Chemical and Thermal Stability:** Favored in industrial wastewater treatment due to high liquid entry pressure and resistance.

High Environmental Risk (PFAS) Known as 'Forever Chemicals,' PTFE membranes do not degrade and can persist in nature for over 4,000 years, leading to strict regulations.

THE FLEXIBLE CONTENDERS: PU & TPU

- **Polyurethane (PU) and Thermoplastic Polyurethane (TPU):** Industry standard for leather substitutes, offering lightness and abrasion resistance.
- **Superior Flexibility vs. Reduced Breathability:** Dense PU coatings have high water vapor resistance, significantly reducing breathability.
- **Transition to Water-Based Systems:** The industry is moving to water-based, crosslinkable coatings, reducing VOC emissions to below 1%.

THE SUSTAINABILITY SHIFT

- **The Rise of 'Green' Membranes:** Biopolymers like Chitosan and Cellulose Acetate are emerging as fluorine-free, biodegradable alternatives.
- **18x More Energy Efficient:** Membrane systems operate at ambient temperatures, consuming significantly less energy than traditional thermal methods.
- **Resource Recovery and ZLD:** Integrated systems recover 77% of water and valuable chemicals like chromium and salts.

Membrane technology acts as a selective barrier in the textile and leather industries, controlling the exchange of mass and energy. The industry is shifting toward sustainable solutions to meet European Green Deal and circular economy targets.

- **The Rise of "Green" Membranes** Biopolymers like Chitusan and Cellulose Acetate are emerging as fluorine-free, biodegradable alternatives.
- **18x Thr Flexibility** Membrane systems operate at ambentiamic temperatures, consuming resistancen eooerties.
- **Energy Etficiality** Membrane systems operate at ambient temperatures, consuming significantly less energy than traditional thermal methods.
- **Non-biodegradable** Membrane systems recover, Petrochemical base.

THE INDUSTRIAL WORKHORSES: PES & PAN

- **Polyethersulfone (PES) for Efficient Filtration:** Primary choice for ultrafiltration and wastewater treatment.
- **Polyacrylonitrile (PAN) and Hydrophilicity:** Widely used in technical textiles, achieving oil separation efficiencies as high as 99.95%.
- **Petrochemical Dependency:** Both PES and PAN are non-biodegradable, petroleum-derived synthetics, offering high mechanical strength.

Fig.8. *Comparing five key polymers in textile and leather applications*

- **Thermal Comfort in Leather Garments:** The thermal comfort of traditional leather garments is also directly related to the surface treatments applied and membrane-type coatings [42]. In current studies using thermal manikins, it has been shown that water vapor resistance varies with leather structure and the applied finishing process [43]. For example, while patent leathers, whose surface is covered with a dense polyurethane/lacquer layer, have the highest water vapor resistance (lowest breathability), suede leathers offer the highest breathability, keeping the body cool even in hot climates.

3.2. Leather Processing: Recovery of Tanning Wastes and Membrane Technologies in Leather Surface Coatings

Leather manufacturing is a process in which water consumption and chemical pollution (especially chromium salts) are particularly intense [44]. Membrane technologies have two main functions in managing these wastes and aesthetically enriching the leather:

- **Chromium and Salt Recovery (Zero Liquid Discharge - ZLD):** In the tanning industry, only a portion of chromium sulfate salts penetrates the leather, while the rest mixes into the wastewater [45]. By using integrated membrane systems (Ultrafiltration, Nanofiltration, and Reverse Osmosis), chromium and valuable salts (NaCl, sodium sulfate, etc.) in these wastewaters can be separated, concentrated, and recovered for reuse in tanning baths [46]. These systems, integrated with Reverse Osmosis (RO), enable treated water to be reused within the process, making the Zero Liquid Discharge

(ZLD) concept a reality for the leather sector [23].

- **Surface Coating (Finishing) Applications:** In the surface coatings (topcoats) applied to the final layer of leather, there is a transition from solvent-based systems to water-based membrane polymers due to environmental regulations. High-tech water-based, crosslinkable polyurethane coatings and polymeric matrices provide high friction and water resistance without deteriorating the natural texture (haptic properties) of the leather, while also reducing Volatile Organic Compound (VOC) emissions to below 1% [47].

3.3 Sustainable Trends: Transition from Petroleum-Based Membranes to Biodegradable Membranes

The textile and leather industry is on the verge of structural transformation due to environmental pressures and regulations. At the center of this transformation lies the development of eco-friendly alternatives to replace conventional synthetic membranes.

- **The PFAS and Microplastic Problem:** PTFE (Teflon) and similar fluoropolymer membranes are called "Forever Chemicals" (PFAS) because they do not degrade in nature [48]. Fragments broken off from these membranes during washing or wear mix into water resources as microplastics and can remain non-degraded in nature for more than 4000 years [49]. For this reason, authorities such as the European Union (REACH) and California (AB 1817) are restricting the use of PFAS in textiles, forcing the industry toward fluorine-free water-repellent membranes [50].
- **Biodegradable Synthetics:** In response to these problems, non-recyclable membranes such as cellulose acetate (CA) or polysulfone (PSU) have started to be replaced by membranes produced from biodegradable polymers like Poly (lactic acid) (PLA), Poly (caprolactone) (PCL), and Poly (butylene succinate) (PBS) [51]. These green bioplastics offer a lower carbon footprint in wastewater treatment, oil-water separation, and textile filtration than traditional materials and can decompose into harmless components in nature at the end of their lifespans [52].
- **Plant-Based and Natural Alternatives:** For a completely fossil-fuel-independent ecosystem, toxic solvent-free nanofiltration membranes based on lignin and cellulose derived from wood industry wastes are being developed [53]. At the same time, in the leather and footwear market, plant-based membranes and fibers synthesized from bacterial cellulose obtained through fermentation or pineapple leaves (Piñatex) are rapidly increasing their market share as sustainable and vegan alternatives with high mechanical strength that do not contain toxic chemicals compared to traditional leather and petroleum-derived artificial leathers (PU/PVC) [48, 54].
- **Nanomembranes and Electrospun Nanofibers:** As the industry seeks high-performance yet sustainable alternatives, nanomembranes have emerged as a groundbreaking technology. Nanomembrane filters produced through advanced electrospinning technology significantly outperform traditional filters by offering enhanced filtration efficiency and breathability due to their exceptionally high surface area-to-volume ratio and ultra-fine inter-fiber pore structure [55]. These structures can be manufactured using environmentally sustainable, biocompatible, and biodegradable polymers, emerging as promising candidates to replace conventional polypropylene-based or petroleum-derived synthetic filters. Furthermore, in technical applications such as protective clothing, "PFAS-safe" nanomembranes are successfully replacing traditional ePTFE. Recent studies demonstrate that multi-layer assemblies based on polyimide nanomembranes not only provide a completely fluorine-free (PFAS-free) eco-friendly solution but also exhibit significantly superior structural integrity, particle filtration efficiency, and thermal resistance compared to conventional PTFE membranes even after repeated washing cycles [56]. In the context of industrial wastewater treatment, nanomembranes functionalized with graphene oxide (GO) offer ultrathin selective channels and highly customizable surface chemistries. These advanced nanocomposite structures provide

extraordinary water permeability and fouling resistance, standing out as one of the most powerful tools for achieving sustainable filtration without the environmental burden of conventional synthetics [57].

4. CURRENT RESEARCH TRENDS

Current research on membrane technology in the leather and textile industries focuses on developing bio-based and waste-sourced (waste-to-value) composite materials completely free of PFAS (per- and polyfluoroalkyl substances), known as "Forever Chemicals," under the pressure of strict environmental regulations implemented by the European Union [58]. Accordingly, the integration of "green nanoparticles" derived from agricultural wastes into synthetic or natural polymer matrices has been the most prominent research topic in recent years.

The following table summarizes the recent studies reflecting this radical change:

Table 1: *Current Studies*

Author and Year	Membrane Material	Application Area	Key Findings
Alparslan et al., 2016	Gelatin + Orange Leaf Essential Oil	Biodegradable Film / Coating	A gelatin matrix was blended with herbal orange leaf waste to produce a green, sustainable film/coating material that prevents microbial growth.
Tagliaro et al., 2024	Chitosan	PFAS-Free Coating for Fabrics	Superhydrophobicity was achieved by reaching a contact angle of 151° without the need for synthetic fluorocarbons; it was proven that the coating withstands up to 8 washing cycles and is completely biocompatible with human skin cells.
Jing et al., 2021	Collagen Fiber / Chitosan Composite	Water and Oil Resistant Coating (Fluorine/PFAS-free)	100% eco-friendly and biocompatible materials based on collagen/chitosan with excellent water and oil resistance were developed without using synthetic fluorocarbons (PFAS) chemicals.
Alberto et al., 2022	GO (Graphene Oxide) + PVDF	Oxide) + PVDF Membrane Distillation (Pore-wetting resistance)	Deposition of multi-layer graphene oxide (GO) onto commercial PVDF membranes provided high pore-wetting resistance to surfactants for over 40 hours without compromising the clean-water flux.
Khader et al., 2025	PAN + Eggplant Waste Nanoparticles (EGW)	Oily Wastewater Treatment (Antifouling)	Nanoparticles synthesized from eggplant waste increased the surface hydrophilicity of the PAN membrane by reducing its water contact angle, achieving 99.95% oil separation efficiency.

García-García et al., 2025	PAN + Melanin (from Pecan Nutshell)	Skin Care / Functional Membrane	Electrospun membranes loaded with melanin pigment derived from pecan nutshell waste exhibited high antioxidant (82.36%) and antimicrobial properties, while also inhibiting skin aging enzymes.
Ghadhban et al., 2024	PLA/PBAT + Banana Peel Nanoparticles (BP-NPs)	Oily Water Separation	Banana peel nanoparticles significantly improved the wettability and mechanical stability of the composite membrane, providing 95.2% oil removal in water contaminated with diesel oil.
Nthunya et al., 2024	Various Polymers (PVDF, PTFE) + AI Integration	Dye Wastewater Treatment (MD Optimization)	Comprehensive analysis demonstrated that integrating Artificial Intelligence (AI) and machine learning models with membrane distillation significantly optimizes dye removal efficiency and mitigates complex fouling in textile effluents.
Aka and Akşit, 2025	Cellulose + Silane/Phosphate Nano-Sol	Flame Retardant (FR) Coating for Textiles	Cellulose dissolved and transferred onto cotton fabric was coagulated with a nano-sol-gel formulation, successfully imparting high LOI (Limiting Oxygen Index) flame retardancy via an eco-friendly approach.
Dolez et al., 2025	Polyimide / Polyurethane + Graphene Track	Smart Protective Clothing (End-of-Life Sensor)	Graphene-based conductive tracks, combined with sacrificial polymers (sensitive to UV, moisture, and heat), were developed to monitor real-time degradation and end-of-life conditions of fire-protective clothing.

The comprehensive PFAS restriction regulations (REACH restrictions) planned by the European Union for the years 2025-2026 have made the use of conventional fluorocarbon-based membranes in the textile and leather sectors a legal and commercial risk. Therefore, researchers have turned to biodegradable polymers (e.g., chitosan, PLA) and "green nanoparticles" derived from agricultural waste [59]. While traditional synthetic nanoparticles (e.g., silver or chemical TiO2) have disadvantages such as environmental toxicity and high cost, bio-based nanoparticles obtained from plant wastes (eggplant, banana, or pecan nutshell) enhance the hydrophilicity, fouling resistance, and oil rejection performance of the membranes in an eco-friendly way thanks to the hydroxyl and carboxyl groups they contain [60].

5. FUTURE PERSPECTIVE AND CONCLUSION

The textile and leather industries are currently undergoing a mandatory ecological transformation driven by strict environmental regulations and the urgent need to mitigate their immense water footprint. As discussed throughout this review, membrane technologies have proven to be the cornerstone of this transition. Moving beyond simple physical filtration, these advanced systems now serve as the primary engineering tools capable of achieving Zero Liquid Discharge (ZLD) targets and facilitating valuable resource recovery.

Looking forward, the future of membrane applications in these sectors lies in the seamless integration of high-performance, PFAS-free, and fully biodegradable materials. The current reliance on petroleum-derived polymers and synthetic fluorocarbons is no longer ecologically or legally sustainable. Instead, the next generation of smart membranes will increasingly utilize natural polymers and nanocomposites synthesized directly from agricultural or industrial wastes. However, a significant engineering challenge remains achieving the mechanical strength and chemical stability in these 100% bio-based membranes to match or exceed those of their synthetic counterparts under harsh industrial conditions.

Furthermore, addressing the persistent bottlenecks of membrane fouling and high operating costs is critical to broader industrial adoption. The integration of advanced nanomaterials, such as graphene oxide (GO) and metal-organic frameworks (MOFs), alongside thermally driven processes like membrane distillation, presents a highly promising pathway to overcome these barriers. Future research and field applications must prioritize the techno-economic optimization of these hybrid systems, developing dynamic anti-fouling surfaces and efficient cleaning protocols that ensure long-term operational stability. Ultimately, membrane technologies will not merely serve as end-of-pipe wastewater treatment tools; they will be the core drivers of a "closed-loop" industrial symbiosis, transforming waste into high-value resources and establishing a truly circular economy in the textile and leather sectors.

This study has been prepared to contribute to researchers in industry and academia who investigate and implement membrane applications across various sectors. The literature reviews and comparative analyses presented in this study, along with their detailed summaries, are expected to contribute to membrane research.

REFERENCES

[1] L.N. Nthunya, J. Pinier, A. Ali, C. Quist-jensen, H. Richards, "*Valorization of acid mine drainage into potable water and valuable minerals through membrane distillation crystallization.*" Sep. Purif. Technol. 2024, pp. 334, 126084 https://doi.org/ 10.1016/j.seppur.2023.126084.

[2] J. Buljan, K.V. Emmanuel, M. Viswanathan, M. Bosnić, and I. Král, "*Assessment of performance of Zero Liquid Discharge (ZLD) operations in some tannery clusters Vellore Districts*", 2017, Tamil Nadu, India

[3] A. Gupta, "*Zero Liquid Discharge (ZLD) and Sludge Valorization: Dual Pathways for Sustainable Wastewater Management in India.*" International Journal of Advanced Research (IJAR), 13(10), 2025, pp. 395-409.

[4] N. Radha, Sharma, S. Prakash, N. Kumari, D. Sharm, R. Laller, A. Pundir and S. Puri, "*From challenges to opportunities: exploring minimum liquid discharge and zero liquid discharge strategies for wastewater management and resource recovery*" InRole of science and technology for sustainable future: Volume 2-applied sciences and technologies 2025 Jan 8 pp. 371-394, Singapore: Springer Nature Singapore.

[5] R.H. Khudher, A.A. Hasan, T.M. Albayati, S. Zendehboudi, N.M. Saady, "*Green polymer nanocomposite membranes for treating oily wastewater: A comprehensive review.*" Environmental Engineering Research. 2026 Apr;31(2).

[6] H. Lin and M. Zhang, "*Advanced membrane technologies for wastewater treatment and recycling*" Membranes, 13(6), 2023, p.558.

[7] M. Ghonimy, A. Alharbi, S.A. Saad, and N.S. Hussein, "*Improving wastewater quality using ultrafiltration technology for sustainable irrigation reuse*" Water, 17(6), 2025, p.870.

[8] S.S. Muthu, "*Textile science and clothing technology*" (No Title), 2017.

[9] M.O. González-Díaz and M. Aguilar-Vega, "*Recent Advances in Polymeric Membranes—Preparation and Applications*" Membranes, 2025 Dec 22;16(1):3.

[10] B. Ocak, "*Development of novel collagen hydrolysate bio-nanocomposite films extracted from hide trimming wastes reinforced with chitosan nanoparticles*" Environmental Science and Pollution Research, 2021 Jul;28(26):35145-56.

[11] K.A. Motaleb, S. Islam, M.S. Faheem, A. Khan, M.B. Hasan, H. Jamshaid, J. Janutėnienė and A. Tadžijevas, "Valorisation of bio-waste for the development of sustainable technical textiles" Textile Progress, 2025 Jul 3;57(3):117-217.

[12] E.H. Khader, T.J. Mohammed, T.M. Albayati, B.J. Kadhim and N.E. Fard, "Application of Statistical Modeling and Optimization for Industrial Oily Wastewater Treatment by Hybrid Photocatalytic-Membrane Reactor System" Water, Air, & Soil Pollution, 2026 Apr;237(8):475.

[13] K. Geng, H. Tang, Q. Ju, H. Qian and N. Li, "*Symmetric sponge-like porous polybenzimidazole membrane for high temperature proton exchange membrane fuel cells*" Journal of Membrane Science, 2021 Feb 15;620:118981.

[14] H. Wu, H. Zhao, Y. Lin, X. Liu, H, Yao, L. Yu, H. Wang and X. Wang, "*Fabrication of polysulfone membrane with sponge-like structure by using different non-woven fabrics*" Separation and Purification Technology, 2022 Sep 15;297:121553.

[15] N.H. Othman, N.H. Alias, N.S. Fuzil, F. Marpani, M.Z. Shahruddin, C.M. Chew, Ng K.M. David, W.J. Lau and A.F. Ismail, "*A review on the use of membrane technology systems in developing countries*" Membranes, 2021 Dec 27;12(1):30.

[16] A.I. Osman, Z. Chen, A.M. Elgarahy, M. Farghali, I.M. Mohamed, A.K. Priya, H.B. Hawash, and P.S. Yap, "*Membrane technology for energy saving: principles, techniques, applications, challenges, and prospects*" Advanced Energy and Sustainability Research, 2024 May;5(5):2400011.

[17] S. Kato, and Y. Kansha, "*Comprehensive review of industrial wastewater treatment techniques*" Environmental Science and Pollution Research, 2024 Aug;31(39):51064-97.

[18] F. García-Ávila, A. Zambrano-Jaramillo, C. Velecela-Garay, K. Coronel-Sánchez, and L. Valdiviezo-Gonzales, "*Effectiveness of membrane technologies in removing emerging contaminants from wastewater: Reverse Osmosis and Nanofiltration*" Water Cycle, 2025 Jan 1;6:357-73.

[19] R. Kamalesh, S. Karishma, A. Saravanan, and P.R. Yaashikaa, "*Emerging breakthroughs in membrane filtration techniques and their application in agricultural wastewater treatment: Reusability aspects*", Sustainable Chemistry for the Environment, 2024 Dec 1;8:100183.

[20] X. Chen, G. Liu, and W. Jin, "*Natural gas purification by asymmetric membranes: An overview*", Green Energy & Environment, 2021 Apr 1;6(2):176-92.

[21] Y. Jia, K. Wong, C.Z. Liang, J. Wu, T.S. Chung, and S. Zhang, "*Recent development of membranes for carbon capture: From materials to asymmetric membranes*", Progress in Materials Science, 2024 Dec 1;146:101324.

[22] S.P. Miguel, A.F. Moreira, and I.J. Correia, "*Chitosan based-asymmetric membranes for wound healing: A review*" International journal of biological macromolecules, 2019 Apr 15;127:460-75.

[23] A. Pundir, M.S. Thakur, B. Goel, Radha, A. Kumar, S. Prakash, M. Thakur, and M. Kumar, "*Innovations in tannery wastewater management: a review of zero liquid discharge technology*" International Journal of Environmental Science and Technology, 2025 Mar;22(5):3873-94.

[24] M.A. Aboulhassan, and S. Souabi, "*Sustainable Practices in the Tannery Industry*" 2025.

[25] H. Gulhan, M.E. Pasaoglu, H. Ozgun, M.E. Ersahin, V. Vatanpour, and I. Koyuncu, "*Nutrient recovery in zero liquid discharge systems: A critical review of technologies and integration strategies*" Journal of Water Process Engineering, 2026 Apr 1;86:109843.

[26] K.A. Motaleb, S. Islam, M.S. Faheem, A. Khan, M.B. Hasan, H. Jamshaid, J. Janutėnienė, and A. Tadžijevas, "*Valorisation of bio-waste for the development of sustainable technical textiles*" Textile Progress, 2025 Jul 3;57(3):117-217.

[27] Y. Chang and F. Liu, "*Review of waterproof breathable membranes: preparation, performance and applications in the textile field*" Materials, 2023 Jul 29;16(15):5339.

[28] W. Zhou, J. Yu, and S. Zhang, "*Environmentally friendly waterproof and breathable membranes via electrospinning*", The Journal of The Textile Institute, 2024 Mar 3;115(3):504-26.

[29] M.A. Vega, "*Recent Advances in Polymeric Membranes*", 2026

[30] D. Şarapnal, and A. Berkay, "*DESIGN AND PERFORMANCE EVALUATION OF FLAME-RESISTANT PROTECTIVE FABRICS*" İZMİR, 2025.

[31] R. Kumari, R.S. Rengasamy, and R. Chattopadhyay, "*A study on the mechanical and physiological performance of the nylon outer shell of extreme cold weather clothing*" Fibers and Polymers, 2024 Jan;25(1):357-73.

[32] Y. Chang, and F. Liu. "*Review of waterproof breathable membranes: preparation, performance and applications in the textile field*", Materials, 2023 Jul 29;16(15):5339.

[33] A. K. Pandey, "*Soft material engineered synthetic polymer membranes: bridging design and application*", Molecular Systems Design & Engineering, 2026;11(1):7-49.

[34] Y. Wang, X. Li, and Y. Chen, "*Research on innovation and application of thermoplastic polyurethane elastomer bionic leather fabric from the perspective of sustainable design*", InIOP Conference Series: Earth and Environmental Science, 2021 Mar 1 (Vol. 706, No. 1, p. 012032). IOP Publishing.

[35] P. Sikdar, T.M. Dip, A.K. Dhar, M. Bhattacharjee, M.S. Hoque, and S.B. Ali, "*Polyurethane (PU) based multifunctional materials: Emerging paradigm for functional textiles, smart, and biomedical applications*", Journal of Applied Polymer Science, 2022 Oct 10;139(38):e52832.

[36] S.A. Suhaimi, W.S. Ruznan, R.N. Hussain, M.A. Nor, N.H. Aziz, N.I. Madarsa, and M.R. Ahmad, "*Thermophysiological Comfort Assessment of Football Jersey Fabrics used in Hot and Humid Weather*", International Journal of Integrated Engineering, 2025 Dec 31;17(9):117-34.

[37] H. MacKeown, B. Benedetti, C. Scapuzzi, M. Di Carro, ans E. Magi, "*A review on polyethersulfone membranes in polar organic chemical integrative samplers: preparation, characterization and innovation*", Critical Reviews in Analytical Chemistry, 2024 Aug 17;54(6):1758-74.

[38] M. Irfan, T. Nasir, U. Haider, and M. Irfan, "A Review of Synthetic Polymers in Hemodialysis Membranes: Impact on Biocompatibility and Performance", Journal of Applied Membrane Science & Technology, 2025 Aug 1;29(2):157-68.

[39] V.A. Maske, A.M. Kokate, P.A. More, R.S. Salunkhe, and A.P. More, "*A comprehensive review of polyacrylonitrile membranes: modifications and applications*" Polymer Bulletin, 2024 Dec;81(18):16415-55.

[40] M. Aslam, T. Khan, M. Basit, R. Masood, and Z.A. Raza "*Polyacrylonitrile-based electrospun nanofibers–A critical review*" Materialwissenschaft und Werkstofftechnik, 2022 Dec;53(12):1575-91.

[41] B. Danagody, N. Bose, and K. Rajappan, "Electrospun polyacrylonitrile-based nanofibrous membrane for various biomedical applications", Journal of Polymer Research, 2024 Apr;31(4):119.

[42] S.M. Çolak, N. Özdil, M. Ekinci, and Ö. Kaplan, "*Thermophysiological comfort properties of the leathers processed with different tanning agents*" Textile and Apparel" 2016 Oct 1;26(4):436-43.

[43] F. Gamna, G. Maculotti, A. Sarnataro, M. Galetto, C. Florio, and S. Ferraris, "*Advances in the physical and chemical characterization of tanned leather*", Journal of Materials Science, 2026 Jan 13:1-24.

[44] F. Chiampo, S. Shanthakumar, R. Ricky, G.P. Ganapathy, "*Tannery: environmental impacts and sustainable technologies*" Materials Today: Proceedings, 2023 Feb 14.

[45] Z. Hassan, N. Jamil, and R. Batool, "*Confronting Challenges in Technological Development Within Sustainable Leather Manufacturing: Barriers and Routes*", InSustainable Practices in the Tannery Industry: Strategies for Eco-Friendly Leather Manufacturing 2025 Jul 29 (pp. 227-252). Cham: Springer Nature Switzerland.

[46] E. Drioli, and A. Cassano, "*Membranes and integrated membrane operations as clean technologies in the leather industry*" Clean Technologies" 2023 Feb 16;5(1):274-96.

[47] M.Y. Ghadhban, H.S. Majdi, K.T. Rashid, Q.F. Alsalhy, D.S. Lakshmi, I.K. Salih, and A. Figoli "*Removal of dye from a leather tanning factory by flat-sheet blend ultrafiltration (UF) membrane*" Membranes, 2020 Mar 18;10(3):47.

[48] C. Ng, I.T. Cousins, J.C. DeWitt, J. Gluge, G. Goldenman, D. Herzke, R. Lohmann, M. Miller, S. Patton, M. Scheringer, and X. Trier, "Addressing urgent questions for PFAS in the 21st century", Environmental Science & Technology, 2021 Sep 14;55(19):12755-65.

[49] A. Bour, T.B. Christensen, A.D. Hunka, A. Palmqvist, E. Skjold, and K. Syberg, "Implications of circular textile policies for the future regulation of hazardous substances in textiles in the European Union", Science of The Total Environment, 2023 Oct 20;896:165153.

[50] M.H. Whittaker, and L. Heine, "*Toxicological and environmental issues associated with waterproofing and water repellent formulations*" InWaterproof and water repellent textiles and clothing 2018 Jan 1 (pp. 89-120), Woodhead Publishing.

[51] N. Sheraz, A. Shah, A. Haleem, and F.J. Iftikhar, "*Comprehensive assessment of carbon-, biomaterial-and inorganic-based adsorbents for the removal of the most hazardous heavy metal ions from wastewater*" RSC advances, 2024;14(16):11284-310.

[52] A. Yarahmadi, B. Dousti, M. Karami-Khorramabadi, and H. Afkhami, "*Materials based on biodegradable polymers chitosan/gelatin: a review of potential applications*" Frontiers in Bioengineering and Biotechnology, 2024 Aug 2;12:1397668.

[53] S. Rajendran, A. Al-Samydai, G. Palani, H. Trilaksana, T. Sathish, J. Giri, R. Saravanan, J.I. Lalvani, and F. Nasri, "*Replacement of Petroleum Based Products With Plant-Based Materials, Green and Sustainable Energy—A Review*", Engineering Reports, 2025 Apr;7(4):e70108.

[54] A. Alsobh, M.M. Zin, G. Vatai, and S. Bánvölgyi, "*The application of membrane technology in the concentration and purification of plant extracts: a review*" Periodica Polytechnica Chemical Engineering, 2022 May 17;66(3):394-408.

[55] B. Mahltig, "*Nanomaterials and textiles: Review on materials and applications*", Journal of Engineered Fibers and Fabrics, 2025 Feb;20:15589250251318010.

[56] F. Michel, "*High Performance Fabrics, Nanomembranes and Lamination Process Improvements for Firefighters Hoods Sustainability*" *11th European Conference on Protective Clothing (ECPC)*, Kuşadası, Türkiye, 2025, p.171

[57] S. Barua, A.A. Sabri, T. Chauhan, M.R. Choudhury, and A.H. Pinto, "*Graphene Oxide-Based Membranes for Wastewater Treatment: Current Status and Future Outlook*", Sustainability & Circularity NOW. 2026;3(continuous publication).

[58] I. Tagliaro, M. Mariani, R. Akbari, M. Contardi, M. Summa, F. Saliu, R. Nisticò, and C. Antonini, "*PFAS-free superhydrophobic chitosan coating for fabrics*", Carbohydrate polymers, 2024 Jun 1;333:121981.

[59] P. Qi, S. Wang, W. Wang, J. Sun, H. Yuan, and S. Zhang, "*Chitosan/sodium polyborate based micro-nano coating with high flame retardancy and superhydrophobicity for cotton fabric*", International journal of biological macromolecules, 2022 Apr 30;205:261-73.

[60] A. Mohammadi, N Hashemi, M Ghassabzadeh, A. Sharafi, A. Yazdinezhad, and H. Danafar, "*Green synthesis and toxicological evaluation of zinc oxide nanoparticles utilizing Punica granatum fruit Peel extract: an eco-friendly approach*", Scientific reports, 2025 Jul 1;15(1):20853.

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SUSTAINABLE HAIR WIGS AND EXTENSIONS FROM BANANA AND SILK FIBRES: A REVIEW USING PRISMA METHODOLOGY

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Abstract: *Petroleum-based synthetic fibers and chemically processed human hair, both linked to excessive resource consumption, microplastic pollution, and hazardous chemical exposure during dyeing and finishing, dominate the global wig and hair extension market. These products are linked to carbon emissions, plastic waste, and environmental problems at the end of their useful lives. Although natural fibers like banana and silk offer renewable and biodegradable alternatives, their use in wig and extension systems is still understudied. This study conducts a systematic review of the literature on sustainable hair substitutes made from silk and banana fibers. The Preferred Reporting Items for Systemic Reviews and Meta-Analyses (PRISMA) methodology was used to synthesize peer-reviewed studies on fiber production, extraction, characterization, textile processing, performance evaluation, and consumer acceptance. Results show that while silk offers better lustre, flexibility, and tactile qualities, banana fiber offers high tensile strength and is readily available as an agricultural waste. Nevertheless, there is a scarcity of empirical research that specifically examines their incorporation into hair wig systems. There are notable research gaps in consumer acceptance studies, durability benchmarking, thermal styling performance, and lifecycle assessment. The review concludes that while banana/silk hybridization is technically feasible and beneficial for the environment, it needs multidisciplinary validation through materials engineering and market research.*

Key words: *Banana fiber, Hair extensions, Hair wigs, Prisma, Silk fiber.*

1. INTRODUCTION

The global market for wigs and hair extensions has grown dramatically as a result of protective hairstyling techniques, medical hair loss treatment, and fashion trends. According to [1]; [2]; [3], conventional wigs and extensions are primarily made from petroleum-based synthetics or chemically processed human hair, both of which are linked to high energy consumption, chemical loads, and end-of-life microplastic, all of which will have an impact on landfills. Figure 1 shows hair extension made of synthetic material. In general, the textile industry is a significant polluter, contributing to persistent waste, greenhouse gas emissions, and contamination of water and soil [4]; [2]. Figure 2 shows circular economy of material for sustainability.

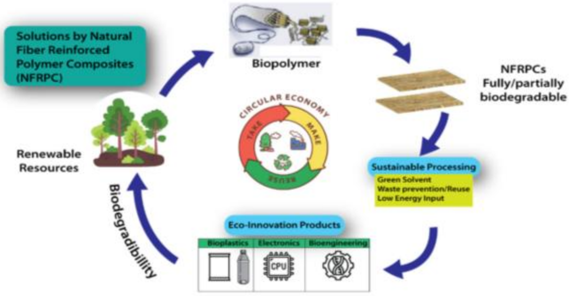

Fig. 1. *Synthetic hair extension [5]* ***Fig. 2.*** *Circular economy of material for sustainability [6]*

As a result, the textile industry has embraced sustainable material paradigms that are in line with institutionally promoted circular economy frameworks. The circular economy 5Rs (Refuse, Reduce, Reuse, Repurpose and Recycle) are key strategies to waste minimization and optimal resource use. The approaches create a hierarchy which first prevent consumption and moving towards material recovery to enhance materials and products longevity, reducing pollution and embracing conservation of resources for sustainable growth. Systematic reviews of textile sustainability highlight the need for bio-based, circular materials and eco-design to reduce microfiber release, effluent impacts, and waste generation [7]; [8]; [9]; [10].

Banana fiber, obtained from banana pseudostem agro-waste, is increasingly recognised as a biodegradable, low-impact textile resource with good tensile strength, breathability, and potential to substitute synthetic fibres in fashion applications [1]; [2]; [4]; [11]. Figure 3 shows banana fibers extracts from three different extraction methods. Silk remains a high-value natural protein fibre prized for lustre and drape; blending silk with other sustainable fibres is being explored to improve functionality and reduce dependence on any single resource [12]; [13]. Figure 4 shows silk fiber and cocoons. Table 1 shows the main attributes of banana and silk fibers. Developing research on silk and banana blended textiles using natural dyes and bio-mordants reveals environmentally friendly coloring and finishing techniques [13].

Fig. 3. *Extracted banana fibers (a) Water retting, (b) Boiling in water (c) Caustic soda aqueous solution [14]*

Fig. 4. *(a) Silk cocoon and (b) silk fiber [15]*

Table 1 *Key attributes of banana and silk fibers attribute*

Characteristic	**Banana fiber**	**Silk fiber**	**References**
Resource base	Agro-waste (pseudostem, leaves)	Sericulture by-product or waste silk	[1]; [2]; [16]; [17]; [18]; [19]; [20]; [21].
Biodegradability	High; lignocellulosic	Protein-based, biodegradable	[1]; [2]; [16]; [19]; [20].
Sustainability	Waste valorization, reduced burning/landfill	Upcycling of textile waste, high strength alternative to nylon/Kevlar	[1]; [2]; [17]; [18]; [19]; [20]; [21].
Mechanical profile	Good tensile strength, moderate stiffness	Very high strength/toughness (esp. engineered spider silk)	[1]; [12]; [16]; [17]; [19]; [20]; [21].

Natural fibers have become more popular in clothing and composite materials because they are biodegradable, renewable, and have lower embodied carbon. Nevertheless, there is still little scholarly research on their use in hair wig and extension systems. Although there isn't a study that specifically assesses banana or silk fibers in wigs and extensions, evidence from textiles, circular fashion, and PRISMA-based sustainability reviews enables the creation of a methodical, PRISMA-aligned overview of their potential as sustainable hair product substitutes. There is increasing pressure to switch to circular, renewable, and biodegradable fiber systems in place of these materials [1-3], [18].

2. MATERIALS AND METHODS

This review employed the PRISMA methodology framework, which ensures a careful search strategy, screening, suitability assessment, and synthesis. The Preferred reporting items for systematic reviews and meta-analyses, is a guideline designed to improve the reporting of systematic reviews. It is an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses which provides authors with guidance and examples of how to completely report why a systematic review was done, what methods were used, and what results were found.

A systematic search was conducted across major scholarly databases for interdisciplinary coverage of materials science, textile engineering, sustainability, and consumer studies. Searches were restricted to peer-reviewed articles published between 2000 and 2025. The PRISMA process involved an initial retrieval of 1,243 articles where 312 duplicates were removed leaving 931 articles. Abstract screening excluded 701 unrelated studies and 230 full-text articles met inclusion criteria. This is demonstrated by Figure 5. The databases that were used are Scopus, google Scholar, Web of Science, Science Direct and PubMed. Keywords combined with Boolean operators were used as follows; “banana fibre” OR “Musa fibre” OR “banana pseudostem” AND “sustainable” OR “eco-friendly” OR “biodegradable” OR “life cycle” “silk fibre” OR “sericin” OR “natural silk” OR “silk textile”. The analysis was exclusively for banana and silk fibers application in hair wigs and extensions.

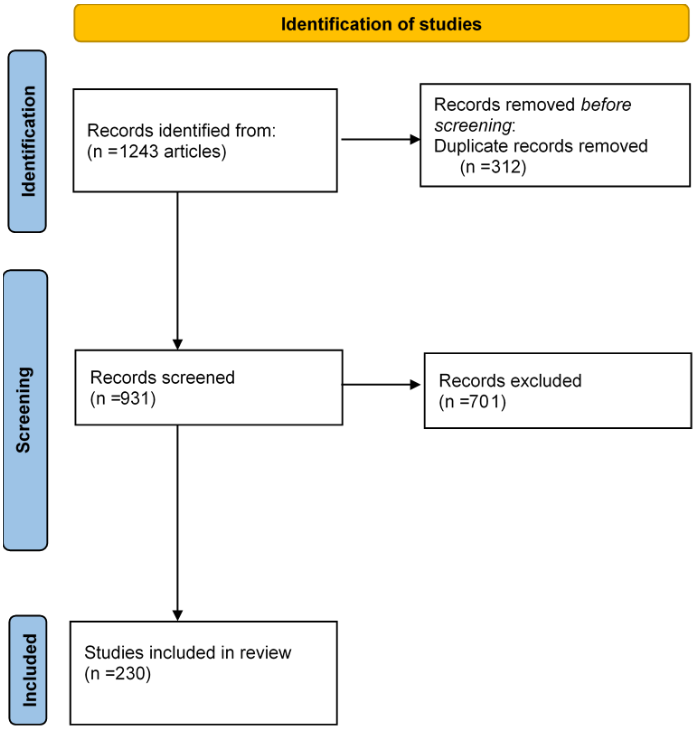

Fig. 5: *Systemic Literature review stages using PRISMA methodology*

Inclusion eligibility criteria for the search involved empirical or review studies on banana or silk fiber production and characterization, studies on natural fiber textile applications research on sustainability assessments (LCA, carbon footprint) and the consumer behavior studies on sustainable fashion. The exclusion criterion was based on on-peer reviewed articles, studies unrelated to textile or fiber applications and exclusive biomedical silk research not applicable to textiles.

3. DISCUSSION

The global wig and hair extension market is dominated by petroleum-based synthetic fibers and chemically processed human hair, which are associated with high resource use, microplastic pollution, and toxic chemical exposure throughout processing procedures. Synthetic materials, often produced from modacrylic and polyethylene terephthalate fibers, are not neither ecofriendly nor sustainable. The literature consistently identifies synthetic wig fibers as environmentally burdensome due to high carbon emissions, end of life environmental burden, petrochemical dependency, and non-biodegradability. Lifecycle assessments of polyester and acrylic textiles reveal significant energy consumption and greenhouse gas emissions during polymerization and extrusion processes. Microplastic release and landfill accumulation are made worse by end-of-life disposal of these synthetic fibers. Natural fibers such as banana and silk present biodegradable and renewable alternatives, yet their application in wig and extension systems remains underexplored.

Natural fiber substitutes have less impact on the environment, especially when they come from agricultural waste streams like banana pseudostems. Banana-producing nations in Asia and Africa have an abundance of banana fiber. High banana production volumes in sub-Saharan Africa are confirmed by reports from the Food and Agriculture Organization, indicating the availability of raw materials. Mechanical research shows high moisture regain, good biodegradability, and tensile strengths between 400 and 600 MPa. However, applications needing a fine hair-like texture face difficulties due to the fiber inherent coarseness and diameter variability. Alkali treatment increases surface smoothness and flexibility, but if effluent management is poorly done, then environmental challenges might overshadow the beneficial effects of the treatment.

In contrast, silk, a protein based biodegradable fiber has remarkable elongation capacity, tensile strength, sheen and excellent moisture management the properties that makes the fiber desirable for luxury textiles and biomedical applications. Silk fiber is sustainable evidence by mulberry cultivation as well as degumming/finishing chemistry, where waste silk can be recycled providing a circular route. Wet spinning of waste silk into regenerated silk fibroin fibres allows structural control of the fiber (circular, bean-shaped, U-shaped, lumen-containing) via coagulation conditions [20]. The morphology of degummed silk fibers demonstrate is softness when compared to human hair. Suitability for moderate styling conditions is improved by thermal resistance up to about 140 up to 160°C. Sericulture inputs, however, continue to make silk production resource-intensive. Silk has a significant attribute of been protein-based and biodegradable, but sustainability discussions raise concerns about labour intensity and land use.

Although blended natural fiber systems are rarely used in wig applications, they are extensively researched in composite engineering. Combining plant and protein fibers can improve their structural and tactile qualities, according to research on natural fiber blending. Silk adds flexibility, lustre, and softness, while banana fibers provide structural integrity and tensile strength. Performance results are strongly influenced by fiber blending ratios. This clearly is a glaring research gap. Even so, there are no identified studies found that directly test banana or silk fibers in commercial wig structures.

According to comparative research, natural fibers besides been biodegradable, have a lower carbon footprint than synthetic ones. However, uniformity and durability often favor the synthetic fiber. From the lifecycle analyses, bio-based textiles use less energy than polyester, but occasionally more water. Therefore, cradle-to-grave evaluation, not just biodegradability, must be included in sustainability claims. Consumer research on sustainable fashion indicates that consumers are becoming more inclined to buy environmentally friendly goods, provided that the prices are comparable and the products are aesthetically pleasing. The literature on the theory of planned behavior shows that purchase intention is positively correlated with environmental concern, although this relationship is moderated by perceived performance and affordability. There is a substantial knowledge gap due to the scantiness of wig-specific research. Demand patterns are influenced, especially in African markets, by cultural considerations, fashion trends, and protective hairstyling norms.

The PRISMA methodology analysis demonstrate research gaps in regards to banana and silk fiber hair wigs and extensions which need to be addressed. Limited empirical studies as well as thermal styling performance data for natural fiber wig fabrication tops the list of gaps. Standardized testing protocols for wig durability and comfort would add weight to application of banana and silk fiber for hair wigs and extensions. Scanty research on consumer acceptance that focus on natural hair products and the inadequate Lifecycle assessment that is very specific to wig application need substantial research attention.

4. CONCLUSIONS

This systematic review shows that silk and banana fibers have complementary mechanical, aesthetic, and environmental qualities that make them viable options for environmentally friendly hair extensions and wigs. The literature demonstrates strong potential for sustainable, high-performance materials that align with circular economy principles. Banana fiber offers structural strength and circular bio-economy benefits through agro-waste value addition, while silk contributes softness, elasticity, and visual appeal.

Nevertheless, the literature remains disjointed across cultivation, materials science, and sustainable fashion trends. No wide-ranging empirical research that currently validate banana and silk hybrid hair wigs and extensions under laboratory and consumer-use conditions. Although no studies yet directly target banana and silk fibers hair wigs and extensions, the underlying science strongly supports the feasibility in application of banana and silk fibersin hair products including the wigs and extensions as environmentally preferable alternatives to conventional synthetic hair. Additionally, literaturein has no clear address on sustainable alternatives to synthetic hair wigs and alternatives.

Consequently, a focused research agenda on aesthetic performance, durability under cosmetic use, and full life-cycle impacts is necesary to translate the feasibility into commercial, scalable sustainable hair products. It is also desirable that the future studies should integrate the optimization of protocols for banana and silk fiber extraction and eco friendly treatment, fiber blending and standardization of characterization for fiber properties. Life cycle assessment as well as market feasibility and market perception studies are equally reccomnded.

In conclusion, hair wigs and hair extensions synthesized from banana and silk fibers represent a technically conceivable pathway which is not only sustainable but is ecofriendly as well. Nevertheless, before commercial adoption of this product, a robust interdisciplinary experimental validation is essential. This review establishes a consolidated evidence base and classifies clear directions for advancing sustainable hair wig technologies within a circular bio-economy framework.

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REFERENCES

[1] Balda, S., Sharma, A., Capalash, N., & Sharma, P., "*Banana fibre: a natural and sustainable bioresource for eco-friendly applications*", Clean Technologies and Environmental Policy, 23, 2021, pp1389 - 1401. https://doi.org/10.1007/s10098-021-02041-y

[2] Akatwijuka, O., Gepreel, M., Abdel-Mawgood, A., Yamamoto, M., Saito, Y., & Hassanin, A., *"Overview of banana cellulosic fibers: agro-biomass potential, fiber extraction, properties, and sustainable applications",* Biomass Conversion and Biorefinery, 14, 2022, 7449 - 7465. https://doi.org/10.1007/s13399-022-02819-0

[3] Makinde-Isola, B., Taiwo, A., Oladele, I., Akinwekomi, A., Adelani, S., & Onuh, L., *"Development of sustainable and biodegradable materials: A review on banana and sisal fibre-based polymer composites',* Journal of Thermoplastic Composite Materials, 37, 2023, 1519 - 1539. https://doi.org/10.1177/08927057231186324

[4] Singh, J., & Pant, S., "*Banana fiber: A sustainable revolution in fashion and textiles*", International Journal of Agriculture Extension and Social Development. 2025 https://doi.org/10.33545/26180723.2025.v8.i9a.2368

[5] Ewulu A, Amibang R, Deng M., *"Review of hair prosthetic options for patients with alopecia",* J Cosmet Dermatol. 23, 2024, pp8-16. doi:10.1111/jocd.15907

[6] Kamarudin, S.H., Mohd Basri, M.S., Rayung, M.; Abu, F.;, Ahmad, S.; Norizan, M.N., Osman, S.,Sarifuddin, N., Desa, M.S.Z.M., Abdullah, U.H., *"A Review on Natural Fiber Reinforced Polymer Composites (NFRPC) for Sustainable Industrial Applications",* Polymers 2024, 14, 3698. https://doi.org/10.3390/polym14173698

[7] Allen, E., Henninger, C., Garforth, A., & Asuquo, E., *"Microfiber Pollution: A Systematic Literature Review to Overcome the Complexities in Knit Design to Create Solutions for Knit Fabrics',* Environmental Science & Technology, 58, 2024, 4031 - 4045. https://doi.org/10.1021/acs.est.3c05955

[8] Ramírez-Escamilla, H., Martínez-Rodríguez, M., Padilla-Rivera, A., Domínguez-Solís, D., & Campos-Villegas, L. (2024). Advancing Toward Sustainability: A Systematic Review of Circular Economy Strategies in the Textile Industry. *Recycling*. https://doi.org/10.3390/recycling9050095

[9] Aguiar, G., Almeida, L., Fernandes, B., Gavazza, S., Silva, G., & Santos, S., *"Use of life cycle assessment as a tool to evaluate the environmental impacts of textile effluents: a systematic review",* Environmental Science and Pollution Research, 30, 2023, 76455-76470. https://doi.org/10.1007/s11356-023-27785-6

[10] Karim, M., & Hasan, M., *"Innovative textile recycling and upcycling technologies for circular fashion: reducing landfill waste and enhancing environmental sustainability",* American Journal of Interdisciplinary Studies. 2022, https://doi.org/10.63125/kkmerg16

[11] Ali, A., *"Banana Fiber: Environmental Friendly Fabric: A way to Health and Wealth",* International Journal for Research in Applied Science and Engineering Technology. 2022, https://doi.org/10.22214/ijraset.2022.45071

[12] R., S., R., P., Kumar, S., & Chandan, N., *"Experimental Investigation on the Spinnability of Chemically Treated Banana Fibres and their Blends with Spun Silk",* International Journal of Innovative Science and Research Technology, 2025, https://doi.org/10.38124/ijisrt/25nov589

[13] Pars, A., *"Dyeing of banana-silk union fabrics with cochineal using different concentrations of bio-mordant",* International Journal of Secondary Metabolite, 2024 https://doi.org/10.21448/ijsm.1479530

[14] Fokam, Maurane & Fokam, Christian & Chengoué, Anatole & Rougier, Valentin & Halawani, Nour & Bienvenu, Kenmeugne & Michaud, Véronique., *"Influence of Growth Location and Extraction Method on the Properties of Cameroonian Musa acuminata Leaf Vein Fibers",* Journal of Natural Fibers. 22, 2025, 10.1080/15440478.2025.2457505.

[15] Temesgen AG, Turşucular ÖF, Turşucular ED., *"A Review on Silk Fibers and Their Medical Applications",* Recent Progress in Materials; 6(1): 008, 2024, doi: 10.21926/rpm.2401008

[16] Badanayak, P., Jose, S., & Bose, G., *"Banana pseudostem fiber: A critical review on fiber extraction, characterization, and surface modification",* Journal of Natural Fibers, 20, 2023, https://doi.org/10.1080/15440478.2023.2168821

[17] Gomes, C., Araújo, J., Chaves, D., Fangueiro, R., & Ferreira, D., *"Improving textile circular economy through banana fibers from the leaves central rib: effect of different extraction methods",* Food and Bioproducts Processing, 2024, https://doi.org/10.1016/j.fbp.2024.06.002

[18] Provin, A., d'Alva, A., De Aguiar Dutra, A., De Andrade Guerra, J., & Cubas, A., *"Closing the cycle: circular economy strategies for the textile industry using banana farming waste",* Journal of Cleaner Production, 2024, https://doi.org/10.1016/j.jclepro.2024.143352

[19] Azriena, H., Kaur, K., Ilyas, R., Kamaruddin, Z., Neenu, K., Dominic, C., Wirawan, W., Asrofi, M., Dzulkifli, M., Sulong, M., Rased, M., Sari, N., Sapuan, S., & Mahardika, M., *"Recent developments in lignocellulosic banana (Musa spp.) fiber-based biocomposites and their potential industrial applications: A comprehensive review",* International journal of biological macromolecules, 323 Pt 2, 2025, 147180. https://doi.org/10.1016/j.ijbiomac.2025.147180

[20] Mollahosseini, H., Fashandi, H., Khoddami, A., Zarrebini, M., & Nikukar, H., *"Recycling of waste silk fibers towards silk fibroin fibers with different structures through wet spinning technique",* Journal of Cleaner Production, 2019, https://doi.org/10.1016/j.jclepro.2019.117653

[21] Mi, J., Zhou, Y., , S., Zhou, X., Xu, S., Yang, Y., Sun, Y., Xia, Q., Zhu, H., Wang, S., Tian, L., & Meng, Q., *"High-strength and ultra-tough whole spider silk fibers spun from transgenic silkworms",* Matter, 2023, https://doi.org/10.1016/j.matt.2023.08.013

ANNALS OF THE UNIVERSITY OF ORADEA
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THERMOELECTRIC ACTUATORS BASED ON TEXTILE MATERIALS

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Abstract: *Thermoelectric (TE) actuators integrated into textile materials have emerged as a transformative technology at the intersection of smart materials science, textile engineering, and flexible electronics. These systems exploit the Peltier effect, the ability of thermoelectric junctions to generate or absorb heat under an applied electric current, as a mechanism for thermal actuation.*
When incorporated into fibrous architectures such as knits, woven fabrics, or printed textiles, TE actuators enable precise, bidirectional, and solid-state thermal control, which can be coupled with thermoresponsive materials (e.g., shape memory alloys, liquid crystal elastomers, phase-change materials) to produce mechanical motion.
This review examines the fundamental principles governing thermoelectric actuation, the main classes of materials, including inorganic semiconductors, conducting polymers, and nanocomposites, and the fabrication strategies used to develop textile-integrated devices. Applications in wearable thermoregulation, soft robotics, haptic interfaces, and rehabilitation exoskeletons are explored. Key challenges, such as low conversion efficiency, mechanical durability under repeated deformation, and washability, are discussed, and future research directions are outlined.

Key words: *Thermoelectric actuator, Textile, Peltier effect***,** *wearable electronics, flexible thermoelectrics*

1. INTRODUCTION

The convergence of smart materials science, textile engineering, and microelectronics has given rise to a new paradigm of functional textiles that actively respond to environmental or physiological stimuli. Thermoelectrically driven actuators integrated into textile substrates have attracted increasing interest due to their solid-state operation, silent performance, compact form, and bidirectional thermal controllability [1, 2].

Thermoelectric (TE) devices exploit the Peltier effect: when an electric current passes through a junction of two different semiconductors (a p-type and an n-type leg, electrically connected in series and thermally in parallel), one junction absorbs heat while the other releases it. By reversing the current direction, the heating and cooling sides are interchanged. This reversibility represents a fundamental advantage for actuation, allowing the same device to both heat and cool a thermoresponsive material, thereby generating bidirectional mechanical motion without moving parts [3, 4].

Conventional TE devices are rigid, typically using bulk bismuth telluride (Bi_2Te_3) legs soldered between ceramic plates. Although efficient, such assemblies are incompatible with the flexibility, conformability, and breathability requirements of wearable textiles. Over the past decade, significant research efforts have focused on developing flexible and stretchable TE architectures that can be woven, knitted, printed, or coated onto fibrous substrates while maintaining adequate thermoelectric performance [5, 6].

At the same time, thermoresponsive materials such as nickel–titanium (NiTi) shape memory alloys (SMA), liquid crystal elastomers (LCE), phase-change materials (PCM), and hydrogels have been increasingly adopted due to their ability to undergo large and reversible mechanical changes in response to thermal stimuli. The integration of flexible TE devices with these materials enables electrically controlled, autonomous actuators that do not require pneumatic or hydraulic systems [7, 8].

2. PRINCIPLES OF THERMOELECTRIC ACTUATION

2.1 Seebeck and Peltier Effects

The thermoelectric effect encompasses three interrelated phenomena: the Seebeck effect (generation of voltage under a temperature gradient), the Peltier effect (heat pumping under an applied current), and the Thomson effect (heat exchange in a conductor carrying current under a temperature gradient). For actuation, the Peltier effect is of primary relevance, although in multifunctional textile systems the Seebeck effect is often simultaneously exploited for energy generation [9]. The performance of a thermoelectric material is described by the dimensionless figure of merit ZT [10]:

$$ZT = \frac{S^2 \sigma \mathrm{T}}{T} \qquad \textbf{(1)}$$

where S is the Seebeck coefficient (V/K), σ is the electrical conductivity (S/m), κ is the thermal conductivity (W/m·K), and T is the absolute temperature. A high ZT requires simultaneously large S and σ, and low κ. In practice, these parameters are interdependent, making the simultaneous optimization of all three challenging [1, 6].

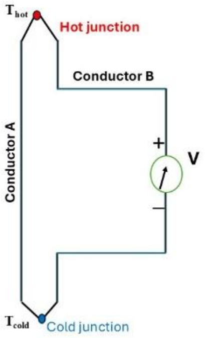

Fig.1 Illustration of Seebeck effect in a thermoelectric junction

The Peltier effect, discovered in 1834, describes how an electrical current forced through a junction of two different conductors causes one side to absorb heat and the other to release it. Reverse the current, and the hot and cold sides swap. In practice, a thermoelectric module pairs multiple p-type and n-type semiconductor legs electrically in series and thermally in parallel, summing the individual temperature differentials. Traditional modules use bismuth telluride (Bi_2Te_3) legs sandwiched between ceramic plates, a configuration that works well for benchtop cooling but is incompatible with the mechanics of a sleeve or glove.

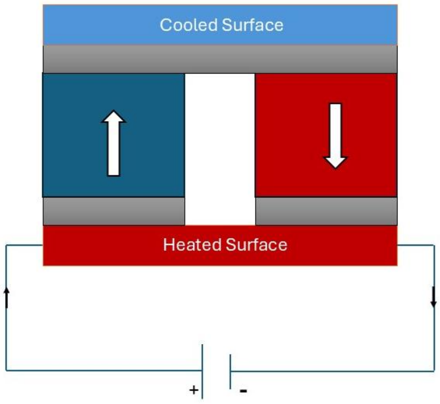

Fig. 2 Schematic representation of the Peltier effect and directional heat flow

3. THERMOELECTRIC MATERIALS FOR TEXTILE INTEGRATION

Three broad material classes are relevant to textile-integrated TE actuators, and their practical trade-offs are quite different (Fig. 3). The choice of material determines not only the achievable temperature differential but also the fabrication route, the mechanical behaviour of the finished textile, and the long-term stability under washing and repeated flexure.

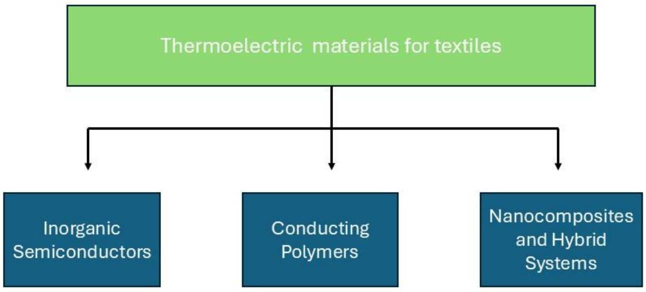

Fig. 3 Classification of thermoelectric material classes for textile-integrated actuators

3.1 Inorganic Semiconductors

Bismuth telluride alloys remain the benchmark near room temperature, with ZT values of 1–1.5 under optimal conditions. Their practical appeal for textile integration has been demonstrated by embedding small rigid TE cuboids within flexible silicone matrices, creating so-called island-bridge architectures. Hong et al. [4] presented a wearable TE device in which Bi_2Te_3 legs were encapsulated in a stretchable elastomer matrix and worn on the wrist; under natural convection, the device generated 17.5 mW at a body-to-air temperature difference of 15 K. More relevant to actuation, Wei et al. [5] added a pin-fin elastomeric heat spreader to a similar architecture, achieving a steady-state skin cooling of 1.5 °C via Peltier operation and a power density of 6.63 μW/cm^2 during energy harvesting, showing that the same module can switch between harvesting and actuating depending on current direction. Beyond island-bridge configurations, researchers have explored embedding Bi_2Te_3 nanoparticles directly into yarn coatings and woven structures. Nanoparticle-loaded polyester fabrics have been used to create dual-mode pressure and temperature sensing arrays, where the thermoelectric voltage provides the temperature signal and the piezoresistive response of the nanoparticle network provides the pressure signal — again within a single fabric layer [1]. The nanoparticle approach sacrifices some ZT relative to bulk single-crystal legs (typical values fall to 0.3–0.6), but gains substantially in mechanical compliance and compatibility with textile manufacturing. The reduction in ZT is primarily a consequence of increased phonon and electron scattering at the numerous grain boundaries in a nanoparticle film, alongside incomplete electrical percolation when particle loading is below the threshold needed for a continuous conductive network. Careful control of particle size distribution and sintering conditions can partially recover the ZT, and several groups have reported ZT values above 0.8 in free-standing nanoparticle films, though transferring these numbers to a rough textile substrate remains challenging. An important materials challenge shared across all Bi_2Te_3 textile systems is the toxicity of tellurium compounds, which becomes a non-trivial concern in skin-contact applications and must be addressed through encapsulation or surface passivation strategies before clinical deployment. Alternative inorganic compositions with lower toxicity including copper selenide (Cu_2Se), tin selenide (SnSe), and Bi-Sb alloys are receiving growing attention for wearable applications, though their room-temperature ZT values currently lag behind optimised Bi_2Te_3 [12].

3.2 Conducting Polymers

The appeal of polymers is their intrinsically low thermal conductivity, mechanical flexibility, and compatibility with roll-to-roll or inkjet processing. PEDOT:PSS is the most studied p-type organic TE material, while coordinated metal-organic compounds such as poly[Na(NiETT)] serve as n-type counterparts. Massetti et al. [6] demonstrated a 32-leg textile TE device printed onto commercial sports fabric using these two inks via stencil transfer; the device produced an open-circuit voltage of ~3 mV at $\Delta T = 3$ K. Scaling the design to 864 legs raised the output to ~47 mV, constituting the first fully polymer-based, through-plane body heat harvester integrated into a wearable.

Carbon nanotube (CNT) yarns offer a complementary route. Zheng et al. [7] dip-coated CNT yarns alternately in PEDOT:PSS and polyethylenimine (PEI) solutions to create p- and n-type legs, then knitted them into a weft-knitted spacer fabric. At $\Delta T = 47.5$ K, the device achieved an output power density exceeding 50 $mW/m \cdot K^2$, with a gravimetric power density of 171.7 $\mu W/g \cdot K^{-1}$, among the highest reported for an all-polymer textile TE system.

3.3 Nanocompozitie si sisteme Hibride

Hybrid approaches aim to combine the high ZT of inorganic fillers with the processability and flexibility of polymer matrices, addressing the key limitation of each material class when considered individually: inorganic semiconductors are too rigid and brittle for textile integration, while organic polymers alone exhibit ZT values that are too low for practical actuation [1, 11]. Nanocomposites navigate this trade-off by dispersing high-performance inorganic nanoparticles within a continuous polymeric or fibrous matrix, resulting in materials that are both mechanically compliant and thermoelectrically functional.One of the more creative demonstrations in this field involves the fabrication of thermoelectric aerogels from recycled cotton, multi-walled carbon nanotubes, and PEDOT:PSS crosslinked with methyltrimethoxysilane. The resulting structure exhibits a dual behavior that is highly relevant for integrated actuator systems. Under mechanical compression, the electrical resistance changes predictably (mechanical sensing mode), while under a thermal gradient and without any applied mechanical load, it generates a measurable thermoelectric voltage (harvesting/actuation mode) [1]. These two responses are physically decoupled, meaning that the same textile element can simultaneously sense contact forces and generate or absorb heat, a combination that is difficult to achieve with single-component materials and is particularly attractive for soft robotic skins.Two-dimensional materials, particularly MXenes (transition metal carbides and nitrides), have emerged as an attractive class of fillers for textile TE composites. $Ti_3C_2T_x$ MXene exhibits electrical conductivities exceeding 10,000 S/cm in thin-film form, along with a moderately negative Seebeck coefficient, making it a promising n-type component in hybrid TE textiles [8].

4. FABRICATION STRATEGIES

Dip-coating and immersion impregnation are among the simplest approaches: yarns are repeatedly passed through TE solutions to build up an ակտիվ layer, after which they are incorporated into woven or knitted structures. The main limitation is adhesion, as illustrated by the wash-resistance results reported by Massetti et al. [6] mentioned above.

Stencil printing, screen printing, or inkjet printing enable precise geometric patterning of p- and n-type legs on the textile surface, which is essential for multi-couple TE modules. The primary processing challenge lies in ink rheology: textile surfaces are inherently rough, requiring a careful balance of viscosity to prevent spreading while ensuring electrical isolation between oppositely doped legs.

A more structurally integrated approach employs TE-active fibers or yarns as primary textile elements. Shin et al. [9] wrapped NiTi shape memory alloy (SMA) wires in polyester fibers to prevent short circuits, then knitted the composite yarn into looped structures for textile actuators. Atalay et al. [11] utilized 3D digital knitting to create seamless textile actuators with integrated resistive heaters, achieving peak forces of 50 mN at voltages below 12.5 V; the authors explicitly note that replacing the resistive heater with a Peltier layer represents a logical next step [11].

5. CONCLUSIONS

Thermoelectric actuators integrated into textile platforms represent a promising direction for the development of next-generation smart and wearable systems. By exploiting the Peltier effect, these devices enable solid-state, bidirectional thermal actuation that can be directly coupled with thermoresponsive materials to generate controlled mechanical motion.

The material landscape reveals clear trade-offs. Inorganic semiconductors such as bismuth telluride offer high thermoelectric performance but suffer from brittleness and limited compatibility with deformable textile systems. Conducting polymers provide excellent flexibility and processability, although their thermoelectric efficiency remains comparatively low. Hybrid nanocomposites emerge as a compelling compromise, combining improved electrical performance with mechanical adaptability and multifunctionality.

Fabrication strategies play a critical role in determining device performance and durability. While coating and printing techniques enable scalable integration, challenges such as adhesion, ink rheology, and washability persist. Structurally integrated approaches based on thermoelectric fibers or yarns show significant potential for improving mechanical robustness and long-term stability in wearable applications.

Despite significant progress, several challenges remain. The inherently low temperature gradients available in wearable environments limit power output and actuation efficiency. Additionally, ensuring mechanical durability under repeated deformation and maintaining performance after washing cycles are key barriers to practical deployment.

Future research should focus on enhancing thermoelectric efficiency in flexible materials, optimizing thermal management within textile architectures, and developing robust, scalable fabrication methods.

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6. BIBLIOGRAFIE

[1] Vivekananthan, V. et al. Flexible Thermoelectrics for Wearable Electronics: Trends and Benchmarks in Solid-State and Ionic Materials, Textile Architectures, Interface Engineering, and Device Performance. Adv. Electron. Mater. 2026, 12, e00396.

[2] Masiulis, L. et al. Body heat energy driven knitted thermoelectric garments with personal cooling. Appl. Therm. Eng. 2024, 257, 124123.

[3] Kim, S. et al. Bioinspired untethered soft robot with pumpless phase change soft actuators by bidirectional thermoelectrics. Chem. Eng. J. 2022, 446, 137274.

[4] Hong, S. et al. Wearable thermoelectrics for personalized thermoregulation. Sci. Adv. 2019, 5, eaaw0536.

[5] Wei, H.; Zhang, J.; Han, Y.; Xu, D. Soft-covered wearable thermoelectric device for body heat harvesting and on-skin cooling. Appl. Energy 2022, 326, 119941.

[6] Massetti, M. et al. Fully printed textile thermoelectric generators based on organic p- and n-type thermoelectric inks. Nat. Commun. 2021, 12, 1–11.

[7] Zheng, Y. et al. High-output wearable thermoelectric generator from carbon nanotube/PEDOT: PSS knitted spacer fabrics. Adv. Mater. 2022, 34, 2106184.

[8] Gao, L. et al. MXene-based multifunctional flexible electronic textiles for healthcare and human-machine interaction. Adv. Funct. Mater. 2023, 33, 2214200.

[9] Shin, J. et al. Shape memory alloys in textile platform: smart textile-composite actuator and its application to soft grippers. Sensors 2023, 23, 1518.

[10] Abhishek Tewari (ed.), ZT-value of thermoelectric materials, SpringerMaterials, 2024, online available: https://materials.springer.com/thermoelectric-materials/property/254/ZT-value

[11] Atalay, O. et al. Thermally driven 3D seamless textile actuators for soft robotic applications. Adv. Intell. Syst. 2024, 6, 2400133.

[12] Cao, T.; Shi, X.-L.; Chen, Z.-G. Advances in the design and assembly of flexible thermoelectric devices. Prog. Mater. Sci. 2023, 131, 101003.

ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

AN APPLIED STUDY OF THE HYBRID WORKFLOW IN THE DIGITAL REPRESENTATION OF FASHION ILLUSTRATION

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Abstract: *This paper examines the representation of contemporary fashion collections through a hybrid workflow, analyzed on the basis of examples developed by students in the Fashion Design program. The study takes as its starting point the practical value of these visual approaches in the development of the fashion project, in the articulation of design variations, and in sustaining the overall coherence of a collection. Its main focus lies on the relationship between the expressive dimension of fashion illustration and the digital tools integrated successively into the process of representation.*

The workflow under examination includes four stages: hand sketching, vectorization in Adobe Illustrator, image processing in Adobe Photoshop and/or Procreate, and 3D prototyping in Style3D. The research is practice-based and relies on a comparative framework structured around five criteria: the authenticity of fashion illustration, the clarity of design variations, the spatial verification of garment form, the visual coherence of the collection, and the relationship between artistic expression and digital precision. Within this sequence, hand sketching establishes the expressive intention, vectorization organizes the formal structure, digital processing enhances the visual density of the image, and 3D prototyping enables the evaluation of the relationships between silhouette, volume, and the collection as a whole.

The analysis highlights the expanded role of fashion illustration within a contemporary design methodology in which representation actively supports the exploration, refinement, and verification of visual solutions. The contribution of the paper lies in proposing an applied perspective on hybrid representation that is relevant both to fashion design practice and to academic training in the field.

Key words: *creative process, hand drawing, fashion design, visual coherence, collection development.*

1. INTRODUCTION

Recent research dedicated to digital fashion shows that the representation of clothing collections has shifted from the sphere of final presentation toward that of the actual development of the project. A substantial part of international research focuses on those practices in which digital technologies intervene directly in sketching, product development, simulation, and the articulation of the collection image. Case studies devoted to designers who work entirely or predominantly in 3D environments demonstrate that digital tools are no longer perceived as a technical adjunct, but as a professional medium in its own right, capable of reorganizing the design process and the status of the author within it .

The practice of illustrating contemporary collections is defined by the circulation of the image across several working media. The sketch remains essential at the moment when the idea is formed, since it is here that the initial direction of the silhouette, the composition, and the relationship between intention and gesture are established. The collection image no longer has an exclusively representational role, but becomes the place where the collection is visually explored [1]. The present research emerges from several years of pedagogical and practice-based observation conducted within the Industrial Fashion Design program at the Technical University of Moldova, where the curriculum of courses related to the digital environment is oriented toward the application of hybrid graphic representation methods aimed at preserving the author's imprint and authenticity. Within this context, the present study aims to identify the digital tools that prove effective in the development of visual representation and to examine how they can be integrated into a hybrid workflow without affecting the authenticity of fashion illustration.

2. THEORETICAL ASPECTS

The theoretical foundations of this study draw on the contributions of Hans Belting and W.J.T. Mitchell to image theory. Belting argues that images are inseparable from the medium that produces and transmits them, and that any change of medium entails a redefinition of the image itself [2][3]. Applied to fashion design, this perspective suggests that the transition from manual sketch to digital vector and 3D simulation is not merely a technical process, but rather a series of transformations through which the fashion image acquires successive layers of precision and spatial coherence, without the author's plastic intention dissolving at any stage. Mitchell, in turn, maintains that the image functions as an active form of thought [4]; in fashion design, this means that representation participates actively in the constitution of the collection rather than being limited to its documentation.

The term *"hybrid"* does not describe the simple juxtaposition of different techniques. Rather, it designates a mode of working in which the transition from one medium to another constitutes the continuation of the same cognitive process through a different technical configuration, without conceptual rupture. The digital image, understood as a processual entity, remains permanently open to revision and reorganization, and within the hybrid workflow this property extends beyond the digital medium to encompass the entire trajectory of the project, including the manual stages, which may be reactivated whenever the process calls for formal freedom [6]. Consequently, the continuous interaction between manual drawing, digital intervention, and three-dimensional simulation leads to the emergence of a hybrid graphic language in which the expressiveness of the artistic gesture is combined with the precision and flexibility of digital media. This form of representation belongs neither exclusively to traditional drawing nor entirely to digitally generated imagery, but is constituted as an intermediate visual language capable of preserving the author's imprint while simultaneously extending the possibilities for analysis and formal construction within the collection [7].

The central finding that underpins the present study emerges from research conducted over several years of academic practice in the training of young designers. Systematic observation and comparative analysis of the visual results produced through three working modes - exclusively manual, exclusively digital, and hybrid - have led to a general methodological argument: the hybrid workflow is the most effective in simultaneously meeting two essential requirements of fashion illustration, namely the preservation of the author's imprint and the achievement of superior visual expressiveness. Works produced exclusively through digital means showed a recurrent tendency toward stylistic uniformity, while those created exclusively by hand preserved individual imprint but limited the possibilities for analysis and did not allow for the spatial verification of form. Didactic observation also confirmed that the moment at which the digital medium is introduced is decisive: when introduced before sketching, it directs formal decisions before the idea has fully matured;

when introduced afterward, it becomes a tool for developing an already personalized intention, in keeping with Kevin Tallon's observation that digital tools should serve the gesture rather than replace it [5] [8].

3. APPLIED STUDY: THE HYBRID WORKFLOW MODEL

The applied study confirms that the effectiveness of digital tools depends less on their complexity and more on the position they occupy within the sequence of stages. When the digital medium is introduced too early, there is a risk that the image becomes structured before the idea has fully matured. When it is introduced after the manual execution of the sketch, the relationship changes: the drawing preserves its distinctiveness, while digital intervention assumes the role of clarification, development, and control. For this reason, the applied research has focused on testing a hybrid model in which manual sketching, scanning, 2D digital processing, and 3D simulation form successive stages of the same visual construction [6].

3.1. Hand sketching as the foundational stage

The first stage in developing the model remains manual work. This choice does not stem from a sentimental attachment to traditional drawing, but from the observation that the authenticity of the gesture what, in studio language, may be called the designer's imprint is preserved most faithfully in the sketch. In the initial drawing, the rhythm of the line, the degree of body stylization, the way compositional accents are distributed, and the energy of the first formal attempt become more clearly visible (fig.1). Research on the ideation process confirms that, at this stage, sketching functions simultaneously as a cognitive and visual instrument, offering a space for the exploration and testing of ideas before they undergo more rigorous processing [6]. This stage is decisive in shaping an individual visual position, since it compels the student to formulate an initial formal solution before entering the phase of correction, refinement, and digital finishing.

3.2. Digital processing in Adobe Photoshop and Procreate

Photoshop and Procreate operate through raster and layer-based systems, oriented toward the manipulation of visual values color, texture, and light within a flexible framework that allows gradual and non-destructive intervention. The focus shifts toward the visual depth of the image: color, texture, light, emphasis, and atmosphere. Customizable brushes and the layer mask system support flexible editing, in which areas can be hidden, revealed, and progressively adjusted without destroying the original layer. It is precisely this flexibility that makes it possible to preserve continuity with the hand sketch: the scanned line is not erased, but reworked and further developed (fig.1). Photoshop and Procreate prove effective where the image requires expressive density, confirming that the visual surface alone does not resolve the problem of the concept, but must remain consistent with the structure already formulated.

3.3. Vectorization in Adobe Illustrator

Adobe Illustrator operates through a vector-based system grounded in mathematical curves and control points, enabling the precise construction and adjustment of forms independent of resolution. The program becomes useful when the drawing needs to be structurally stabilized and translated into a form that allows precise intervention. The *Image Trace* function facilitates the conversion of raster sketches into editable vector graphics, transforming hand-drawn lines into scalable curves characterized by contour clarity and by the possibility of accurately adjusting forms, proportions, and relationships between elements (fig.1). This stage serves a role of ordering and formal clarification: it does not erase the individuality of the original sketch, but rather gives it geometric coherence and greater usability in the process of analysis, systematic comparison, and the development of design variants [9].

3.4. 3D Prototyping

The three-dimensional stage, carried out in Style3D, was introduced as a means of spatial verification. The program's ability to work with patterns, avatars, materials, and physical simulations makes it useful for testing how well the two-dimensional image holds up when transferred into volume [10]. This stage fulfills a clear function: to demonstrate that the illustration developed in 2D remains coherent in relation to the body, proportion, fabric drape, and the actual tension of the construction. Where the sketch and digital image suggested a promising solution, the 3D simulation either confirmed it or required a critical return to the previous stages (fig.1). This feedback function is one of the most valuable contributions of the hybrid model: it prevents premature fixation on a two-dimensional solution that later proves formally or materially unsustainable when translated into three dimensions.

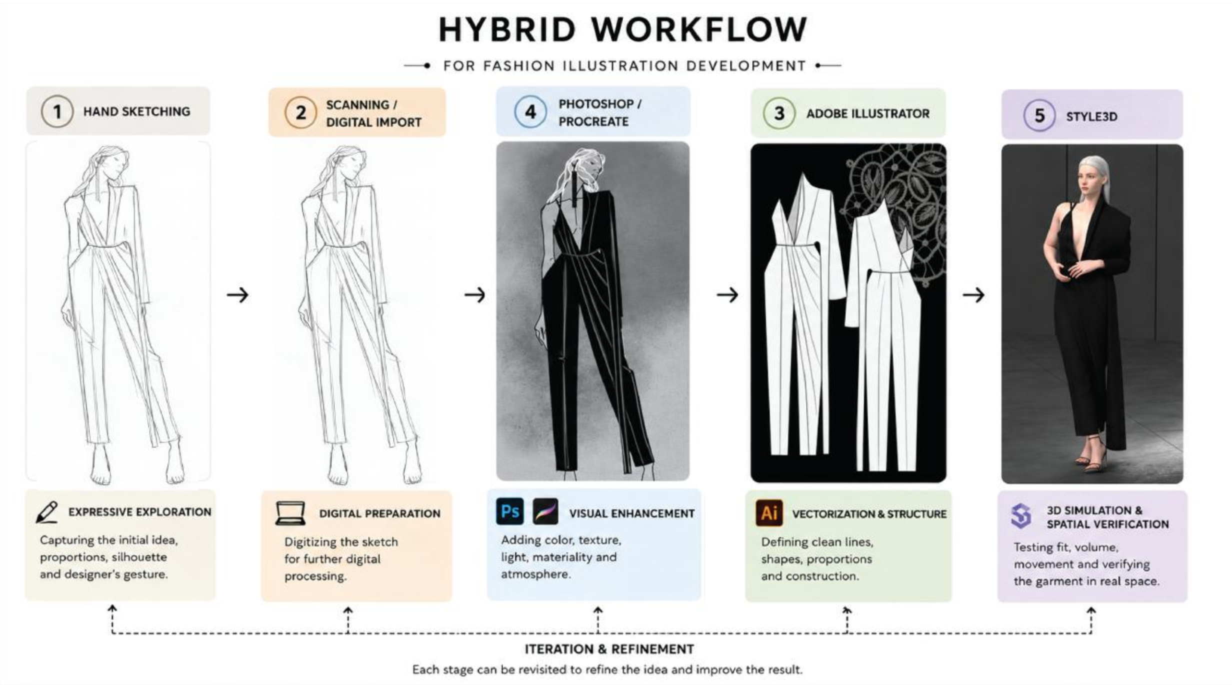

Fig.1 *Hybrid workflow in the digital representation of fashion illustration*

4. RESULTS AND DISCUSSION

The results of the applied observations showed that the effectiveness of digital technologies in fashion illustration depends less on their technical complexity than on the way they are integrated into a coherent workflow. When used separately, each tool provides only a partial response to the demands of representation. By contrast, the articulation of hand sketching, vectorization, digital image processing, and 3D simulation into a logical sequence generates a more complete working process, capable of supporting the exploration, comparison, refinement, and verification of visual solutions at the same time.

A first important result concerns the authenticity of fashion illustration. Comparative observations showed that the author's imprint is best preserved when the process begins with manual sketching and digital tools are introduced only afterward. At this initial stage, the energy of the line, the rhythm of the composition, and the individual character of the image are established. When the digital medium intervenes too early, there is a risk that the representation becomes prematurely formalized and less personal.

With regard to the clarity of design variations, Adobe Illustrator and Photoshop/Procreate proved essential for the development and comparison of visual alternatives. Vectorization contributed to the organization and clarification of the sketch structure, while raster-based processing allowed the rapid testing of chromatic, textural, and atmospheric variations. This flexibility made it possible to evaluate several options within the same workspace, reducing the risk of premature fixation on a single solution (fig.2).

Fig.2. *Fashion illustrations created through a hybrid workflow, from hand sketches to processing in Adobe Photoshop/Procreate, produced by Turcu Victoria, student in Industrial Fashion Design.*

Another relevant result concerns the spatial verification of garment form through Style3D. Three-dimensional simulation enabled the testing of the relationship between silhouette, body, proportion, and material behavior, revealing situations in which a visually convincing 2D solution required adjustment once translated into volume. Therefore, the 3D stage does not replace the physical prototype, but it introduces a useful intermediate form of verification that reduces the analytical risk of premature materialization. At the same time, the simulation environment allows the designer to evaluate the coherence between image, volume, and material behavior before the realization of the physical garment, contributing to a more controlled and analytically grounded design process. (fig. 3).

Fig 3*. Fashion illustrations created through a hybrid workflow, from hand sketches to processing in Adobe Illustrator/Photoshop and three-dimensional simulation in Style3D, produced by Industrial Fashion Design students Efros Marialina and Levițchi Cristina.*

The hybrid workflow also proved effective in maintaining the visual coherence of the collection. The continuous transition between media facilitated the evaluation of relationships among garments, compositional rhythm, graphic accents, and the overall atmosphere. In this way, the process supported not only the development of individual images, but also the construction of a unified collection identity.

At the same time, the results showed that the hybrid model enables a balanced relationship between artistic expression and digital precision. The sketch preserves spontaneity and authorial character, while digital tools introduce clarity, control, and the possibility of revision. The effectiveness of this model does not lie in replacing drawing with technology, but in the fact that each medium complements the function of the other.

Another significant finding concerns the methodological importance of the sequence itself. The observations showed that the hybrid workflow becomes most effective when the stages follow a progression from intuition to control: hand sketching as a space of exploration, vectorization as structural clarification, digital processing as expressive enhancement, and 3D simulation as spatial verification. When this sequence is altered, the process tends to lose coherence, as the image may become technically resolved before the concept has been sufficiently developed. This confirms that the value of the hybrid model lies not only in the combination of tools, but also in the logic of their successive use.

From a pedagogical perspective, these results are equally relevant. In academic training, students often associate digital tools with professional finish and visual accuracy; however, the study showed that technical refinement alone does not guarantee a strong fashion image. The most successful outcomes were those in which students were able to preserve their conceptual intention while moving across different media. In this sense, the hybrid workflow supports not only the production of more coherent representations, but also the development of critical judgment, helping students understand when to sketch freely, when to refine, and when to verify their ideas through digital means.

Compared with exclusively manual or exclusively digital methods, the hybrid workflow proved superior because it combines the expressiveness of gesture with the analytical advantages of digital media. Consequently, the results confirm that hybrid representation should be understood not as a simple sequence of tools, but as an integrated method in which each stage plays a distinct and necessary role in the development of the fashion project.

5. CONCLUSIONS

The applied study conducted within the framework of university teaching practice in the Industrial Fashion Design program at the Technical University of Moldova confirms, through systematic observation and multi-year comparative analysis, that the hybrid workflow model - hand sketching, vectorization in Adobe Illustrator, processing in Photoshop/Procreate, and prototyping in Style3D produces fashion representations that are more complete, more analytical, and more spatially verifiable than the isolated use of any of these tools. This conclusion is not theoretical but empirical: it results from the direct comparison of the visual outcomes obtained by students through the three working methods investigated.

From the perspective of preserving the author's imprint, the study confirms that hand sketching is the irreducible stage of any authentic representational workflow. The energy of the gesture, the productive imprecision of the line, and the compositional tension of the first attempt cannot be reproduced by any digital interface without losing precisely what makes them valuable. Subsequent digital intervention vectorization, raster processing, and 3D simulation does not replace this value, but rather continues and amplifies it, adding levels of clarity, expressive density, and spatial verification that manual gesture alone cannot sustain without compressing its own freedom.

The integration of digital methods into the development of fashion collections does not imply the abandonment of graphic tradition, but its extension through technological means that enhance the capacity for analysis, refinement, and visual communication. The real effectiveness of these tools does not depend on their degree of sophistication, but on the designer's critical position toward the medium: the risks of digitalization stylistic standardization, dependence on presets, and detachment from materiality systematically emerge when the tool is treated as a substitute for aesthetic judgment. When subordinated to artistic intention and critical discernment, the same digital medium can intensify precisely those qualities that fashion design consistently requires: clarity, coherence, flexibility, and expressiveness.

The pedagogical implications of this research are direct and immediately applicable. The development of digital competencies, in the absence of a solid foundation in artistic education, risks producing efficient software users whose visual voice remains fragile. The relevant competence in contemporary fashion design does not lie in the advanced technical mastery of a single tool, but in the ability to know what one is seeking and to construct meaningful transitions between different media while preserving the conceptual coherence and visual authenticity of the project throughout the entire workflow. In this sense, the proposed hybrid model is not merely a position shared by international practice, but a conclusion validated locally through years of didactic observation within a specific context of academic training.

Future research directions include the comparative testing of the hybrid model across different educational programs and professional contexts, the development of assessment tools calibrated to the three parameters identified in the present study, and the investigation of how generative tools based on artificial intelligence may be responsibly integrated into hybrid workflows without compromising the designer’s critical and curatorial agency. In all of these directions, the fundamental conclusion of this research remains valid: high-quality fashion representation does not result from tools themselves, but from the designer’s ability to orchestrate them coherently in the service of an original visual intention.

REFERENCES

[1] Särmäkari, N., & Vänskä, A. (2022). *‘Just hit a button!’ – fashion 4.0 designers as cyborgs, experimenting and designing with generative algorithms*. International Journal of Fashion Design, Technology and Education, 15(2), 211–220. https://doi.org/10.1080/17543266.2021.1991005

[2] Belting H., *An Anthropology of Images. Princeton:* Princeton University Press, 2011, pp. 9-14.

[3] McKelvey, K.,; Munslow J, *Fashion Design: Process, Innovation and Practice*, 2nd ed., Wiley-Blackwell, Oxford, 2012.

[4].Mitchell, W.J.T., *Picture Theory: Essays on Verbal and Visual Representation*, University of Chicago Press, Chicago, 1994.

[5]Cross, N. *Design Thinking: Understanding How Designers Think and Work*. 1st ed., Oxford, Berg, 2011.

[6] Habib A, Akter S, Akter F, et al. *Hybrid digital fashion illustration: techniques and innovations in the contemporary fashion design process*. J Textile Eng Fashion Technol. 2025; 11(6):329–335. DOI: 10.15406/jteft.2025.11.00441.

[7] Spagnoli, Alessandra & Fabro Cardoso, Gabriela. (2023). *Dematerializing fashion. Improving design-led sustainable and hybrid retail experiences via digital twins*. Researchgate DOI:10.26530/9789401496476-073

[8] Amalia Drakou, Evridiki Papachristou, Theodore Tarnanidis, Nikolaos Bilalis. (2024). *Transforming Fashion Education: The Impact of AI-Driven 3D Design on Learning, Creativity, and Sustainability.* In Proceedings of the 13th Hellenic Conference on Artificial Intelligence (SETN '24*)*. Association for Computing Machinery, New York, NY, USA, Article 59, 1–6. https://doi.org/10.1145/3688671.3688794

[9] Zheng, J., Potamias, R. A., & Zafeiriou, S. (2024). *Design2cloth: 3d cloth generation from 2d masks*. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (pp. 1748-1758).

[10] Florea-Burduja, E., Cangaș, S., & Burduja, V. *Digital fashion–a sustainable alternative for the future*. Journal" Annals of University of Oradea. Fascicle of Textiles, Leatherwork, 26(2), 39-42.https://textile.webhost.uoradea.ro/Annals/AUO_FTL_Vol%2024_no%201_2023.pdf

ANNALS OF THE UNIVERSITY OF ORADEA
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TEXTILE WASTE RECYCLING IN THE CONTEXT OF CIRCULAR ECONOMY: A BIBLIOMETRIC AND VISUAL ANALYSIS USING WEB OF SCIENCE AND VOSVIEWER

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Abstract: *The rapid growth of the global textile industry has led to a significant increase in textile waste, raising major environmental concerns and intensifying the need for sustainable waste management strategies. Textile waste recycling has emerged as a key component of the circular economy, aiming to reduce resource consumption, minimize environmental impact, and promote sustainable production and consumption patterns. This study provides a comprehensive bibliometric and historical analysis of research on textile waste recycling using data extracted from the Web of Science database. The analysis covers the period 2000–2025 and employs VOSviewer to map scientific knowledge structures and identify research trends. The results highlight a significant increase in publications over the last decade, reflecting growing academic and industrial interest in sustainable textile practices. Key research clusters are identified, including mechanical recycling, chemical recycling technologies, circular economy frameworks, and waste management strategies. The study also reveals the most influential authors, countries, and journals contributing to this field. Furthermore, the historical evolution of research themes is examined, providing insights into emerging directions such as fiber regeneration and sustainable materials innovation. The findings contribute to a better understanding of the intellectual structure of textile waste recycling research and offer valuable guidance for future studies and policy development.*

Key words: *textile waste, recycling, circular economy, bibliometric analysis, sustainability, VOSviewer, Web of Science*

1. INTRODUCTION

The textile industry is one of the largest contributors to global environmental pollution, due to intensive resource consumption, chemical use, and large volumes of post-consumer waste [1], [2]. The rapid expansion of fast fashion has significantly accelerated textile production cycles, leading to increased waste generation and environmental degradation [3].

Traditional linear production models based on “take–make–dispose” are no longer sustainable. As a result, the transition toward circular economy principles has become essential in addressing the environmental challenges associated with textile waste [4]. The circular economy promotes material reuse, recycling, and regeneration, aiming to reduce waste and improve resource efficiency.

Textile waste [5], [6] recycling plays a crucial role in this transition, offering opportunities to recover materials and reduce environmental impacts. However, the growing volume of scientific literature in this field makes it difficult to identify key trends and research directions. Therefore, bibliometric analysis provides a systematic approach to understanding the structure and evolution of research in textile waste recycling.

2. LITERATURE REVIEW

Textile waste has become a critical global environmental issue due to increasing consumption and reduced product lifespans [3]. Large quantities of textile products are disposed of in landfills or incinerated, leading to environmental problems such as greenhouse gas emissions, water pollution, and microplastic contamination [7].

Recycling technologies are generally classified into mechanical and chemical processes. Mechanical recycling involves shredding and reprocessing fibers, but often results in reduced material quality [8]. In contrast, chemical recycling enables the recovery of high-quality raw materials, particularly for synthetic fibers such as polyester [9].

The concept of circular economy has gained increasing attention in textile research, promoting sustainable production and consumption systems [4], [10]. Strategies such as product redesign, recycling-friendly materials, and closed-loop systems are essential for achieving sustainability in the textile sector [11].

Environmental assessment tools such as life cycle assessment (LCA) are widely used to evaluate the impact of textile recycling processes [7], [12], [13]. These methods allow for a comprehensive analysis of environmental performance across the entire lifecycle of textile products.

Despite significant progress, challenges remain in the recycling of blended fibers and the implementation of large-scale recycling systems [14], [15]. Recent research emphasizes the need for innovative technologies and integrated approaches to improve efficiency and sustainability [16].

3. METHODOLOGY

The bibliometric analysis was conducted using the Web of Science Core Collection database, which provides high-quality and peer-reviewed scientific publications. A total of 883 articles published between 2000 and 2025 were selected, considering only English-language articles.

The search query included terms related to textile waste, recycling, and circular economy. The bibliographic data were exported as plain text files and analyzed using VOSviewer, a specialized tool for constructing and visualizing bibliometric networks.

The analysis focused on keyword co-occurrence, enabling the identification of thematic clusters and relationships between research topics. A minimum occurrence threshold was applied to ensure the relevance of selected keywords.

4. RESULTS: CLUSTER ANALYSIS

The VOSviewer network visualization illustrates the relationships between keywords in textile waste recycling research. The analysis identifies three main clusters, representing distinct research directions.

Cluster 1: Material Composition and Recycling Technologies

This cluster focuses on material properties and recycling processes, including keywords such as fibers, cotton, polyester, and depolymerization [17], [18]. These terms reflect research on fiber recovery and material degradation, as well as mechanical and chemical recycling methods [8], [15].

The presence of both natural and synthetic fibers highlights the complexity of textile waste streams and the need for advanced recycling technologies [16]. The inclusion of depolymerization indicates the growing importance of chemical recycling technologies, particularly for synthetic materials [19], [20], [21].

This cluster suggests a strong research focus on: fiber recovery and material degradation processes, mechanical and chemical recycling methods, optimization of material properties after recycling .

Overall, it represents the technological foundation of textile waste recycling, where engineering and material science intersect to improve recycling efficiency and product quality.

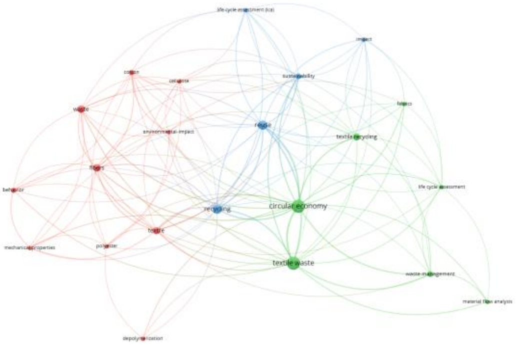

***Fig. 1**: Keyword Co-occurrence Network*

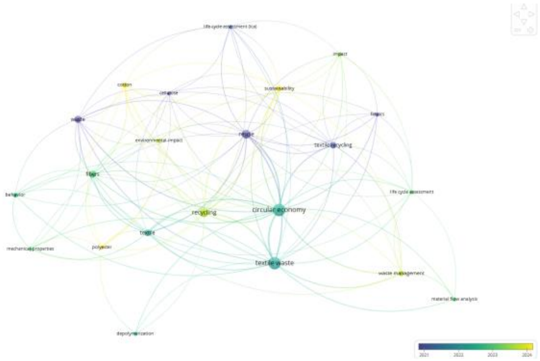

***Fig. 2**: Overlay Visualization (Historical Trends)*

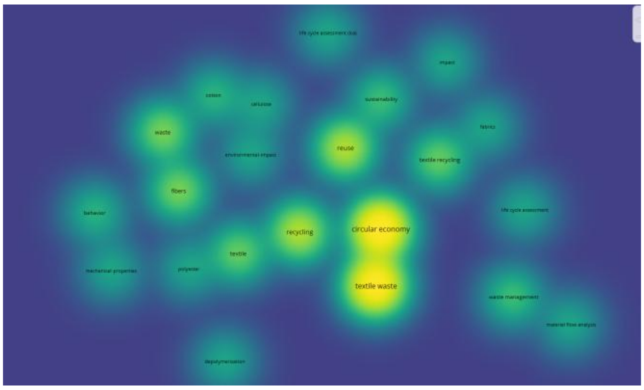

***Fig. 3**: Density visualization of keyword co-occurrence in textile waste recycling research (VOSviewer)*

Cluster 2: Circular Economy and Waste Management

This cluster is centered on systemic approaches to textile waste management, including circular economy, textile waste, and waste management. The prominence of these terms reflects the increasing importance of sustainability frameworks and resource efficiency strategies [4], [11].

The inclusion of material flow analysis indicates the growing use of quantitative tools to optimize waste management systems [19]. This cluster reflects: closed-loop production systems, resource efficiency strategies, policy-oriented approaches to waste management .

The strong interconnection between textile waste and circular economy suggests that current research is increasingly focused on transforming waste into valuable resources within sustainable systems.

Cluster 3: Sustainability and Environmental Assessment

This cluster emphasizes environmental evaluation, including keywords such as sustainability, life cycle assessment, and environmental impact. [22], [23]. [24]. These concepts reflect the shift toward assessing the environmental performance of recycling systems [7], [2].

The increasing importance of LCA highlights the need for evidence-based approaches in sustainable textile management.

Density Analysis

The density visualization reveals that the most prominent research areas are concentrated around circular economy, textile waste, recycling, and reuse. These high-density regions indicate the core focus of current research.

Emerging topics such as life cycle assessment and environmental impact show moderate density, suggesting growing interest in sustainability evaluation. Lower-density areas represent specialized or developing topics, such as material properties and advanced recycling methods.

This cluster demonstrates a shift toward: environmental performance assessment, sustainability metrics and indicators, integrated evaluation of recycling systems. It represents the analytical and evaluative dimension of textile waste research, linking environmental science with industrial practices.

4. RESULTS: DISCUSSION

The bibliometric analysis reveals not only the thematic structure of textile waste recycling research, but also a clear maturation of the field from isolated technical solutions toward integrated sustainability-oriented systems.

The first cluster, centered on material composition and recycling technologies, reflects the technological foundation of this research domain. The strong presence of keywords such as cotton, polyester, fibers, and depolymerization indicates an increasing scientific interest in overcoming one of the most critical technical barriers in textile recycling, namely the separation and recovery of mixed-fiber materials [8], [15], [17], [18]. The growing relevance of chemical recycling methods, particularly depolymerization, suggests a transition toward higher-value material recovery and improved resource efficiency [9], [16], [19]. From an industrial perspective, these findings highlight the necessity of investing in advanced recycling infrastructure capable of processing increasingly complex textile waste streams.

The second cluster, associated with circular economy and waste management, demonstrates that textile recycling is no longer perceived solely as end-of-life treatment strategy, but increasingly as a systemic component of sustainable production and consumption models [4],[10],[11]. The prominence of circular economy as a central keyword suggests that the research community increasingly recognizes recycling as part of broader value-chain redesign and closed-loop production systems [21], [25]. From a policy perspective, these findings support the implementation of regulatory instruments such as extended producer responsibility, eco-design requirements, and material traceability frameworks aimed at accelerating circular textile ecosystems [26], [27].

The third cluster, focused on sustainability and environmental assessment, reflects the growing importance of evidence-based decision-making in textile waste management. The increasing occurrence of keywords such as life cycle assessment and environmental impact indicates that both researchers and industrial stakeholders are increasingly concerned not only with recycling efficiency, but also with measurable environmental performance [7], [12], [13], [22]. This trend confirms the growing role of environmental assessment tools in supporting sustainable material selection, process optimization, and strategic decision-making [23], [24].

Importantly, the interaction between these three clusters suggests that textile waste recycling research is evolving toward convergence between technological innovation, environmental accountability, and systemic circularity. This evolution reflects the transition from traditional recycling approaches focused mainly on waste reduction toward integrated strategies [4], [7], [25].

However, the bibliometric analysis also reveals several emerging research gaps. Despite the growing interest in chemical recycling and circular economy frameworks, keywords related to digital technologies such as artificial intelligence, blockchain, digital twins, and smart waste management systems remain relatively underrepresented. This suggests that the digital transformation of textile recycling processes remains insufficiently explored. Furthermore, the relatively limited presence of socio-economic and policy-related terms indicates that non-technical dimensions of circular textile systems require further investigation.

Future research should therefore prioritize interdisciplinary approaches that integrate advanced recycling technologies, environmental assessment methods, digital innovation, supply-chain transparency, and supportive policy frameworks. Such integration may significantly accelerate the transition toward sustainable textile production and consumption systems.

5. CONCLUSIONS

This study provides a comprehensive bibliometric and visual analysis of research on textile waste recycling in the context of the circular economy, based on scientific publications indexed in the Clarivate Web of Science database between 2000 and 2025. The results reveal three dominant research directions: recycling technologies and material recovery, circular economy and waste management strategies, and sustainability assessment through environmental evaluation tools.

The field has evolved from predominantly technical studies focused on fiber recovery toward more integrated approaches that combine technological innovation, environmental accountability, and systemic circularity. The increasing prominence of concepts such as life cycle assessment, resource efficiency, and circular economy indicates a growing emphasis on evidence-based and multidisciplinary solutions.

From an industrial perspective, the results highlight the urgent need for scalable recycling infrastructures, improved sorting and separation technologies, and greater integration of digital solutions for waste tracking and process optimization.

The analysis also identifies important research gaps, particularly in the integration of digital technologies such as artificial intelligence, blockchain, and smart waste management systems, as well as in the socio-economic evaluation of circular textile systems. Addressing these gaps may significantly accelerate the transition toward sustainable textile production and consumption.

Overall, this study contributes not only to mapping the intellectual structure of textile waste recycling research, but also to identifying strategic directions for future scientific investigation, industrial implementation, and policy development within circular textile ecosystems.

REFERENCES

[1] J. M. Allwood, S. E. Laursen, C. M. Rodríguez, and N. M. P. Bocken, "*Well dressed? The present and future sustainability of clothing and textiles in the United Kingdom*" University of Cambridge, 2006.

[2] R. Kant, "*Textile dyeing industry environmental impact*" Natural Science, vol. 4, 2012.

[3] K. Niinimäki, G. Peters, H. Dahlbo, P. Perry, T. Rissanen, and A. Gwilt, "*The environmental price of fast fashion*," Nature Reviews Earth&Environment, vol.1, pp.189–200, 2020.

[4] J. Kirchherr, D. Reike, and M. Hekkert, "*Conceptualizing the circular economy: An analysis of 114 definitions" Resources, Conservation and Recycling*, vol. 127, pp. 221–232, 2017.

[5] H. Dahlbo et al., "*Environmental impacts of textile waste*" Waste Management, vol. 60, pp. 210–221, 2017

[6] M. R. Islam et al., "*Textile waste management practices*" Cleaner Engineering and Technology, vol. 2, 2021.

[7] G. Sandin and G. M. Peters, "*Environmental impact of textile reuse and recycling – A review*," Journal of Cleaner Production, vol. 184, pp. 353–365, 2018.

[8] Y. Wang, "*Fiber and textile waste utilization*" Waste Management, vol. 30, no. 11, pp. 247–257, 2010.

[9] K. Shirvanimoghaddam, B. Motamed, S. Ramakrishna, and M. Naebe, "*Death by waste: Fashion and textile circular economy case,"* Science of the Total Environment, vol. 718, 2020.

[10] N. M. P. Bocken et al., "*Product design and business model strategies for a circular economy*" Journal of Industrial and Production Engineering, vol. 33, no. 5, pp. 308–320, 2016.

[11] M. Ellen MacArthur Foundation, "*A new textiles economy: Redesigning fashion's future*" 2017.

[12] M. Islam and N. Huda, "*Environmental assessment of textile waste recycling*" Journal of Cleaner Production, vol. 202, pp. 119–131, 2018.

[13] B. Zamani, G. Sandin, and G. M. Peters, "*Life cycle assessment of clothing libraries*" Journal of Cleaner Production, vol. 162, pp. 1368–1375, 2017.

[14] D. Palm and M. Elander, "*Textile recycling in Sweden: Environmental and economic perspectives*" Waste Management, vol. 60, pp. 393–400, 2017.

[15] A. Patnaik et al.,"*Recycling of textile fibers*" Materials Today: Proceedings, vol.26, 2020.

[16] X. Zhang et al., "*Sustainable textile recycling*" Journal of Cleaner Production, vol. 258, 2020.

[17] J. Shen, "*A review of textile recycling*" Resources, Conservation and Recycling, vol. 63, pp. 1–8, 2012.

[18] H. Klepp et al., "*Reuse and recycling of textiles*" Sustainability, vol. 12, 2020.

[19] E. E. Okafor et al., "*Sustainable textile waste management*" Environmental Science and Pollution Research, vol. 28, 2021.

[20] A. Horrocks and S. Anand, *Handbook of Technical Textiles*, Woodhead Publishing, 2016.

[21] J. Morley et al., "*Circular economy in textiles*" Waste and Resource Management, vol. 170, 2017.

[22] S. Cuc and M. Vidovic, "*Environmental sustainability through clothing recycling*" Operations and Supply Chain Management, vol. 7, no. 2, pp. 108–115, 2014.

[23] S. S. Muthu, "*Assessing the environmental impact of textiles*" Textile Progress, vol. 46, no. 2–3, 2014.

[24] S. Hasanbeigi and L. Price, "A *technical review of emerging technologies for energy and water efficiency in textile industry*" Journal of Cleaner Production, vol. 95, 2015.

[25] T. Rissanen and M. McQuillan, *Zero Waste Fashion Design*, Bloomsbury, 2015.

[26] S. Muthu, *Handbook of Sustainable Textiles*, Woodhead Publishing, 2015.

[27] H. Goworek et al., "*The sustainable clothing market*" International Journal of Retail & Distribution Management, vol. 40, no. 12, pp. 935–955, 2012

ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

COFFEE-BASED BIOMATERIAL FOR THE FASHION INDUSTRY

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Abstract: *The fashion industry is facing challenges related to reducing its negative environmental impact, sustainability becoming one of the central directions of development in the contemporary textile sector. The aim of this study is to investigate the possibility of developing a biodegradable biomaterial, specifically a bio-based leather alternative derived from coffee grounds, intended for use in experimental fashion design. The research includes a theoretical analysis of biomaterials obtained from organic waste and their areas of application in the fashion industry, as well as an experimental component focused on the development, production, and practical testing of the proposed biomaterial. As a part of the study, multiple experimental samples were created using natural ingredients such as gelatin, agar-agar, glycerin, water, and coffee grounds, different conditions of processing and drying being analyzed to optimize composition and structural stability. The obtained biomaterials were evaluated from both physico-mechanical and aesthetic perspectives by examining flexibility, handling resistance, dimensional stability, and behavior during processing. To validate the material's practical applicability, a wearable physical prototype was developed in the form of a corset, confirming the feasibility of integrating the biomaterial into contemporary garment structures. The research results confirm the potential of coffee ground–based biomaterial as a sustainable alternative for the development of experimental fashion products and open perspectives for future research aimed at improving mechanical performance and expanding its commercial applicability.*

Key words: *sustainability, bio-leather, circularity, biodegradation, textiles, innovation*

1. INTRODUCTION

Sustainable fashion promotes an integrated approach in which environmental responsibility is aligned with the social and economic dimensions of garment production. This orientation involves rethinking how clothing items are designed, produced, distributed, and used, with an emphasis on quality, durability, and long-term value. One of the key aspects of sustainable fashion is the selection of materials. The use of responsibly cultivated natural fibers, recycled materials, or those obtained from innovative alternative sources, contributes to reducing the ecological footprint. Organic cotton, certified wool, regenerated cellulosic fibers, as well as biomaterials developed from agricultural or organic waste, represent viable solutions for decreasing the consumption of non-renewable resources and the pollution associated with traditional textile production processes.

This study aims to investigate the potential of valorizing coffee grounds as a secondary raw material for the development of a biodegradable biomaterial, specifically a bio-leather alternative intended for applications in experimental fashion design. The research focuses on the development of the biomaterial, the analysis of process parameters involved in its production, the evaluation of its physico-mechanical properties, and the practical validation of its applicability through integration into an experimental garment prototype.

2. BIO MATERIALS FROM ORGANIC WASTE

Against the backdrop of growing environmental concerns, the textile industry is increasingly exploring alternative resources, transforming organic waste into innovative textile materials. These solutions not only reduce pollution and the consumption of natural resources, but also support the circular economy by promoting the “waste-to-fashion” concept whuch represent the transformation of biodegradable residues into sustainable, aesthetic, and durable products.

Organic waste represents biological resources with high potential, generated after crop harvesting or as a result of food processing [1]. In the last 10 years, numerous start-ups, university laboratories, and sustainable fashion brands have demonstrated that these resources can be transformed into high-performance textile materials, with aesthetic and technical properties comparable to leather or synthetic fibers. Through this circular approach, fashion not only gains access to new materials, but also achieves a reduced impact on soil, water, and carbon dioxide emissions.

Through the application of innovative technological processes, organic waste is valorized and transformed into sustainable biomaterials, contributing to the development of eco-friendly alternatives for the fashion industry. Relevant examples include AppleSkin [2], made from apple peels; VEGEA Wine Leather [3], manufactured from grape processing waste; mycelium-based bio-leather [4], derived from the filamentous structure of fungi; SCOBY leather [5], created through fermentation using Kombucha bacteria; bio-leather with propolis additives [6], based on biopolymeric components and propolis; coffee-based bio-leather [7], developed by incorporating coffee grounds into the material composition; and bioplastic derived from orange peels [8], obtained from biopolymers extracted from citrus waste. The materials developed in this way are sustainable and biodegradable, emphasizing the reduction of environmental impact compared to animal leather or other synthetic materials.

3. EXPERIMENTAL PART

3.1. Material and method

The experimental research presented in this study aims to develop a bio-leather by valorizing natural ingredients and organic waste, with a particular focus on the use of coffee grounds as the main raw material.

The adopted methodology in this study is of experimental-artisanal matter and is based on successive testing, direct observation, and the progressive adjustment of process parameters. Given the innovative and experimental character of the investigated biomaterial, the study does not exclusively aim the obtaining of a fully functional final product, but also the examiningof the difficulties encountered throughout the fabrication process, in order to identify technological limitations and opportunities for further optimization.

To obtain the biomaterial, exclusively natural-origin ingredients were selected, without the inclusion of plastic, synthetic, or toxic additives, in order to ensure the full biodegradability of the product and its compatibility with the principles of eco-design and the circular economy. The raw materials used in the biomaterial composition are gelatin, agar-agar, glycerin, coffee grounds, and water.

From a methodological perspective, the research is based on the application of the experimental method through the practical fabrication of the biomaterial, complemented by direct observation used to monitor structural and behavioral changes during the drying process. Comparative analysis is employed to evaluate the material's behavior under different temperature conditions and drying methods, while the iterative method enables the repetition of the fabrication process and the adjustment of parameters, following the identification of defects or nonconformities. At the same time, photographic documentation is used to record the experimental stages and to highlight the difficulties encountered throughout the process.

3.2. Stages of obtaining coffee-based biomaterials

The process of obtaining coffee-based biomaterials has many steps, including raw material preparation, composition development, thermal treatment, casting into molds, and drying of the material, each stage influencing the final properties of the biomaterial. The research aimed to establish optimal ingredient ratios in order to obtain samples with characteristics similar to natural leather.

The basic recipe used, according to bibliographic sources [9], included 3 g of agar-agar, 20 g of gelatin, 15 ml of glycerin, and 400 ml of water, with the mixture being boiled at approximately 80°C for 25–35 minutes.

To obtain a biomaterial sample, the following quantities of ingredients were used: 20 g of coffee grounds, 30 ml of glycerin, 4 g of agar-agar, 20 g of gelatin, and 400 ml of water. The ratio of ingredients was determined through repeated experiments until a biomaterial sample with properties similar to natural leather was obtained. The ingredients were accurately weighed and placed into a heat-resistant container, then mixed to ensure homogeneity. The mixture was heated and boiled for 20–25 minutes under continuous stirring until a viscous liquid was obtained.

Subsequently, the resulting solution was poured into a rectangular mold with dimensions of 27 × 18 cm, where it was left to dry at room temperature. After 3 days, the material was removed from the mold and placed under a press for a period of 7 days to ensure dimensional stabilization and to prevent deformation. The drying process was monitored to avoid the formation of possible imperfections.

Although the results obtained were satisfactory, replication of the process revealed several technological difficulties. At temperatures between 25–30°C, cracks and fractures become visibls (Figure 1a), a phenomenon associated with rapid water loss and irregular material shrinkage. Under lower temperature conditions, between 12–16°C, mold growth was detected, caused by high humidity and prolonged drying time (Figure 1b). Additionally, differential drying between the edges and the center of the molds was noted, a phenomenon determined by the uneven distribution of coffee grounds in the composition and variations in the particle size of the solid components (Figure 1c).


a) *b)* *c)*

***Fig. 1**: Biomaterial samples*

Samples that exhibited defects, such as cracks or biological contamination, were reintegrated into the process through reprocessing. They were dissolved by adding a small amount of water, reheated for 5–7 minutes until a homogeneous composition was obtained, and subsequently reused for casting new experimental samples.

The research results demonstrate that obtaining bio-leather is a process that requires successive adjustments and careful monitoring of each technological parameter. Although difficulties such as mold growth, uneven drying, cracking, or texture variations were identified, these can be mitigated through optimization of the composition, control of material thickness, and regulation of drying conditions.

3.3. Analysis of the proprieties of the experimental biomaterial

After obtaining the coffee ground–based biomaterial, its physical, mechanical, and aesthetic properties were evaluated to determine its compatibility with specific applications in fashion design. It was used methods as the experimental and practical methode, being conducted through direct observation, manual manipulation, and comparative testing between the obtained samples.

To validate the obtained biomaterial from a scientific perspective, it was subjected to biodegradability and thermal stability tests. For the assessment of biodegradability, the material was immersed in an aqueous environment for 24 hours and subsequently left to dry for another 24 hours. A surface mass reduction of approximately 40% was observed, allowing an estimated complete degradation time of about 60 hours.

The melting temperature of the biomaterial was determined to be 85°C.

The flexibility of the biomaterial was analyzed through repeated bending test. The results indicating that the samples from initial experiments exhibited high rigidity and rapid cracking, while the optimal sample demonstrated satisfactory elasticity and structural stability. This behavior was supported by the appropriate proportion of glycerin and the reduced amount of coffee grounds, which contributed in the development of a more uniform structure.

The resistance to the usage was evaluated through manual tensile tests, with the biomaterial demonstrating suitable properties for decorative uses, surface applications, and conceptual fashion elements, but limitations in areas subjected to high mechanical stress. Physical and mechanical testing of the biomaterial using standardized methods (tensile strength, elongation) represents a future research direction.

From an aesthetic perspective, the biomaterial exhibits a natural organic texture and a visual appearance similar to matte or semi-gloss leather. The surface quality was found to be directly influenced by the degree of coffee grounds grinding, with finer particles leading to more uniform and homogeneous surfaces.

Regarding to processability, the biomaterial allows cutting, perforation, and sewing operations, demonstrating good performance when technical parameters are adapted to its structure.

3.4. Results and discussion

The obtained results confirm that the coffee ground–based biomaterial can be integrated into simple garment structures, such as applications, decorative panels, or modular elements, validating its potential as a sustainable alternative for the development of experimental fashion prototypes. To validate the obtained results, it was decided to create a physical clothing prototype in the form of a corset.

In the preliminary stage, prototyping of the design and pattern development were carried out digitally using the CLO 3D platform, which enabled dimensional and structural optimization prior to physical execution (Figure 2).

***Fig. 2**: Prototipul digital al modelului*

The first stage of the physical realization of the garment involved pattern layout on the material, a process carried out with the aim of optimizing consumption and reducing technological waste. The cutting stage was performed manually, this method being considered optimal for precise control of contours and for preventing damage to the material edges. Observations made during the process highlighted that the biomaterial exhibits stable behavior during cutting, without pronounced tendencies toward cracking or delamination, confirming its satisfactory processability at the cutting stage. The sewing was carried out using specialized equipment for leather-like materials, and the technological parameters of the sewing machine were adapted to the specific characteristics of the biomaterial by adjusting stitch length and thread tension.

In the final evaluation stage, the prototype was analyzed from both an aesthetic and functional perspective, focusing on its behavior during wear and the interaction between structure, material, and the wearer's body. The results highlighted good dimensional stability, satisfactory comfort, and the maintenance of structural form during use, confirming the viability of the adopted technical solutions. The physical prototype made from the experimental biomaterial is presented in Figure 3.

***Fig. 3**: Physical prototype made from the experimental biomaterial*

4. CONCLUSIONS

This research highlights the importance of sustainable approaches in fashion design and the potential of valorizing organic waste for the development of innovative materials intended for the fashion industry. The experimental results demonstrated that the coffee ground–based biomaterial can be obtained by combining natural ingredients such as gelatin, agar-agar, glycerin, and water, resulting in a flexible, biodegradable material with an appearance similar to natural leather.

The final properties of the biomaterial are influenced by the ratio of ingredients, the grinding degree of the coffee grounds, material thickness, and drying conditions, with their optimization being essential to prevent structural defects. The realization of the physical prototype validated the applicability of the biomaterial and the proposed construction solutions, demonstrating their potential for integration into experimental fashion products and for the further development of commercial applications in the field of sustainable fashion.

The main original contribution on this research consists in the practical validation of the developed biomaterial through the creation of a wearable physical prototype in the form of an experimental corset, which demonstrates the material's real applicability in fashion design and confirms its functional and aesthetic potential. The realization of the prototype enabled the assessment of the biomaterial's behavior under real usage conditions and demonstrated the feasibility of integrating it into contemporary garment structures.

The obtained results confirm that the coffee ground–based biomaterial represents a viable sustainable alternative for the development of experimental fashion prototypes and for the creation of decorative elements in fashion industry. Future research may focus on improving mechanical strength, increasing moisture stability, and optimizing material durability in order to expand its potential applications at a commercial scale.

REFERENCES

[1] Ufitikirezi, J. and others. Agricultural Waste Valorization: Exploring Environmentally Friendly Approaches to Bioenergy Conversion. *Sustainability*, *16*(9), 2024. 3617. https://doi.org/10.3390/su16093617

[2] ***https://www.stellamccartney.com/ae/en/stellas-world/appleskin-apple-waste-vegan-leather-alternative.html

[3] *** https://www.lamadia.com/la-scelta-vegana/il-vegan-e-moda/

[4] Benetti B., Conti F., Dimitriadis P. Mycelium-based leather: a review on post-processing treatments and material enhancements. Environmental and Climate Technologies. 29. 2025. 390-404. 10.2478/rtuect-2025-0026. DOI:10.2478/rtuect-2025-0026

[5] ***https://www.yankodesign.com/2025/01/15/kombucha-by-product-used-to-create-leather-for-traditional-shadow-puppet-exhibit/

[6] Raru A., Miron N. Innovation in biomaterial industry –propolis as an complementary element. In: Journal "Annals of University of Oradea. Fascicle of Textiles, Leatherwork". Vol 25. No.2, pp. 75-80. ISSN 1843-813X. Romania, 2024. Disponibil: https://textile.webhost.uoradea.ro/Annals/Vol%2025%20no%202-2024/Art%20593%20pag%2075-80.pdf

[7] Yontar A., Şensoy G. A green polymer biomaterial functionalized with waste coffee grounds for anti-hemolytic and antibacterial applications. Polymer Bulletin. 82. 2025. DOI: 10.1007/s00289-025-05861-w

[8] Jayachandra S. Yaradoddi, Nagaraj R. Banapurmath, Sharanabasava V. Ganachari, Manzoore Elahi M. Soudagar, Ashok M. Sajjan, Shrinidhi Kamat, M.A. Mujtaba, Ashok S. Shettar, Ali E. Anqi, Mohammad Reza Safaei, Ashraf Elfasakhany, Md Irfanul Haque Siddiqui, Masood Ashraf Ali. Bio-based material from fruit waste of orange peel for industrial applications, Journal of Materials Research and Technology, Volume 17, 2022, Pages 3186-3197, ISSN 2238-7854. DOI: https://doi.org/10.1016/j.jmrt.2021.09.016

[9] *** https://class.textile-academy.org/classes/2025-26/week07/

ANNALS OF THE UNIVERSITY OF ORADEA
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PRACTICAL ASPECTS OF THE EFFECT OF SUITABLE ELECTROLYTES ON COTTON DYEING

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Abstract: *Reactive dyes are the most important class of dyes for cellulose fibers and are most commonly used in industry by the exhaustion method. The low affinity of these dyes requires the addition of large amounts of various salts and auxiliary materials to the dyeing bath. The number of ions formed by the dissociation of the electrolyte determines the ionic strength of the solution and has a stimulating effect on the exhaustion of reactive dyes on cotton cellulose. In this work, the influence of neutral salts (NaCl and* Na_2SO_4*) and alkaline salt (*Na_2CO_3*) on the color strength of cotton fabric dyed with bifunctional reactive dyes was investigated. The reactive dye solution with a higher ionic strength of the neutral salt has a higher exhaustion dye and higher color strength. The difference in color strength in the* Na_2SO_4 *bath compared to the NaCl bath ranged from 1.2 to 36%. The substantivity of the reactive dyes used is 4.5 to 18% higher in the* Na_2SO_4 *bath. The addition of an alkaline salt to activate the chemical dye/fiber reactions has an additional effect on exaustion dye as a result of further increasing the ionic strength of the solution.*

Key words: *reactive dyes, ionic strength, color strength, substantiality of dyes, promotional effect*

1. INTRODUCTION

Reactive dyes are the most important class of dyes for dyeing cotton and other cellulosic fibers. Different dyeing methods, a wide range of shades and permanent and brilliant dyeing are the advantages that are characteristic of these colors. Today, reactive dyes make up about 60 % of the world's consumption of dyes for cellulose fibers [1]. Despite the enormous popularity of reactive dyes, there are numerous environmental challenges due to the low level of dye utilization. The dyeing bath contains large amounts of electrolytes and supplements that increase the uniformity and durability of the dyeing [2]. Baffoun published a paper in which a comparative study of the effectiveness of two electrolytes on the dyeing of cotton with the reactive dye Sumifix Supra Yellow E-XF was carried out [3]. In a recently published paper, a group of authors used the Taguchi method for evaluation of process parameters on exhaustion and fixation of bifunctional dye C.I. Reactive Red 195 on cotton fabric [4]. The results showed that the concentration of salt has the greatest influence, followed by the concentration of alkali, followed by temperature and dyeing time.

In this work, the influence of inorganic electrolytes on the dyeing of cotton fabric with bifunctional reactive dyes was examined the dyeing, results are related to the ionic strength of the solution.

2. EXPERIMENTAL PART

2. 1. Material and working methods

In the experiment, the 100 % cotton fabric samples were dyed, surface mass 220 g m^{-2} with warp density 43 cm^{-1} and weft 22 cm^{-1}. The fabric is industrially prepared for dyeing. The samples for dyeing had a mass of 5 g. Chemicals used in the work are as follows: Bezaktiv blue S-FR$_{150\%}$, bifunctional reactive dye (MCT/VS, Bezema - Switzerland), Bezaktiv red S-3B$_{150\%}$, bifunctional reactive dye (MCT/VS, Bezema - Switzerland), Bezaktiv yellow S-3R$_{150\%}$, bifunctional reactive dye (MCT/VS, Bezema - Switzerland), NaCl - salt, an agent of increasing dye exhaustion, Na_2SO_4 - salt, an agent for increasing dye exhaustion, Na_2CO_3 - salt, an agent for regulating the pH of the solution.

Dyeing was performed by an Ahiba apparatus (TYP G7B) in glass cuvettes with vertical movement of the material. Dyeing was carried out isothermally at t=60 °C for 60 and 120 minutes. In the bath that contained dye and salt to increase dye exhaustion, the dyeing time was 60 minutes. The samples that were dyed for 120 minutes were first dyed for 60 minutes with the addition of salt to increase the exhaustion of the dye, and then salt was added to regulate the alkaline bath and the dyeing was continued for another 60 minutes. The concentration of the dye was 1.5 and 4 % (based on the mass of the material), and the concentration of NaCl and Na_2SO_4 was 50 and 100 g dm^{-3}. The concentration of Na_2CO_3 was 15 and 20 g dm^{-3} and the volume of the bath is 150 cm^3 (R 1:30). After dyeing and washing with distilled water, the samples that were dyed for 120 min were processed in a soapy solution at 90 °C for 15 minutes, washed again and air dried.

Reflection spectrophotometer Spectraflash SF600X (Datacolor - USA) measured the reflection of the sample at wavelengths 400 - 700 nm and CIELab color coordinates were determined. Based on the reflection value at the wavelength of maximum adsorption for each sample, the color strength (K/S) was calculated according to the Kubelka-Munk equation:

$$\frac{K}{S}=\frac{(1-R)^2}{2R} \tag{1}$$

Where: *K* – absorption coefficient, *S* – scattering coefficient, *R* – reflection for light D65/10. The maximum absorption wavelengths have the following values: Bezaktiv blue S-FR$_{150\%}$ 630 nm, Bezaktiv red S-3B$_{150\%}$ 550 nm and Bezaktiv yellow S-3R$_{150\%}$ 440nm.

Using a colorimeter CO7500 (WPA England), the absorbance of the solution was measured at the wavelength of maximum absorption, at the beginning and at the end of dyeing (after 120 min). Using equation 2, the percentage of color exhaustion (*E*) is determined [5] :

$$\%E=\left[\frac{(A_o-A_1)}{A_o}\right]\times 100 \tag{2}$$

where:
A_o – absorbance of the solution at the beginning of dyeing,
A_1 – absorbance of the solution at the end of dyeing.

For each dyeing system (with a dyeing time of 120 minutes), dye substantiality (*K*) was determined, which is a measure of the dyes ability to transfer from the solution to the fiber under certain dyeing conditions. Substantiality is determined using equation (3) [6]:

$$K = \frac{[\%E \times L]}{[100 - \%E]} \qquad \textbf{(3)}$$

where: $\%E$ – exhaustion dye, L – bath ratio.

The ionic strength *(I)* of the solution was calculated using equation 4 [7]:

$$I = \frac{1}{2}\sum_{i=1}^{n} c_i z_i^2 \qquad \textbf{(4)}$$

where: $c_1, c_2 \ldots c_i$ - concentration of ions present in the solution (mol dm^{-3}), $z_1, z_2 \ldots z_i$ - charge of ions present in the solution.

The promotional effect of the neutral salt was determined using equation 5 [8]:

$$\%\,\text{promotional salt effect} = \frac{\%E\text{s} - \%E\text{o}}{\%E\text{s}} \qquad \textbf{(5)}$$

where is:

$\%E$s – equilibrium dye exhaustion for samples dyed with the addition of salt,

$\%E$o – equilibrium dye exhaustion for samples dyed without the addition of salt.

To determine the promotional effect of salt, samples were dyed for 120 minutes with 1.5% dye without and in the presence of salt (NaCl and Na_2SO_4), at 60 °C. The color fastness to washing (at 60 °C) of cotton fabric samples was determined according to ISO 105-C06:2010 standard, using AATCC 1993 standard reference detergent. Color fastness to washing was determined on samples dyed for 120 minutes. Table 1 gives the markings of the dyed cotton samples.

Tab. 1. *Designations of samples*

Designations of samples	Concentration of dye (%)	Concentration of NaCl (gdm^{-3})	Concentration of Na_2SO_4 (gdm^{-3})	Concentration of Na_2CO_3 (gdm^{-3})	Dyeing time (min)
B1; R1; Y1	1.5	50	-	-	60
B2; R2; Y2	1.5	-	50	-	60
B3; R3; Y3	1.5	50	-	15	120
B4; R4; Y4	1.5	-	50	15	120
B5; R5; Y5	4	100	-	-	60
B6; R6; Y6	4	-	100	-	60
B7; R7; Y7	4	100	-	20	120
B8; R8; Y8	4	-	100	20	120

B1-B8, samples dyed with Bezaktiv blue S-FR$_{150\%}$; R1-R8, samples dyed with Bezaktiv red S-B$_{150\%}$; Y1-Y8, samples dyed with Bezaktiv yellow S-3R$_{150\%}$

3. RESULTS AND DISCUSSION

3. 1. Substantivity of dyes

Substantivity is the ability of the dye to transfer directly from the solution to the fiber, and it largely depends on the chemical composition and structure of the dye. Substantivity also depends on bath temperature and salt concentration. Dyes of greater substantivity have greater equilibrium exhaustion and vice versa. Dyes to the small molecules, reactive dyes have a low substantivity and the addition of inorganic electrolytes has a great influence on the dyeing from the solution onto the fiber for the following reasons:

1) the color changes from ionic to molecular form, i.e. the solubility of the dye decreases,
2) the negative surface charge of the fiber is reduced, so that the electrostatic repulsive forces between the dye and the fiber are reduced and
3) the chemical potential of the dye in the solution increases.

Table 2 shows the values substantivity of dyes (K) based on dye exhaustion during a dyeing time of 120 min, which corresponds to a real dyeing system. The substantivity of all dyes was higher when dyeing with a higher concentration of dyes and electrolytes and when the bath contains Na$_2$SO$_4$. In the range of dyes used, red has the lowest substantivity (K) and blue has the highest. The substantivity of Bezaktiv blue S-FR$_{150\%}$, is 18 and 12% higher when the technological solution contains Na$_2$SO$_4$ compared to the system with NaCl for a lighter and darker tone, respectively. When applying Bezaktiv red S-3B$_{150\%}$ increase in substantivity when NaCl is replaced with Na$_2$SO$_4$ amounts to 8% (for a light shade) and 13% (for a dark shade). With Bezaktiv yellow S-3R$_{150\%}$ the substantivity is higher by 9% for a lighter shade and 4.5% for a darker shade, for the system with Na$_2$SO$_4$ compared to the system with NaCl. The chemical composition and constitution of the molecules of reactive dyes have the greatest influence on the ability of the dye to transfer from the solution to the cotton fiber. The addition of salt, which increases the number of ions in the solution, affects the displacement of the final distribution of reactive dye molecules on the fiber side. The obtained results indicate the important and complex role of the present electrolytes in increasing the exhaustion of reactive dyes on cotton. It is likely that the efficiency of the electrolyte for the transfer of reactive dye molecules to the cotton fiber depends on the number of ions produced by the dissociation of the electrolyte, i.e. from the ionic strength of the solution.

Tab. 2. *Substantivity (K) Bezaktiv blue S-FR$_{150\%}$, Bezaktiv red S- 3B$_{150\%}$ and Bezaktiv yellow S-3R$_{150\%}$*

Designations of samples	K	Designations of samples	K	Designations of samples	K
B3	41.4	R3	32.5	Y3	45.0
B4	48.9	R4	35.2	Y4	48.9
B7	95.0	R7	35.2	Y7	48.9
B8	106.4	R8	29.8	Y8	51.1

3.2. Color strength

Color strength (K/S) were calculated using the Kubelka-Munk equation and are shown graphically in Figures 1-3. The color strength of cotton fabrics depen ds on the formulation of the dyeing solution and the dyeing time. Samples dyed with Bezaktiv blue S-FR$_{150\%}$ have higher K/S values when Na_2SO_4 is used as a salt to increase exhaustion compared to samples dyed in a NaCl bath (Figure 1). After 120 minutes of dyeing in a lighter shade, the difference is minimal (2,5%), but after dyeing in a darker shade, the difference is significant and amounts to 33%. These results indicate a greater effect of Na_2SO_4 on the condition of the dye in the solution and the transition to cotton, as well as that this effect becomes more distinct the higher the concentration of the dye in the bath. The addition of alkali (Na_2CO_3), which primarily has the role of regulating the alkalinity of the solution, is also reflected in the increase in the color strength of the dyed samples. On samples of a lighter shade, that increase amounts to 68% (bath with NaCl) and 53% (bath with Na_2SO_4). When dyeing in a darker shade, the effect of added alkali is even greater because the color strength is twice as high after 120 min of dyeing. Color strength of cotton fabric samples dyed with Bezaktiv red S-3B$_{150\%}$ depends on the formulation of the technological solution and the time of dyeing (Figure 2). Samples dyed in a bath with Na_2SO_4 have a higher color strength compared to the system with NaCl, and the difference for the lighter shade is 28%, and for the darker shade 36%. The addition of Na_2CO_3 has a significant influence on the final result of red coloring, which increases the color strength from 15 to 35%. When dyeing with Bezaktiv yellow S-3R$_{150\%}$ in the bath with Na_2SO_4, the color strength is 11 and 14% higher for a light shade, after 60 and 120 minutes of dyeing, respectively, compared to the bath with NaCl (Figure 3). By dyeing in a dark shade, the differences are minimal. When applying this dye, a great influence of the addition of Na_2CO_3 on the dyeing of the cotton fabric is observed, because the exhaustion of the dye increases further and K/S has higher values by about 55% for a lighter shade and a darker shade by about 83% compared to the first 60 minutes of dyeing. The higher color strength of cotton with reactive dyes in the Na_2SO_4 solution is explained by the higher ionic strength of the solution (Table 3), because dissociation produces twice as many Na^+ ions compared to the NaCl solvent. A greater number cations of inorganic electrolyte in the technological solution for dyeing cotton with anionic dyes, to a greater extent reduces the fiber/dye repulsive forces and increases the chemical potential of the dye in the solution, which practically manifests it self as greater dye exhaustion.

***Tab. 3.** Electrolyte concentration and ionic strength*

Concentration 50 g dm^{-3}		Concentration 100 g dm^{-3}	
Electrolyte	Ionic strength (I) mol dm^{-3}	Electrolyte	Ionic strength (I) mol dm^{-3}
NaCl	0.85	NaCl	1.71
Na_2SO_4	1.06	Na_2SO_4	2.13

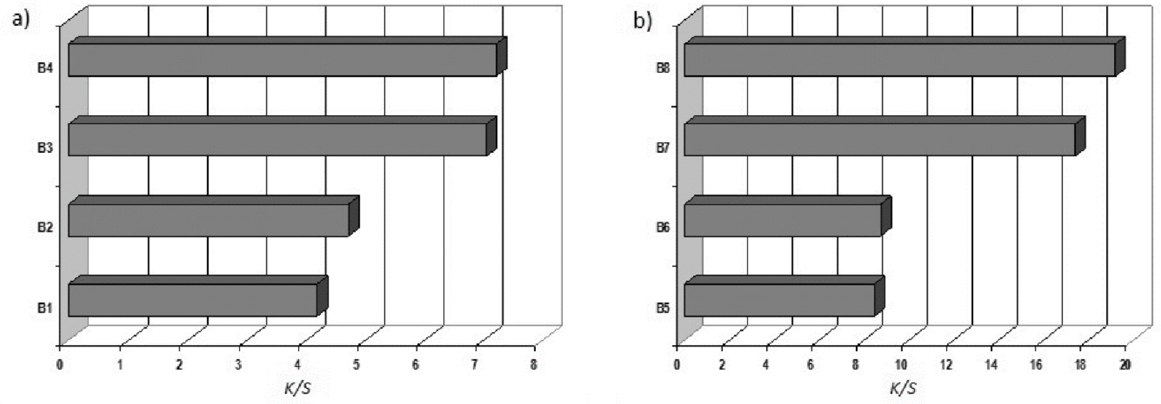

Fig. 1. *Color strength samples dyed with 1.5 % (a) i 4 % (b) Bezaktiv blue S-FR*$_{150\%}$

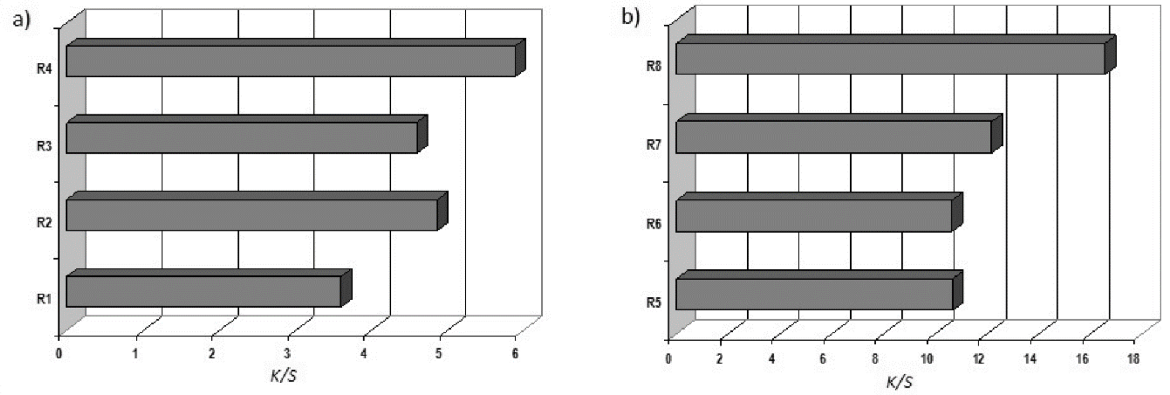

Fig. 2. *Color strength samples dyed with 1.5 % (a) i 4 % (b) Bezaktiv red S-3B*$_{150\%}$

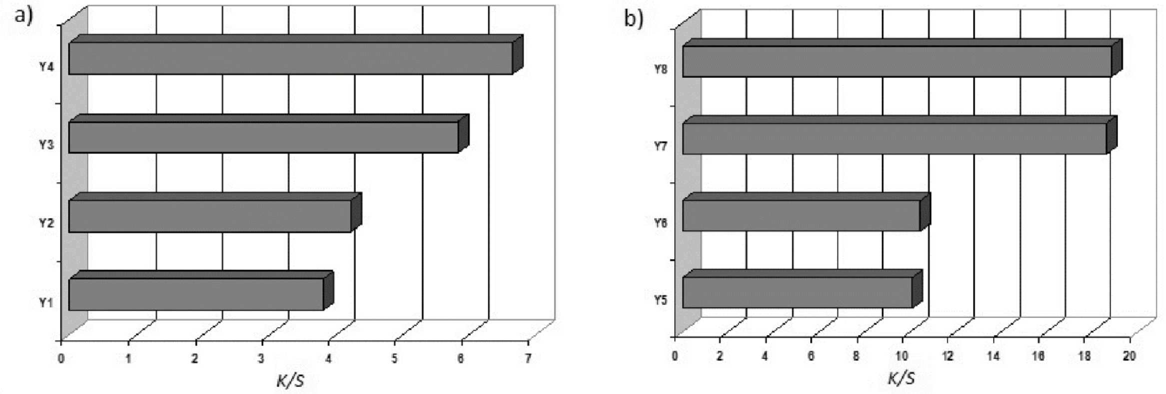

Fig. 3. *Color strength samples dyed with 1.5 % (a) i 4 % (b) Bezaktiv yellow S-3R*$_{150\%}$

3.3. Promotional effect of neutral salt

The promotional effect of neutral salts represents the sensitivity of a dye to the presence of neutral salts in the dyeing bath, i.e. an increase in dye exhaustion in the presence of a neutral salt compared to a salt-free system. From the results shown in table 4, higher values of the promotional effect of Na_2SO_4 can be seen compared to the promotional effect of NaCl. The promotional effect of neutral salts is different for different dyes. The greatest promotional effect is achieved with Bezaktiv yellow S-3R$_{150\%}$, where there is also the smallest difference in promotional effects between the neutral salts used. The lowest promotional effect of neutral salts was achieved with red dye and is twice as small compared to blue to yellow dye in the experiment. This data indicates a very heterogeneous sensitivity of dyes of the same class to the addition of salt, which may have practical implications in trichromatic dyeing in industrial conditions in order to achieve equal coloring.

Tab. 4. *Promotional effect of inorganic salts on the exhaustion of reactive dyes*

Dye	Promotional effect (%)	
	NaCl	Na_2SO_4
Bezaktiv blue S-FR$_{150\%}$	77.4	83.1
Bezaktiv red S-3B$_{150\%}$	29.8	44.3
Bezaktiv yellow S-3R$_{150\%}$	83.1	84.2

3.4. Color fastness to washing

All samples have a high color fastness to washing as a result of established covalent bond of reactive dye groups with the hydroxyl group of cotton cellulose (Table 5).

Tab. 5. *Color fastness to washing*

Samples	Change in color	Samples	Change in color	Samples	Change in color
B3	4-5	R3	4-5	Y3	4-5
B4	4-5	R4	4-5	Y4	4-5
B7	4-5	R7	4-5	Y7	4-5
B8	4-5	R8	4-5	Y8	4-5

4. CONCLUSION

In this work, the influence of neutral salts (NaCl and Na_2SO_4) and alkaline salts (Na_2CO_3) on the color strength of cotton fabric with bifunctional reactive dyes was examined. The samples were dyed for 60 and 120 minutes with the aim of examining the effect of alkaline salt on the secondary exhaustion of the dye, i.e. color strength.

Based on the obtained results, the following conclusions can be drawn:

Substantivity of all colors is higher when Na_2SO_4 is used as a salt to increase exhaustion. The substantivity of Bezaktiv blue S-FR$_{150\%}$ is 18 and 12% higher when the technological solution contains Na_2SO_4 compared to the system with NaCl for a lighter and darker shade, respectively. Substantivity of Bezaktiv red S-3B$_{150\%}$ is higher by 8% for light shade and 13% for dark shade, and for Bezaktiv yellow S-3R$_{150\%}$ by 9% for lighter shade and 4,5% for darker shade, for the system with Na_2SO_4 compared to the system with NaCl.

The color strength of cotton fabrics depends on the formulation of the dyeing solution and the dyeing time. All samples dyed in a bath with Na_2SO_4 at the end of dyeing had a higher color strength compared to samples dyed in a bath with NaCl. The largest difference of 36% was registered on samples dyed with 4% Bezaktiv red S-3B$_{150\%}$, and the smallest difference of 1,2% on samples dyed with 4% Bezaktiv yellow S-3R$_{150\%}$. The higher color strength is the result of the higher ionic strength of the Na_2SO_4 solution due to twice the number of Na^+ ions, which more effectively neutralizes the fiber/dye repulsive forces and facilitates the transfer of dye from the solution to the surface of the fiber.

The promotional effect of neutral salts is different for different dyes. The greatest promotional effect was achieved with Bezaktiv yellow S-3R$_{150\%}$, and twice as little promotional effect with Bezaktiv red S-3B$_{150\%}$. Na_2SO_4 has the greatest promotional effect at all dyes. Heterogeneous sensitivity of dyes of the same class is of practical importance for trichromatic dyeing in industrial conditions in order to achieve equal coloring.

The type of electrolyte is not important for color fastness.

REFERENCES

[1] S. M. Burkinshaw, G. Salihu, "The role of auxiliaries in the immersion dyeing of textile fibres: Part 7 theoretical models to describe the mechanism by which inorganic electrolytes promote reactive dye uptake on cellulosic fibres", *Dyes Pigm.* vol. 161, no. 1, pp. 605-613, 2019. https://doi.org/10.1016/j.dyepig.2017.09.024

[2] S. M. Burkinshaw, G. Salihu, "The role of auxiliaries in the immersion dyeing of textile fibres: Part 1 an overview", *Dyes Pigm.* vol. 161, no. 1, pp. 519-530, 2019. https://doi.org/10.1016/j.dyepig.2017.08.016

[3] A. Baffoun, "Comparative study between two types of elektrolyte used in the reactive dyeing of cotton", *Ind. Textila*. vol. 70, no. 1, 30-36, 2019. https://doi.org/10.35530/IT.070.01.1392

[4] M. Y. Hossain, S. Sarker, M. Zakaria, M. R Islam, R. U. Fayaz, S. Acharjya, "Influence of process parameters on exhaustion, fixation and color strength in dyeing of cellulose fiber with reactive dye", *J. Text. Eng.* vol. 3, no. 1, pp. 1-10, 2020. https://doi.org/10.29011/2690-0106.100027

[5] N. Ristić, I. Dodić, I. Ristić, "The influence of surfactant structure on the dyeing of polyamide knitting with acid dye", *Chem. Ind. Chem. Eng. Q.* vol. 24, no 2, pp. 117-125, 2018. https://doi.org/10.2298/CICEQ161102025R

[6] C. W. Kan, C.W. M. Yuen, "Dyeing behavior of low temparature plasma treated wool", *Plasma Proc. and Polym.* vol. 3, no. 8, pp. 627–635, 2006. https://doi: 10.1002/ppap.200600086

[7] E. A. Preoteasa, C. Ionescu-Tîrgovişte, "Ionic structure in mineral waters. a conductometry study", *Proc. Rom. Acad., Series B*, vol.17, no. 3, pp. 201–213, 2015.

[8] S. M. Burkinshaw, G. Salihu, "The role of auxiliaries in the immersion dyeing of textile fibres: Part 9 practical aspects of the role of inorganic electrolytes in dyeing cellulosic fibres with pure reactive dyes", *Dyes Pigm.* vol. 161, no. 1, pp. 628-641, 2019. https://doi.org/10.1016/j.dyepig.2017.10.014

CHARACTERIZATION OF REAL TEXTILE EFFLUENTS AND PREPARATION OF A WATER TREATMENT PROTOCOL USING HYDROTALCITE

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Abstract: *Textile wet processing generates wastewater streams with markedly different chemical profiles. This paper evaluates the use of calcined hydrotalcite as a selective adsorbent for real textile wastewater, focusing specifically on washing water and cotton reactive dyeing effluent. The adsorbent was prepared by calcining hydrotalcite at 600 °C for four hours and then cooling it in a desiccator prior to use. To link structural activation with process performance, the calcination step was interpreted using a qualitative FTIR scheme derived from a companion characterisation study. Calcination suppresses the carbonate band characteristic of hydrotalcite and enables the memory effect, favouring the reincorporation of anionic species when the solid comes into contact with water. Two industrial wastewater streams were studied and compared before and after treatment with hydrotalcite using total organic carbon (TOC), total carbon (TC), inorganic carbon (IC), total nitrogen (TN), pH, conductivity, biological oxygen demand (BOD), total suspended solids (TSS) and chemical oxygen demand (COD). The cotton dyeing wastewater exhibited the most significant response, with reductions in TOC and COD of 78.5% and 74.6%, respectively. The washing effluent showed more limited improvements, with TOC and COD reductions of 18.6% and 27.6%, respectively. This difference can be explained by the difference in pH between the two streams: a higher pH increases adsorption values. Therefore, the treatment appears promising as a selective pre-treatment for segregated dyeing streams. However, the associated increase in pH and conductivity indicates that a later neutralization or polishing step would still be required.*

Key words: *hydrotalcite; water treatment; textile effluent; cotton dyeing process; washing processes.*

1. INTRODUCTION

Textile wet processing is one of the industrial activities most strongly associated with water use and variable wastewater composition. Washing, dyeing, rinsing and finishing operations generate effluents that may contain dyes, salts, alkalis, surfactants, lubricants and other additives, meaning that the final analytical profile depends not only on the substrate, but also on the exact stage of the process [1]-[3].

This distinction is particularly important in dyehouses. Cotton reactive dyeing wastewater is typically rich in alkaline chemicals and unfixed dye-related compounds, whereas washing wastewater usually contains a lower chromatic load, but appreciable amounts of organic auxiliaries. Studies based only on model dye solutions often overlook this heterogeneity. Nevertheless, adsorption remains attractive in the textile sector because it can be applied as a selective polishing step for colour and dissolved organics using relatively simple equipment [2]-[4].

Hydrotalcite-type layered double hydroxides are particularly interesting adsorbents because their positively charged, brucite-like layers contain exchangeable interlayer anions [5, 6]. After calcination, these solids are converted into mixed oxides that can regain a layered structure when rehydrated in water. This so-called memory effect enables new anionic species to be incorporated from the treated medium [5], [7], [8]. For textile applications, this behaviour is relevant whenever the wastewater contains dye-derived anions or other species that are compatible with the reconstruction of the layered structure.

Recent papers in the Oradea textile journal show ongoing interest in adsorption and in new wastewater treatment strategies for textile processes [3], [4]. However, there is still a need for conference contributions based on real segregated industrial streams and explicitly connected to adsorbent activation. The aim of the present work was therefore to adapt the hydrotalcite calcination study to a textile-focused paper and compare the response of two real industrial streams - washing and cotton dyeing wastewater - before and after treatment with calcined hydrotalcite.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Nanoclay and Textile Effluents used

Two types of industrial wastewater were collected from a textile company (Table 1): wastewater from washing and from cotton dyeing. The first one is a cellulose dyeing bath with reactive dye chemistry, whereas the washing water represented a more auxiliary-rich stream.

Table 1: *Selected textile streams treated with hydrotalcite*

Stream	Textile process	Main reported bath composition
W	Washing	2 g/L lubricant (polyacrylamide) + 5 g/L wetting agent (ethoxylated fatty alcohol)
C	Cotton dyeing	1 g/L wetting agent + 60 g/L sodium silicate + 6 g/L NaOH + 0.451% reactive dye

2.2 Methods

2.2.1 Treatment method

The hydrotalcite and wastewater dosages are described in

Table *2*. The hydrotalcite was previously calcinated at 600ºC for 4 hours and then cooled in a desiccator to minimize moisture uptake from the atmosphere. This step is important because if it remains exposed to humid air, calcined hydrotalcite can progressively reconstruct its layered structure. The nanoclay-wastewater dispersion was left for 1 h in maximum agitation, followed by 24 h with minimum agitation.

Table 2: *Stream and hydrotalcite quantities used.*

Sample	Stream quantity used (mL)	Stream used	[Hydrotalcite used] (g/L)
W+HT	300	W	23

C+HT	300	C	32

Finally, the dispersion was filtared for 24 hours using filter paper with a grammage of 130 g/m^{-2}, a pore size of 25–30 µm and a thickness of 430 µm. The collected water was analysed.

2.2.2 Water parameters analyzed

The streams were analysed before and after treatment using the following parameters: pH; conductivity; total suspended solids (TTS); total organic carbon (TOC); total carbon (TC); inorganic carbon (IC); total nitrogen (TN); chemical oxygen demand (COD); and biological oxygen demand (BOD). TOC, TC, IC and TN were measured using a Shimadzu TOC-VCSH analyser after filtration through 0.45 µm PTFE membranes, while pH was measured using a CRISON micropH 2002 meter and conductivity using a CRISON microCM 2101 conductimeter at 21 °C. COD was obtained by digestion and photometric measurement. BOD was measured using an OxiTop respirometric system. For the COD and BOD measurements, dilutions were selected to maintain measurable oxygen consumption without complete depletion. A total correction factor was applied based on dilution. TSS was assessed gravimetrically by filtering, drying, and weighing of the retained solids. For concentration-based parameters, the relative change caused by treatment was calculated as follows:

$Removal\ (\%) = ((C0 - Ct) / C0)\ x\ 100$

2.2.3 Hydrotalcite FTIR

FTIR analysis was conducted in ATR mode using a ZnSe prism with a Jasco FTIR 4700 IRT 5200 spectrometer with a DTGS detector. Spectra were recorded from 64 scans at aresolution of 4 cm^{-1}. The analysis was performed on hydrotalcite before and after calcination, as well as on hydrotalcite that had been calcinated and stored in the lab.

3. RESULTS AND DISCUSSION

3.1 Hydrotalcite FTIR

To connect structural activation with textile performance, FTIR analysis was conducted across the three stages we mentioned before. As shown in Fig. 1, the untreated solid displays the broad hydroxyl/water region and a characteristic carbonate absorption peak near 1365 cm^{-1} , as observed in hydrotalcite materials [8]-[10]. After calcination, this carbonate feature is strongly suppressed, which is consistent with the removal of interlayer carbonate and dehydroxylation. The partial recovery of hydrotalcite-like features after air exposure is in turn consistent with the memory effect [10].

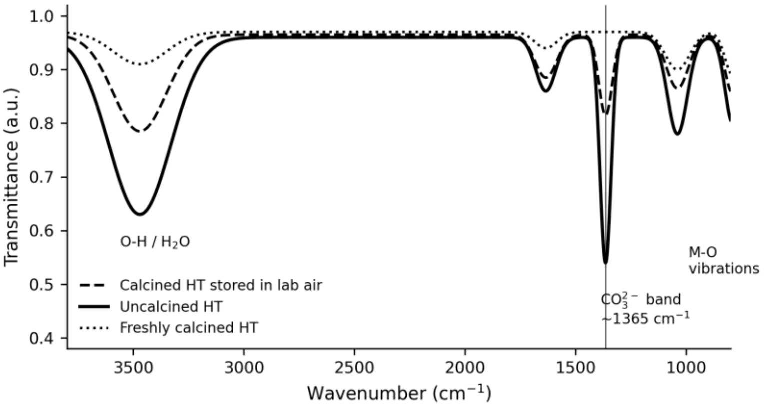

***Fig. 1**: Schematic FTIR comparison of hydrotalcite before calcination, immediately after calcination and after atmospheric exposure*

3.2 Stream characterization before and after treatment

As shown in Table 2, the response to calcined hydrotalcite depended strongly on the origin of the wastewater. The washing effluent was nearly neutral before treatment and mainly contained a lubricant and a wetting agent. In contrast, the cotton dyeing wastewater was strongly alkaline as it came from a reactive dyeing bath containing sodium silicate and sodium hydroxide. From a textile processing viewpoint, the cotton stream therefore represented dye-bearing bath chemistry, whereas the washing stream represented a more dilute auxiliary-dominated water.

The cotton dyeing effluent experienced the strongest reduction in organic load. TOC fell from 554.3mg/L to 119.1 mg/L (a 78.5% reduction), while COD fell from 1161 mg O_2/L to 295 mg O_2/L (a 74.6% reduction). These values demonstrates the ability of calcined hydrotalcite to remove a significant fraction of the carbonaceous load present in a real cotton dyeing wastewater.

***Table 3:** Carbon, oxygen-demand, pH, conductivity and TSS parameters before and after hydrotalcite treatment*

Parameter	W raw	W + HT	C raw	C + HT	Change W (%)	Change C (%)
TOC (mg/L)	437.3	355.9	554.3	119.1	18.6	78.5
TC (mg/L)	445.0	360.5	584.6	140.0	19.0	76.1
IC (mg/L)	7.664	4.61	30.3	20.9	39.8	31.0
TN (mg/L)	59.24	46.38	4.118	4.539	21.7	-10.2
COD (mg O2/L)	1329	962	1161	295	27.6	74.6
BOD (mg O2/L)	2200	0	300	30	100	90
pH	6.42	12.32	11.43	12.9	-91.9	-11.4
Conductivity at 21 °C (µS/cm)	685	1480	4620	10900	-116.1	-135.9
TSS (mg)	2.9	7.7	5	4.2	-165.5	16

The washing water showed a much more modest response. TOC decreased from 437.3 mg/L to 355.9 mg/L (a 18.6% reduction) and COD from 1329 mg O_2/L to 962 mg O_2/L (a 27.6% reduction). TN also decreased in the washing stream, from 59.24 mg/L to 46.38 mg/L. However, the cotton stream showed no reduction in nitrogen and even exhibited a slight increase within the experimental range, which may be due to an experimental error. The treatment was therefore selective rather than universal, preferentially removing dye-related or other anion-rich fractions. This can be explained by the pH, other studies have found that Hydrotalcite shows better adsorption values at higher pH values [11][12].

However, it is also due to the type of compounds the washing water contains, which are usually neutral and too large.

Regarding BOD, the reduction was above 90% in both cases, indicating that the treatment was highly successful. In the case of the cotton effluent, this decrease is consistent with the COD trend, as both parameters are expected to follow a similar pattern. However, for the washing effluent, the discrepancy observed between COD and BOD may be explained by the preferential removal of more biodegradable compounds, leaving behind less biodegradable substances that still contribute to COD but not to BOD.

Regarding TSS, we observed an increase in the W+HT and a decrease in the C+HT, which may be due to an error during filtration.

The difference between the two types of water can be explained in terms of textile chemistry and hydrotalcite reconstruction. Cotton reactive dyeing baths contain unfixed or hydrolysed dye species together with strong alkali. When calcined hydrotalcite rehydrates, its mixed oxides can recover a layered structure and capture new anions from the liquid phase [5], [7], [8]. The rationale of Fig. 1, based on FTIR, supports this mechanism: the removal of carbonate by calcination frees the interlayer environment for the incorporation of other anionic species once the solid enters water.

In contrast, the washing water was dominated by auxiliaries such as polyacrylamide lubricant and ethoxylated wetting agents. It is not expected that tese compounds will interact with calcined hydrotalcite in the same way as reactive dye-related anions. Consequently, the adsorbent only produced partial reduction in TOC and COD.

Despite the decrease in organic load, pH and conductivity increased in both waters after treatment, as summarised in Table 3. This behaviour is important for water reuse strategies because it indicates that adsorption was accompanied by the release or redistribution of alkaline species.

In the washing stream, for example, the pH rose from 6.43 to 12.32, while conductivity increased from 685 µS/cm to 1480 µS/cm. In the cotton dyeing stream, the pH increased from 11.43 to 12.90, and the conductivity increased from 4620 µS/cm to 10900 µS/cm. Therefore, calcined hydrotalcite cannot be considered a complete one-step solution for textile water reuse. Its main value lies in selective reduction of organic and probably chromophoric loads, which could simplify a subsequent biological, membrane or neutralisation stage.

This interpretation is consistent with the broader literature on textile wastewater, where combined treatment are generally considered to be more robust than a single isolated unit operation [1]-[3].

4. CONCLUSIONS

This study demonstrates the potential of using calcined hydrotalcite as an adsorbent for treating real textile wastewater, although its effectiveness is highly dependent on the type of effluent. Treatment was particularly effective for cotton reactive dyeing wastewater, achieving significant reductions in organic pollution (around 78% total organic carbon (TOC) and 75% chemical oxygen demand (COD) removal). In contrast, washing wastewater exhibited much lower removal efficiency, potentially due to the pH conditions and compounds present in the effluent.

The results confirm that the adsorption mechanism involves the “memory effect” of the reconstruction of calcined hydrotalcite, enabling the material to capture anionic species present in dyeing effluents. However, the treatment also increases pH and conductivity, meaning an additional step, such as neutralisation or polishing, is still needed before water can be reused or discharged.

This work's main contribution is evaluating hydrotalcite treatment using real segregated textile effluents rather than model dye solutions and connecting the treatment performance to the structural activation of hydrotalcite after calcination. This provides practical insight into how this material could be used as a pre-treatment step in textile wastewater treatment protocols.

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REFERENCES

[1] C. R. Holkar, A. J. Jadhav, D. V. Pinjari, N. M. Mahamuni and A. B. Pandit, "*A critical review on textile wastewater treatments: Possible approaches*," J. Environ. Manage., vol. 182, pp. 351-366, Nov. 2016. https://doi.org/10.1016/j.jenvman.2016.07.090

[2] M. M. Hassan and C. M. Carr, "*A critical review on recent advancements of the removal of reactive dyes from dyehouse effluent by ion-exchange adsorbents*," Chemosphere, vol. 209, pp. 201-219, Oct. 2018. https://doi.org/10.1016/j.chemosphere.2018.06.043

[3] O. Iordache, C. Tănăsescu, E. Vărzaru, L. Secăreanu, C. Lite, B. Cazan, C. Mihai and A. Săliștean, "*Emerging technologies for wastewater treatment in the textile industry: future prospects*," Annals of the University of Oradea. Fascicle of Textiles, Leatherwork, vol. 24(2), pp. 57-62, 2023.

[4] A. Micic, I. Ristic, S. Djordjevic, N. Ristic and D. Djordjevic, "*Sorption of textile dyes on sorbent made from cotton textile waste - equilibrium adsorption*," Annals of the University of Oradea. Fascicle of Textiles, Leatherwork, vol. 22, no. 1, pp. 47-52, 2021.

[5] F. Cavani, F. Trifirò and A. Vaccari, "*Hydrotalcite-type anionic clays: Preparation, properties and applications*," Catal. Today, vol. 11, no. 2, pp. 173-301, Dec. 1991. https://doi.org/10.1016/0920-5861(91)80068-K

[6] S. Miyata, "*Anion-Exchange Properties of Hydrotalcite-Like Compounds,*" Clays Clay Miner., vol. 31(4), pp. 305-311, Aug. 1983. https://doi.org/10.1346/CCMN.1983.0310409

[7] K.-H. Goh and T.-T. Lim, Z. Dong, "*Application of layered double hydroxides for removal of oxyanions: a review,*" Water Res., vol. 42(6-7), pp. 1343-1368, March 2008. https://doi.org/10.1016/j.watres.2007.10.043

[8] R. M. M. dos Santos, R. G. L. Gonçalves, V. R. L. Constantino, L. M. Costa, L. H. M. da Silva, J. Tronto and F. G. Pinto, "*Removal of Acid Green 68:1 from aqueous solutions by calcined and uncalcined layered double hydroxides,*" Appl. Clay Sci., vol. 80-81, pp. 189-195, Aug. 2013https://doi.org/10.1016/j.clay.2013.04.006

[9] J. T. Kloprogge and R. L. Frost, "*Fourier Transform Infrared and Raman Spectroscopic Study of the Local Structure of Mg-, Ni-, and Co-Hydrotalcites*," J. Solid State Chem., vol. 146(2), pp. 506-515, Sep. 1999. https://doi.org/10.1006/jssc.1999.8413

[10] F. Teodorescu, A. M. Pălăduță and O. D. Pavel, "*Memory effect of hydrotalcites and its impact on cyanoethylation reaction,*" Mater. Res. Bull., vol. 48(6), pp. 2055-2059, June 2013. https://doi.org/10.1016/j.materresbull.2013.02.018

[11] J. Wang, B. Huang, Z. Mao and Y. Wang, "*Study on Adsorption Properties of Calcined Mg–Al Hydrotalcite for Sulfate Ion and Chloride Ion in Cement Paste*," Mater., vol. 14(4), pp. 994, Feb. 2021. https://doi.org/10.3390/ma14040994

[12] O. Díaz, E. González, J. Rodríguez-Sevilla and L. Vera, "*Nutrient removal from secondary wastewater effluent by adsorption with hydrotalcite: effect of calcination temperature and co-existing ions,*" Water Sci. Technol., vol. 90 (6), pp. 1814–1833, Sep. 2024. https://doi.org/10.2166/wst.2024.304

COLLABORATIVE FASHION CONSUMPTION: DIGITAL RESALE PLATFORMS AS ENABLERS OF CIRCULAR FASHION

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Abstract: This paper examines digital resale platforms as key enablers of circular fashion within the broader field of collaborative fashion consumption. It starts from the premise that the fashion industry is moving, albeit unevenly, away from linear models based on ownership, rapid turnover, and disposal towards more circular systems organised around reuse, redistribution, and extended garment utilisation. In this transition, digital resale platforms are analysed as operational infrastructures that keep garments in circulation through authentication, pricing, listing, recirculation, and consumer interaction. The paper focuses on the organisational conditions that make resale viable at scale, including trust-building mechanisms, reverse logistics, quality control, product data management, and customer engagement. Methodologically, it draws on a qualitative comparison of two platform logics: a peer-to-peer model illustrated by Ganni and a buy-back/consignment model illustrated by Patagonia Worn Wear. The analysis further situates resale within the evolving European Union policy environment, particularly with regard to sustainable textiles, digital product information, consumer protection, and platform accountability. A brief contextual observation of the Moldovan market suggests that resale and exchange are currently mediated mainly through fragmented social-media channels rather than structured circular platforms, which points to the relevance of an open, multi-brand digital model with stronger traceability and customer-protection functions. It argues that digital resale platforms are not marginal secondary channels, but strategic infrastructures through which circular fashion acquires commercial, organisational, and regulatory form. In this way, the article contributes to current debates by linking platform-level resale models to the broader governance transformations shaping circular fashion in the European Union.

Key words: *collaborative consumption; circular fashion; resale platforms; reverse logistics; Digital Product Passport; EU textiles policy.*

1. INTRODUCTION

Circular fashion is emerging as a major direction in the contemporary fashion industry. In response to the environmental and economic limits of the linear ‘take-make-dispose’ model, businesses, policymakers, and consumers are paying greater attention to approaches that extend product life, reduce waste, and retain value within product cycles. Within this wider transition, collaborative fashion consumption has gained importance as a practical expression of circularity, shifting attention from ownership towards reuse, redistribution, and prolonged garment utilisation.

Among the mechanisms associated with collaborative fashion consumption, digital resale platforms have become especially prominent as enablers of circular fashion. They translate circular principles into market practice by supporting authentication, listing, pricing, resale, and consumer interaction, thereby extending product lifecycles and generating value beyond the sale of newly manufactured goods. Cases such as Ganni and Patagonia Worn Wear demonstrate how resale can be organised through distinct platform logics while remaining embedded in brand strategy.

This development matters because it reflects a broader redefinition of value creation in fashion. Under linear systems, value is tied mainly to the constant production and sale of new items. By contrast, circular fashion seeks to preserve the value embedded in garments for as long as possible through repeated use, repair, resale, remaking, and related forms of recirculation. In this sense, digital resale platforms function not as marginal sales channels, but as strategic infrastructures connecting consumer behaviour, brand management, and circular business innovation.

At the same time, resale platforms are shaped by wider regulatory and governance changes. In the European Union, the policy agenda on sustainable and circular textiles is evolving rapidly, with growing emphasis on product traceability, consumer protection, environmental claims, online platform accountability, and digital product information. Against this background, the article examines digital resale platforms as enablers of circular fashion, focusing on their operating logic, trust requirements, and policy implications within the emerging EU regulatory environment. Methodologically, it applies a qualitative comparative reading of two brand-led resale configurations, represented by Ganni and Patagonia Worn Wear.

The originality of this article lies in bringing together two levels of analysis that are often discussed separately: the operational logic of digital resale platforms and the emerging European Union regulatory framework for circular and digitalised fashion markets. In this sense, the paper does not approach resale merely as a secondary sales practice, but as a form of circular infrastructure shaped by platform design, trust mechanisms, product-data requirements, and governance obligations. Methodologically, the article applies a qualitative comparative case approach to two brand-led resale configurations, represented by Ganni and Patagonia Worn Wear. These cases were selected because they illustrate two contrasting yet influential logics of digital resale: peer-to-peer facilitation and buy-back/consignment under stronger brand control. The comparison is structured around four analytical dimensions: platform architecture, allocation of logistics responsibility, quality-control mechanisms, and the relationship between resale operations and regulatory preparedness.

2. DIGITAL RESALE PLATFORMS AS CIRCULAR INFRASTRUCTURE

2.1. From ownership to recirculation

Digital resale belongs to a broader shift from ownership-based consumption towards service-, access-, and reuse-oriented fashion practices. In this transition, value is increasingly linked to utility rather than mere possession. Consumers assess garments not only by novelty, but also by affordability, flexibility, and recirculation potential [1], [2]. Market analyses also indicate continuing growth in rental and second-hand segments, suggesting that recirculation is becoming an economically relevant part of the apparel market [2]. From a sustainability perspective, resale matters because it prolongs use and delays disposal in a sector facing growing waste-management pressure [3]. Yet its environmental contribution depends on operational conditions: poor product data, inconsistent quality control, and inefficient reverse logistics may weaken circular outcomes. Resale should therefore be treated as a managed system of value retention rather than simple re-commerce.

2.2. Platform architecture and operating models

A brand-led digital resale platform is more than an e-commerce extension. It combines a customer interface for pre-owned items, a seller module for simplified listing, and a back-end layer supporting authentication, classification, and traceability. In more advanced versions, seller portals can reduce friction by reusing historical product data, while back-end systems support condition grading, provenance checks, and standardised product presentation. Such architecture is essential because the platform must create trust without losing operational speed.

The comparison of Ganni and Patagonia Worn Wear illustrates two dominant resale logics [6], [7]. In peer-to-peer systems the brand mainly facilitates trust while the physical transfer occurs between users. In buy-back or consignment systems the brand takes possession of the garment, controls inspection and presentation, and resells it directly. The choice affects cost structure, quality assurance, data capture, and customer experience.

Table 1: *Comparison of peer-to-peer and buy-back resale models*

Criteria	Peer-to-peer model	Buy-back/consignment model
Brand role	Facilitator and trust intermediary	Direct resale operator
Logistics responsibility	Mainly distributed between users	Centralised under brand control
Quality control	More limited and variable	Higher and more standardised
Operational cost	Lower direct handling cost	Higher processing and presentation cost
Strategic advantage	Scalability and speed	Brand consistency and data capture

Source: author's synthesis based on [6], [7].

The analytical value of this comparison lies in showing that digital resale is not a uniform circular solution. Rather, different platform models redistribute control, cost, trust, and data capture in different ways. Peer-to-peer systems may offer greater scalability and lower direct handling costs, whereas buy-back and consignment models provide stronger brand control over quality, presentation, and customer experience. This distinction is important because it demonstrates that the contribution of resale to circular fashion depends not only on the existence of a digital platform, but also on the organisational design through which resale is implemented.

Regardless of model, viability depends on operational efficiency. Pricing should reflect garment condition, age, and demand; reverse logistics should limit handling costs; and communication should reduce the stigma sometimes attached to pre-owned fashion. Brands also need to consider how products are collected, assessed, cleaned, photographed, and relisted with minimal delay. Loyalty incentives, visible circularity benefits, and convenient return or drop-off options can reposition resale as a branded service rather than a discounted secondary channel.

3. EU POLICY IMPLICATIONS FOR FASHION RESALE

The policy environment for digital resale platforms is becoming more structured within the European Union. Circularity in textiles is no longer framed only as voluntary corporate responsibility, but as part of a broader agenda for product durability, resource efficiency, and digital-market accountability [4], [5].

The Eco-design for Sustainable Products Regulation establishes the framework for a *Digital Product Passport* for relevant product groups [8]. For resale platforms, this is strategically significant: structured data on composition, care, provenance, and repair can reduce information asymmetry, support authentication, and improve the grading of second-life products. Brands that invest early in interoperable product-data architecture may gain both operational and compliance advantages.

European textile policy is also increasing the importance of *take-back pathways and extended producer responsibility* as collection, sorting, and take-back systems. The EU Strategy for Sustainable and Circular Textiles and the revised waste-policy framework strengthen the logic of reuse before disposal and raise the strategic relevance of organised return flows [4], [9]. For brands, resale platforms may therefore function not only as revenue channels, but also as instruments for managing product responsibility after first sale.

Digital resale ecosystems also operate under stricter expectations regarding governance and substantiated communication. Claims linked to resale must be transparent and methodologically defensible, otherwise they risk becoming reputational liabilities rather than assets [5]. In parallel, platform accountability requirements in the Digital Services Act reinforce the need for mechanisms addressing counterfeit listings, illegal content, and marketplace transparency [10]. Regulatory readiness should therefore be treated as part of platform design rather than as an afterthought [11].

4. THE MOLDOVAN MARKET CASE AND IMPLICATIONS FOR OPEN PLATFORM DESIGN

4.1. Informal recirculation through social networks

Actually, the Moldovan market does not have a dedicated brand-led digital resale platform comparable to Ganni or Patagonia Worn Wear. Publicly visible digital circulation is concentrated instead in fragmented channels: local-brand aggregation is represented by DININIMA, while resale and exchange activity is visible mainly through Facebook groups and Instagram-based resale accounts [12]–[14]. This does not mean that secondary circulation is absent; rather, it suggests that it is organised informally and outside a platform architecture specifically designed for circular fashion.

These channels perform an important market function by enabling garments to reach second users at low transaction cost. However, they rarely provide the governance features associated with structured resale platforms. In practice, product descriptions are heterogeneous, condition grading is inconsistent, provenance is difficult to verify, and platform-level mechanisms for authentication, repair history, standardised returns, or dispute handling are weak or absent. As a result, recirculation exists, but it remains only partly traceable and institutionally underdeveloped. For circular fashion, this is a significant limitation because reuse takes place without the data capture, brand involvement, and consumer safeguards that would allow recirculation to become a systematic business model.

The wider e-commerce environment in Moldova nonetheless suggests that a more structured digital solution is feasible. Recent market reporting indicates continued growth in Moldovan e-commerce and strong consumer use of online purchasing channels [15]. In this context, the absence of a dedicated circular-fashion platform should be interpreted less as a lack of demand than as a gap in platform design and market organisation.

4.2. Towards an open digital platform for Moldovan brands

The comparative analysis of global cases points to a strategic direction relevant for Moldova: the development of an open, multi-brand digital platform through which local brands could combine primary sale, controlled resale, exchange, take-back, and repair-related communication within one interoperable environment. Unlike a single-brand system, an open platform would correspond better to the scale of the Moldovan market, where individual labels may not generate sufficient transaction volume to sustain separate resale infrastructures. Such a model could also build on existing initiatives that already aggregate local brands without yet offering structured second-life services [12].

The objective of such a platform should not be simply to digitise informal resale, but to formalise and govern it. Minimum functions would include standardised listing rules, verified seller identities, condition-grading categories, clear photo requirements, traceable transaction histories, and a channel for complaints or post-sale communication. A further design element could be garment-level QR identification. Even in simplified form, a QR code linked to a product record could connect information on composition, care, initial sale, repair history, and subsequent resale or take-back events. This would not constitute a full Digital Product Passport in the regulatory sense, but it would represent a practical traceability mechanism aligned with the broader European shift towards digital product information and platform accountability [8], [10].

For consumers, the value of such an approach lies in improved transparency and stronger procedural safeguards. For brands, the benefits would include better control over product presentation, clearer communication with customers, and the gradual accumulation of data on durability, returns, and second-life demand. In this sense, the study of global brand practices does not imply direct imitation. Rather, it provides a reference framework for building an open, context-appropriate digital infrastructure capable of connecting circular-fashion ambitions with the practical needs of Moldovan firms and clients.

For Moldova, such an open platform would be especially relevant because it could pool transaction volume across multiple brands rather than requiring each label to build its own closed resale system. This is a small-market solution: scale would be created collectively, while trust would be strengthened through common rules, shared data fields, and visible customer-protection procedures.

5. CONCLUSIONS

Brand-led digital resale platforms represent a concrete intersection between collaborative consumption, circular business models, and digital governance in fashion. Their significance lies not only in extending garment life, but also in reorganising how brands capture value after first sale. In this respect, resale is not simply an environmental add-on; it is a strategic mechanism through which circular fashion becomes commercially legible and operationally manageable. The contribution of this article lies in showing that digital resale platforms should be analysed not only as commercial channels, but also as governance-sensitive infrastructures located at the intersection of circular business innovation, brand strategy, and the evolving European regulatory environment.

The comparison between peer-to-peer and buy-back models shows that resale is not a single formula. Different platform architectures distribute control, cost, and responsibility in different ways, and each model requires a specific balance between user convenience and brand oversight. Successful resale initiatives therefore depend on coherent alignment between platform structure, logistics, pricing, and trust mechanisms.

From a policy perspective, the evolving European framework positions resale as an increasingly strategic organisational capability. Product data, take-back capability, substantiated claims, and digital governance are becoming essential features of competitive preparedness. Digital resale platforms should therefore be understood as circular infrastructure rather than short-term marketing innovation. Their long-term value lies in combining commercial recirculation with organisational readiness for a more regulated and sustainability-oriented fashion economy. For brands, this means that platform design, data architecture, and compliance capacity must develop together rather than sequentially.

Seen in this way, the rise of digital resale also signals a broader cultural shift in fashion. It normalises second-life value within mainstream brand environments and links consumer-facing innovation with policy-driven circularity objectives. For companies seeking long-term relevance in a more resource-constrained and regulated market, resale can therefore function as a practical bridge between circular fashion as an industry trend and circularity as an embedded business practice.

For a small market such as Moldova, the next logical step may not be the replication of separate single-brand platforms, but the development of an open digital infrastructure shared across local labels. If such a system integrates resale, exchange, take-back, repair communication, and simple QR-based product histories, it could convert currently fragmented social-media recirculation into a more traceable, customer-oriented, and governable circular ecosystem.

Seen in this way, digital resale platforms do not simply support circular fashion as a market trend; they help institutionalise it as a structured business and governance practice.

REFERENCES

[1] European Commission, A European Agenda for the Collaborative Economy, COM(2016) 356 final, Brussels, 2016.

[2] The Business Research Company, Online Clothing Rental Market Report 2026, 2026.

[3] M.-F. Dondea, E. Visileanu, M. C. Grosu, R. Scarlat and A. Vladu, “Textile waste management in Romania in the context of the circular economy,” Annals of the University of Oradea. Fascicle of Textiles, Leatherwork, vol. 26, no. 1, pp. 49-54, 2025.

[4] European Commission, EU Strategy for Sustainable and Circular Textiles, COM(2022) 141 final, Brussels, 2022.

[5] European Commission, A New Circular Economy Action Plan: For a Cleaner and More Competitive Europe, COM(2020) 98 final, Brussels, 2020.

[6] Ganni, Resale platform information, 2026.

[7] Patagonia, Worn Wear platform information, 2026.

[8] European Union, Regulation (EU) 2024/1781 establishing a framework for setting ecodesign requirements for sustainable products, 2024.

[9] European Commission, Revised Waste Framework Directive: textile sector circularity update, 2025.

[10] European Union, Digital Services Act: summary and implementation guidance, 2024.

[11] Liu, N., Lin, J., Guo, S., “Fashion platform operations in the sharing economy with digital technologies,” Annals of Operations Research, vol. 329, pp. 1175–1195, 2023.

[12] DININIMA, Homepage, 2026.

[13] Facebook Group, “Vânzări haine Republica Moldova”, 2026.

[14] Instagram, “Resale Moldova (@second_chance_md_)”, 2026.

[15] American Chamber of Commerce in Moldova, eCommerce Market in Moldova in 2025, 2025.

ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

COMPARATIVE STUDY ON THE TREATMENTS APPLIED TO ECOLOGICAL TEXTILE MATERIALS USED IN THE MANUFACTURE OF MATTRESS COVERS

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***Abstract:**. The use of organic natural fibres, such as organic cotton and hemp, reflects a sustainable and responsible direction in the textile industry, in the context of increasing awareness of the impact on the environment and the health of users. These materials, being grown without the use of pesticides, herbicides or other harmful chemicals, contribute to reducing the ecological footprint and promote a healthier and more responsible lifestyle. In the work, different materials for the manufacture of the two mattresses covers were treated and tested, using ecological natural fibers, in order to obtain basic information about the chemical process of treating these knitted materials. These treatments included, for example, the application of bio-based flame retardants, which are designed to provide fire-resistant properties without compromising the naturalness of the fibers and without introducing harmful chemicals. The components of the two mattresses covers were analyzed individually by cutting each layer, followed by collecting samples in small, appropriately labeled bags. Each sample was taken from its entire depth, from areas with a cross-section of about 1-2 cm. This paper also highlights the differences in finishing methods, depending on the composition of the knitted materials used to make mattress covers.*

***Key words:** natural organic fibers, organic cotton, mattress cover*

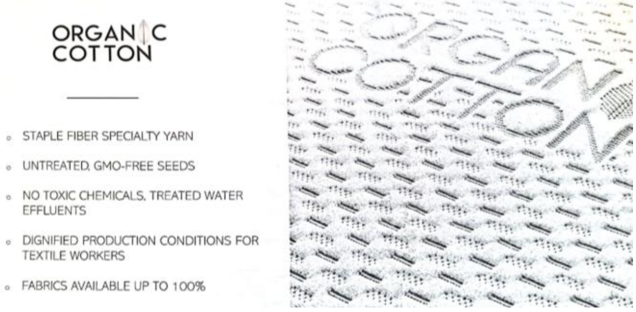
1. INTRODUCTION

California and U.S. regulations were established to protect consumers and prevent fires and accidents caused by flammable textiles and materials. These regulations require that textile products must not be more dangerous than those existing on the market before the introduction of new standards [1]. The inclusion of flame-resistant fibers in mattresses is determined by the flammability regulations of California and the USA, which require that all textiles and materials used in the construction of consumer goods meet certain safety standards in terms of flammability [2]. The use of flame-resistant fibers in mattresses poses a potential health risk, as they can produce harmful fumes and gases when exposed to high temperatures or flames [3]. Such a risk is associated with the development of respiratory diseases, such as chronic bronchitis or lung cancer. Even though the treatments used and the components of the mattress cover are designed to meet safety and environmental requirements, official certification and testing do not explicitly include them, which highlights a possible gap in the product evaluation process [4].

2. GENERAL INFORMATION

In this work, the materials used to make two mattress covers were analyzed and tested, with the aim of obtaining essential information regarding the chemical treatments applied to knitted materials from ecological natural fibers. This research aims to provide essential data on the chemical processing of fibers in new mattress covers [5], [6].

As a novelty, 100% natural fiber yarns composed of 85% organic cotton (BIO) and 15% hemp were used to knit a variant of the fabric. This choice reflects the commitment to meet the sustainability requirements of the textile industry.


ORGANIC
COTTON

- STAPLE FIBER SPECIALTY YARN
- UNTREATED, GMO-FREE SEEDS
- NO TOXIC CHEMICALS, TREATED WATER EFFLUENTS
- DIGNIFIED PRODUCTION CONDITIONS FOR TEXTILE WORKERS
- FABRICS AVAILABLE UP TO 100%

***Fig. 1**: Organic cotton*


***Fig. 2**: Cutting/stamping press G999*

The constituent components of the two mattresses covers were each subsampled by cutting each layer and then proceeding to collect samples in small, labeled bags. Each sample was sampled over its entire layer depth, with cross-section areas of about 1-2cm [7].

The preparation and analysis of the samples were carried out according to a standardized internal procedure, designed to ensure the consistency and reliability of the results in the evaluation of the fibrous content of the materials in the two mattress covers. This standardised methodology has been developed to ensure that each step of the preparation and analysis process is repeatable and accurate, thereby reducing variability in results and ensuring comparability between the samples tested. In the process of preparing the samples, the samples were extracted from the materials in the two mattress covers using a G999 cut/stamping press as shown in the **Fig. 2**.

This press was chosen for its ability to apply controlled and uniform pressure, thus ensuring homogeneous and representative samples for the entire material. The use of this press allowed the creation of precise sections, of standardized sizes and shapes, necessary for the subsequent stages of analysis. This methodological approach ensures that each step of the process has been controlled and documented, contributing to the transparency and reliability of the final results, which are essential for assessing the quality and conformity of the materials used in the production of mattresses

***Table 1:** Treatment of household cover (mattress) type 1*

Treatment	LIKROLL
Recipe	Citric Acid 0.2% Elastofin STO501 1.4%, Temp:130^{0}C
Request width	229-231 cm
Request weight	357-372 gr/m^2
Composition	25% Viscose from bamboo, 75%Pes
Color	Bleached+Natural

Table 2: *Treatment of household cover (mattress) type 2*

Treatment	**LIKROLL**
Recipe	Citric Acid 0.2% Elastofin STO501 1.6%, Bio-based F.R. EN 597 Part 2, Temp:130^0C
Request width	239-244 cm
Request weight	373-391 gr/m^2
Composition	85% Organic Cotton (BIO), 15%Hemp
Color	Natural

Fig. 3*: Treated material for household cover (mattress) type 1*

Fig. 4*: Treated material for household cover (mattress) type 2*

The main components of each mattress cover analysed, together with their compositions, are presented in Table 1 and Table 2. These covers, intended for home use, are made from blends of natural fibers, such as cotton and hemp, combined with additives and chemical treatments to meet safety and performance requirements [8]. In particular, the mixtures contain citric acid and elastofine, applied with a loading method known as 'pick-up', with a percentage of 100%. This process involves treatment at a controlled temperature of 130°C to ensure uniformity and efficiency of treatments. The essential difference between the two mattress covers lies in the Bio-based F.R. flame retardant treatment, applied according to the EN 597 Part 2 standard. This treatment includes rigorous cigarette and small flame tests aimed at increasing the fire resistance of materials, especially cotton and hemp fibers, which are naturally flammable. Natural fibers, being easily flammable, require such treatments to ensure compliance with safety requirements and reduce the risk of fire in daily use.

5. CONCLUSIONS

It is important to note that, in the process of fireproof treatment, the criteria for bio certification of materials have been preserved. This way, the use of harmful or harmful chemicals for the environment was avoided, maintaining the ecological character of the products, according to the requirements for bio and sustainable materials.

This treatment process has been carried out in such a way that it does not compromise the natural properties of the fibers, such as permeability and strength, while ensuring compliance with safety and quality standards.

In conclusion, the combination of these components and treatments ensures a safe, durable and eco-friendly mattress suitable for home use and environmentally conscious consumers.

REFERENCES

[1] Stapleton H.M., Klosterhaus S., Keller A., Ferguson P.L., van Bergen S., Cooper E., Webster T.F., Blum A. Identification of Flame Retardants in Polyurethane Foam Collected from Baby Products. Environ. Sci. Technol. 2011;45:5323–5331. doi: 10.1021/es2007462.

[2] BHGS (California Bureau of Household Goods and Services) Technical Bulletin 117-Residential Upholstered Furniture Standard Fact Sheet. [accessed on 06 aprilie 2026]; Available online: https://bhgs.dca.ca.gov/industry/tb_117_faq_sheet.pdf.

[3] Bohm G., Șuteu, M.D., Doble, L., Fetea, L. - ” Treatments applied to the materials in the composition of mattress covers” Annals of the University of Oradea, Fascicle of Textiles, Leatherwork, ISSN 1843-813X, Oradea, Volume 26, 2025, No. 2, pp. 17-20.

[4] Fiberglass and Other Flame-Resistant Fibers in Mattress Covers Jeff Wagner, Jefferson Fowles, Tracy Barreau Int J Environ Res Public Health. 2022 Feb; 19(3): 1695. Published online 2022 Feb 1. doi: 10.3390/ijerph19031695 PMCID: PMC8835476

[5] Bohm G., Șuteu, M.D., Doble, L., Fetea, L. - ” Analysis of different treatments of materials intended for mattress covers” Annals of the University of Oradea, Fascicle of Textiles, Leatherwork, ISSN 1843-813X, Oradea, Volume 25, 2024, No. 1, pp. 19-22.

[6] Bohm G., Șuteu, M.D., Doble, L., Fetea, L., Porav V. - ” Comparative analysis of the treatments attached to the materials in the composition of the mattress covers” Annals of the University of Oradea, Fascicle of Textiles, Leatherwork, ISSN 1843-813X, Oradea, Volume 24, 2023, No. 2, pp. 19-22.

[7] Șuteu, M.D, Bohm G., Doble, L. - ” Study on the treatment of textile materials for the manufacture of mattress covers” Annals of the University of Oradea, Fascicle of Textiles, Leatherwork, ISSN 1843-813X, Oradea, Volume 23, 2022, No. 2, pp. 71-74.

[8] OEKO-TEX® STANDARD 100, 3rd ed.; OEKO-TEX Service GmbH: Zurich, Switzerland, 2025.

ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

TRADITIONAL TEXTILE DYEING TECHNIQUES AS SUSTAINABLE SOLUTION IN CONTEMPORARY DESIGN

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Abstract: *The study analyzes the potential of traditional textile dyeing techniques as a resource for sustainability and as a pedagogical instrument in contemporary design, based on experimental protocols and textile samples developed within a scientific and educational context. The empirical material highlights a chromatic palette constructed through local or accessible plant-based sources, simple extraction methods, and variable fixation processes, revealing visible differences between natural and synthetic substrates.*

The experiments revealed significant differences between natural and synthetic textile substrates, with natural fibers showing superior dye absorption and color stability. The use of different mordants influenced both chromatic intensity and tonal variation: acetic acid preserved warmer shades, while iron-based mordants generated darker grey and khaki tones. The resulting palette demonstrated a wide diversity of organic colors and confirmed the potential of natural dyeing techniques for sustainable and educational applications in contemporary textile design.

The article interprets these results in relation to current frameworks concerning circularity and textile wet processing, arguing that the sustainable relevance of traditional techniques depends not only on the source of the dye, but also on process control, impact reduction, and the capacity to design for durability.

The proposed approach is interdisciplinary, situated at the intersection of design and heritage, aiming to

Key words: *textile design; fashion design; textile heritage; natural dyeing; color; interdisciplinarity*.

1. INTRODUCTION

In the current context of contemporary design, marked by ecological imperatives and the need to redefine the relationship between production and consumption, traditional textile practices are regaining attention in research as active resources for sustainable innovation [1]. Increasing concerns regarding pollution generated by textile wet processing, excessive water consumption, and the short life cycle of fashion products have encouraged designers and researchers to explore alternative methods based on local resources, circularity, and material responsibility.

Within the present design paradigm, heritage is no longer perceived as a static formal repertoire, but rather as an open system of meanings, susceptible to reinterpretation. In this framework, traditional dyeing techniques are understood not only as utilitarian procedures, but also as forms of accumulated material intelligence, reflecting the direct relationship between humans, the environment, and resources [2], [7]. The integration of these practices into contemporary design implies a shift in emphasis: from product to process; from standardization to variability; from absolute control to co-creation with the material. Thus, color obtained through natural dyeing functions both as an aesthetic attribute and as the result of a dialogue between material, time, and human intervention, shaping an aesthetic of controlled imperfection and authenticity.

At the same time, current approaches to sustainable textile design increasingly emphasize interdisciplinarity, practice-based research, and the educational dimension of material experimentation. Traditional dyeing techniques are therefore reconsidered not only as historical craft practices, but also as instruments for developing ecological awareness and alternative creative methodologies within design education [8]. In this context, experimentation becomes both a technical and reflective process, capable of generating new relationships between heritage, innovation, and sustainability.

In this sense, the revitalization of textile heritage involves not only the preservation of historical techniques, but also their critical reinterpretation and integration into contemporary design processes, where materiality, process, and cultural meaning become inseparable. Accordingly, the study proposes an analysis of natural dyeing experiments conducted in a scientific and educational context, based on the use of plant-based dyes, as well as variations in color fixation achieved through accessible means. Beyond its technical dimension, the approach is framed as practice-based artistic research, in which the visual outcome becomes an instrument of knowledge [8].

2. RESEARCH DESIGN AND ANALYTICAL FRAMEWORK

2.1 Experimental approach

The experimental approach was based on the use of accessible plant resources, particularly: oak leaves (both fresh and dried), onion skins, red cabbage, and spontaneous plants (including leaves and vegetal residues). The dyeing processes included thermal extraction (boiling), maceration, two-stage dyeing (boiling and subsequent immersion), and fixation.

An essential aspect highlighted in the working journals is the duration of the processes (ranging from several hours to several days), which directly influences the intensity and stability of the color. Significant differences were also observed between natural and synthetic textile materials, with natural fibers demonstrating a higher capacity for absorption and color fixation. The methodology does not aim to standardize results; on the contrary, it values variation as a design principle. The experimental dyeing tests were carried out on both natural and synthetic textile substrates. The natural fabrics included 100% cotton, linen, and wool samples, while the synthetic category included polyester-based fabrics. The textile samples were selected in order to compare differences in dye absorption, chromatic intensity, and color fastness depending on fiber composition and surface structure.

2.2 Executive Summary

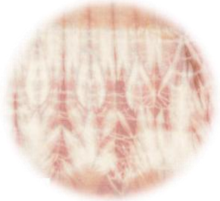
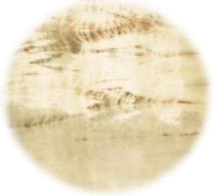
The present analysis brings together experimental data extracted from project protocols (2025–2026) concerning the production of color from plant-based sources (agro-waste, leaves/bark, spices/vegetables), alongside official sources (UNEP, ISO, PLOS; BAT/BREF documentation) [1], in order to formulate a techno-scientific argument: traditional dyeing and botanical printing techniques can reduce chemical risk and support circularity, but only if they are rigorously managed in terms of water and energy use, reproducibility, and effluent control.

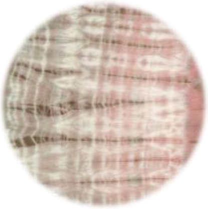
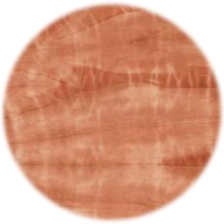
From the perspective of the international framework, the issue is both legitimate and highly relevant. United Nations Environment Programme (UNEP) indicates that the transformation of the textile sector depends on three interconnected directions: shifting consumption patterns, improving practices, and investing in infrastructure, while wet processing remains a critical node of environmental impact. A study published in Public Library of Science on 18 textile processing facilities reports an average consumption of 164 L of water and 449 g of chemicals per 1 kg of processed material. This explains why even a design-oriented study must address, in a clear and informed manner, the dye bath, energy input, mordants, and effluents, rather than focusing solely on visual outcomes [2].

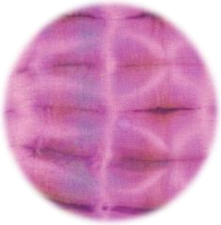
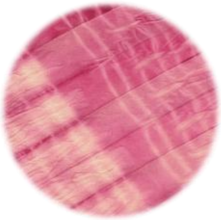
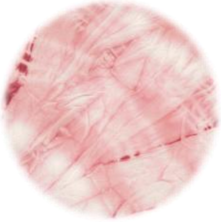
3. EXPERIMENTAL CORPUS AND DATA SYNTHESIS

The experimental data consist of protocols derived from practice-based research, and the table below presents a synthetic overview of selected relevant results.

Table 1: *Synthesis of Experimental Results on Textile Dyeing with Natural Colorants*

Source (dye)	***Type of raw material***	***Method***	***Mordant/fixative***	***Observations on color and stability***	***Examples of samples***
Red grapes (crushed)	*Agro-waste / fruit*	*Boiling -20 min, + $FeSO_4$ (10 g/300 ml H_2O)*	*CH_3COOH (6%) (150 ml/1000 ml H_2O) Aging – 5 days*	*Reddish-brown shades (15 samples), stabilize after fixation*	
Green quince leaves	*Agro-waste/ leaves*	*Boiling -25 min*	*$FeSO_4$ (10 g/300 ml H_2O) Aging – 5 days*	*Ochre – pale yellow – cappuccino shades (18 samples) stabilize after fixation*	
Quince leaves (finely chopped)	*Agro-waste /leaves*	*Boiling - 20 min + 14 hours immersion in the dye bath*	*CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 5 days*	*Pink - ochre – cappuccino; (12 samples) on natural samples, the shades remain more intense than on synthetic ones*	
Nectarine leaves	*Agro-waste /leaves*	*Boiling - 20 min*	*CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 5 days*	*Ochre – cappuccino shades (16 samples) stabilize after fixation*	
Pear leaves	*Agro-waste /leaves*	*Boiling -30 min*	*CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 5 days*	*Ochre–grey, slightly subdued shades (10 samples), good stability*	

Oak leaves	*Leaves*	*Boiling -30 min*	*$FeSO_4$ (10 g/300 ml H_2O) Aging – 5 days*	*Green–khaki shades (21 samples), very good stability*	
Rowan berries	*Agro-waste / fruit*	*Boiling -30 min*	*Left - $FeSO_4$ (10 g/300 ml H_2O) Right- CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 5 days*	*Left – pink; right – beige-grey (14 samples), good stability on natural fibers*	
Dried elderberries	*Agro-waste / fruit*	*Boiling - 30 min*	*$FeSO_4$ (10 g/300 ml H_2O) Aging – 5 days*	*Grey–beige with a cool undertone (18 samples), low stability*	
Oak tree bark	*Agro-waste*	*Boiling -35 min + 14 hours immersion in the dye bath*	*KOH (100ml/1000 ml H_2O)*	*Brown–beige shades (13 samples), good stability*	
Apple tree bark	*Agro-waste*	*Boiling -35 min + 14 hours immersion in the dye bath*	*CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 2 days*	*Ochre–light brown shades (24 samples), very good stability*	
Brown onion peels	*Agro-waste*	*Boiling -35 min*	*CH_3COOH (6%) (150 ml/1000 ml H_2O) Aging – 2 days*	*Ochre–pink–brown shades (15 samples), very good stability*	
Plane tree bark	*Agro-waste*	*Soaking (10 hours) Boiling -40 min+ 48 hours immersion in the dye bath*	*$FeSO_4$ (10 g/300 ml H_2O) Aging – 3 days*	*Ochre–cappuccino and ochre–khaki shades (14 samples), good stability*	

Turmeric	*Spices*	*Boiling - 60 min*	*CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 5 days)*	*Pale yellow–brown shades (8 samples), good stability*	
Turmeric	*Spices*	*Dissolution + short heating (5–7 min)*	*CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 1 days*	*Intense yellow (6 samples) good stability*	
Red onion peels	*Agro-waste*	*Boiling -50 min*	*CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 5 days*	*Ochre–reddish–brown–khaki shades (24 samples), very good stability*	
Red cabbage	*Agro-waste Vegetable*	*Boiling -60 min*	*CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 5 days*	*Purple shades (14 samples), low stability*	
Hibiscus flowers	*Agro-waste*	*Boiling -60 min*	*CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 5 days*	*Burgundy shades (12 samples), good stability*	
Beetroot	*Agro-waste*	*Boiling -20 min*	*CH3COOH (6%) (150 ml/1000 ml H2O) Aging – 5 days*	*Light pink–burgundy shades (13 samples), low stability*	
Dried nettle	*Leaves*	*Boiling -40 min*	*Without fixation Aging – 4 days*	*Beige–light ochre shades (14 samples), good stability*	

The reading of the table suggests several design insights:

- The mordant functions not only as a technical agent, but also as an aesthetic one: acetic acid often preserves warm tones, while iron shifts the palette toward greys, khaki, and muted shades.
- Many observations indicate a perceptible difference between natural and synthetic substrates (textile materials), which transforms fiber selection into a conceptual decision, rather than merely an executional one.
- The series of samples can function as a library of chromatic surfaces, useful in fashion and textile design, particularly for compositional exercises within the educational process [3].

4. SUSTAINABILITY ASSESSMENT BY FEEDSTOK CATEGORIES

Agro-waste—such as onion skins, coffee grounds, and fruit residues—represents, among all categories, the most easily justifiable option within the logic of the circular economy. It valorizes an already existing waste stream and reduces dependence on raw materials cultivated specifically for dyeing purposes. However, this advantage is maintained only if the process remains measured and controlled: the protocols indicate repeated boiling and distinct fixation stages, which imply water and energy consumption even at a small scale. In this context, comparison with industrial wet processing becomes relevant: when the literature reports averages of 164 L of water/kg and 449 g of chemicals/kg, the design studio should not replicate industrial practices, but rather learn to make its own resource consumption visible through simple indicators [1]

Leaves and bark present a different type of potential: they introduce into the process both pigment and memory. From a technical perspective, many of these sources are rich in compounds that can support color fixation, making them promising for biomordanting solutions as well. At the same time, this category requires careful attention to extraction: experiments show that prolonged boiling (up to one hour) is often necessary. From a forward-looking perspective, there is room for long-duration soaking experiments. In BREF terms, this reflects precisely the logic of a process that must be conceived in relation to resource consumption and emissions, not solely through its visual outcome [4]

Spices and vegetables offer the most visually striking colors, but also exhibit the greatest vulnerability to process variations. Turmeric produces an intense yellow; however, experiments show that the introduction of iron can rapidly desaturate it. Red cabbage is highly sensitive to pH changes and to its interaction with different textile substrates. In this case, sustainability must be addressed not only in terms of natural origin, but also in relation to the durability of the aesthetic effect: an unstable color reduces the product’s lifespan and may undermine the very principle of responsible consumption. The United Nations Environment Programme report emphasizes precisely those practices that enhance circularity and extend the lifespan of materials [1].

Across all three categories, chemicals remain the critical point. The protocols include acetic acid, lye, and iron salts. For iron sulfate, the European Chemicals Agency indicates in its substance information that notifications under REACH Regulation identify it as harmful to aquatic life with long-lasting effects. This does not preclude its use in workshop settings, but it does require discipline: minimal dosing, separate collection, neutralization, and the avoidance of uncontrolled discharge [5].

The comparison with industry must be approached with caution. A textile design laboratory cannot—and should not—compete with an industrial facility; however, an analogy based on Life Cycle Assessment is useful. International Organization for Standardization defines, through ISO 14040 and ISO 14044, the framework for life cycle assessment: goal and scope, system boundaries, inventory analysis, impact assessment, and interpretation. For the proposed experiments, a simplified LCA is sufficient [6].

At the industrial level, the BREF document for textiles developed by the Joint Research Centre of the European Commission explicitly states that the scope covers pre-treatment processes such as washing, bleaching, mercerization, and the dyeing of fibers and textiles. This reference does not alter the nature of the experiment, but it provides it with a mature framework, as the project operates at an educational scale within a domain that, at an industrial level, is governed by the logic of Best Available Techniques, resource consumption, and emissions [1].

5. RESULT, INTERPRETATION AND FUTURE TESTING DIRECTIONS

5.1. Results and Visual Interpretation

From a design perspective, the chromatic variations obtained through the experiments represent opportunities for constructing unique visual identities, where each piece becomes non-reproducible.

The analysis of textile samples reveals a rich chromatic palette, characterized by organic hues: tones of yellow, ochre, and cappuccino (onion skins), grey-green and brown shades (oak leaves), as well as variations of purple, grey, and desaturated tones (red cabbage, depending on fixation).

A significant element is the influence of mordants on color: acetic acid preserves warmer and lighter tones, while iron salts generate darker shades, shifting toward grey or khaki.

It was also observed that natural materials produce deeper and more stable colors, whereas synthetic materials result in paler and less durable outcomes.

5.2. Testing Perspectives

One of the most promising perspectives, formulated following experiments with biopigment dyeing, is the gradual transition toward biomordants. A recent review on biomordants indicates that natural materials can reduce dependence on chemical mordanting while supporting color fastness without eliminating technical control. In the present project's experiments, leaves and bark rich in tannin compounds prove to be valuable resources for this stage, especially when combined with the agro-waste materials already tested [7, 9].

Another direction concerns the optimization of extraction processes. Recent literature shows that ultrasound and microwave-assisted extraction can shorten processing time and reduce energy consumption; where such equipment is not available, controlled maceration followed by short heating can achieve similar results.

The experimental results support the idea that traditional dyeing techniques can contribute to reducing environmental impact through: the use of local and renewable resources; decreased reliance on synthetic dyes; and the reduction of pollution associated with industrial processes. However, the relevance of these practices does not reside exclusively in ecological parameters, but rather in their capacity to redefine the relationship between the designer and the material. Sustainability thus becomes not only a set of technical solutions, but also a cultural and ethical positioning that prioritizes conscious and responsible processes.

The multidisciplinary character of textile research—explicitly articulated through the importance of traditional methods of production, dyeing, and maintenance, as well as the preservation and promotion of textile art and the integration of results into the educational process—is essential for the development of an ecological direction and the promotion of responsible and sustainable consumption. In this study, interdisciplinarity is not merely declarative; it becomes a method, supported by sample sheets, metadata, and minimal testing protocols. Traditional dyeing is not only a practice, but also a design principle: materials are conceived to evolve over time, while patina and tonal shifts become part of the product's identity.

The role of small-scale, university-based workshops, for instance, can be understood as a contemporary laboratory of living heritage, capable of producing prototypes, micro-collections, and educational resources. In this way, the training of the contemporary designer shapes the educational dimension of the study. The involvement of students in such experiments fosters: the development of sensitivity toward materials; the understanding of processes, not only outcomes; and the acceptance of variability as an integral part of the creative process. In this context, the workshop becomes a space of research, and experimentation—an essential pedagogical instrument. Students not only reproduce techniques, but also learn to observe, interpret, and integrate results into their own design language. This approach contributes to shaping a generation of designers who operate not solely within the logic of production, but increasingly within that of cultural and ecological responsibility [8].

5. CONCLUSIONS

The experimental results demonstrate that traditional dyeing techniques can support a credible discourse on sustainability only when they are approached simultaneously as heritage, as a design method, and as a responsible practice. Plant-based material alone does not guarantee sustainability; rather, it is the manner in which it is extracted, fixed, measured, and integrated into a culture of durable use that defines its relevance. This also represents the core pedagogical stake—the formation of designers who understand color not merely as an effect, but as a relationship between resource, process, and the subsequent life of the object.

The integration of these practices into design education contributes to the development of an interdisciplinary perspective, in which heritage, materiality, and innovation coexist. In this way, sustainability becomes a form of design culture, constructed through experience, reflection, and responsibility.

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REFERENCES

[1] L. Petrie, *Sustainability and Circularity in the Textile Value Chain*, United Nations Environment Programme, 2023, pp. 17-36, [Online]. Available https://www.unep.org

[2] B. Pizzicato, S. Pacifico, D. Cayuela, G. Mijas , M. Riba-Moliner, *Advancements in Sustainable Natural Dyes for Textile Applications:*Review, https://pmc.ncbi.nlm.nih.gov/articles/PMC10458907/

[3] I. Savitcaia-Baraghin, *The technique of natural dye printing*, nr.2, 2022. [Online]. Available 168172445622.SavitkaiaBaraghin_Tehnica_imprimarii_cu_coloranti.pdf

[4] Roth, J., Zerger, B., De Geeter, D., Gómez Benavides, J., Roudier, *Best Available Techniques (BAT) Reference Document for the Textiles Industry*, 2023, [Online]. Available TXT_BREF_2023_for_publishing ISSN 1831-9424_final_1_revised.pdf

[5] ECHA's public chemicals database, [Online]. Available: https://echa.europa.eu

[6] Textiles — Tests for colour fastness — Part C06: *Colour fastness to domestic and commercial laundering*, ISO 105-C06:2010(en), [Online]. Available ISO 105-C06:2010(en)

[7] Benli H. *Investigation of natural mordants, Bio-mordants: a review,* [Online]. Available https://pmc.ncbi.nlm.nih.gov/articles/PMC10948525/

[8] A. Tocarciuc, *Tradition and innovations in the textile art of Moldova, Summary of the Doctoral Thesis in History*, 2024, [Online]. 21(3), pp. 876–880. Available: https://anacec.md/files/Tocarciuc-rezumat.pdf

[9] Budeanu R. *Colour analysis in the CIE Lab space regarding the dyeing with weld and madder dyes.* Annals of the University of Oradea. Fascicle of Textiles, Leatherwork 2021, 22(2), pp. 11–16. [Online]. Available AUO_FTL_Vol 22-No2-2021.pdf

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18	**COMPARATIVE STUDY ON THE TREATMENTS APPLIED TO ECOLOGICAL TEXTILE MATERIALS USED IN THE MANUFACTURE OF MATTRESS COVERS**	**ŞUTEU Marius Darius[1], BOHM Gabriella[1], DOBLE Liliana[1], FETEA Lucian[2]**	[1]University of Oradea, Faculty of Energy Engineering and Industrial Management, Department Textiles, Leather and Industrial Management, 410058, Oradea, România [2]Lava Knitting srl, Eurobusiness Parc P.P. Carp street 23, 410605, Oradea, România	**141**
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