Sustainable knitwear design: analysis of the impact of engineered structures on functional properties

Živa Zupin[1], Antonija Petrov[2,*], Ivana Salopek Čubrić[2], Goran Čubrić[2], Vesna Marija Potočić Matković[2]
[1] University of Ljubljana, Faculty of Natural Sciences and Engineering, Ljubljana, Slovenia
[2] University of Zagreb Faculty of Textile Technology, Zagreb, Croatia
* Corresponding author: antonija.petrov@ttf.unizg.hr

Received: January 18, 2026
Accepted: February 23, 2026
UDC 677.31.025:677.075:677.017

This work is licensed under a Creative Commons Attribution 4.0 International License

Original scientific paper**

In today's world, where the need for sustainable materials is widely recognized, the demand for the design and production of high-quality textile structures with enhanced properties is increasing. To meet these requirements, it is necessary to carefully consider all aspects of material selection, structural design, and product functionality. After a long period of reduced use, wool is once again attracting attention due to its unique properties, encouraging new efforts to utilize its advantages in the development of functional materials. This paper investigates the relationship between the structure and properties of different knitted fabrics produced using wool yarn. As part of the study, a series of various knitted structures was produced, followed by an examination of a range of physical and mechanical properties. The results showed that thickness largely depends on the structure of the knitted fabric, while surface roughness varies between individual structures and between the front and back of the fabric. The dynamics of wetting and drying confirm that more open structures wet and dry faster, whereas denser structures wet and dry more slowly. The knitted structure influences the air permeability of the fabrics; denser structures have lower air permeability. Among the tested samples, the best elasticity and the least reduction of force are found in fabrics made with double jersey and rib double jersey 2+2 structures.

Keywords: *sustainability; wool; yarn; knitted fabric; functional properties*

Izvorni znanstveni rad**

Održivi dizajn pletiva: analiza utjecaja projektiranih struktura na funkcionalna svojstva

U današnjem svijetu, u kojem je potreba za održivim materijalima široko prepoznata, raste potražnja za dizajnom i proizvodnjom visokokvalitetnih tekstilnih struktura poboljšanih svojstava. Kako bi se ispunili ti zahtjevi, potrebno je pažljivo razmotriti sve aspekte odabira materijala, konstrukcijskog dizajna i funkcionalnosti proizvoda. Nakon dugog razdoblja smanjene uporabe, vuna ponovno privlači pozornost zbog svojih jedinstvenih svojstava, potičući nova nastojanja da se njezine prednosti iskoriste u razvoju funkcionalnih materijala. Ovaj se rad bavi istraživanjem odnosa između strukture i svojstava različitih pletiva proizvedenih korištenjem vunene pređe. Istražen je utjecaj različitih pletenih struktura na ponašanje vunenih pletiva izrađenih pod jednakim proizvodnim uvjetima, s ciljem dobivanja uvida u njihove funkcionalne i dizajnerske potencijale. Izrađen je niz različitih pletenih struktura kojima su ispitana fizikalno-mehanička svojstva. Rezultati su pokazali da je debljina u velikoj mjeri ovisna o strukturi pletiva, a površinska hrapavost razlikuje se kako među pojedinim strukturama, tako i između lica i naličja pletiva. Dinamika kvašenja i sušenja potvrđuje da otvorenije strukture pogoduju bržem kvašenju i sušenju, dok se gušće strukture sporije kvase i suše. Struktura pletiva utječe na propusnost zraka pletiva na način da gušće strukture omogućavaju manju propusnost zraka. Od ispitanih uzoraka, najbolju elastičnost, uz najmanju sfernu deformaciju, imaju pletiva izrađena u glatkom desno-desnom prepletu te desno-desna rebrasta 2+2 pletiva.

Ključne riječi: *održivost; vuna; pređa; pletivo; funkcionalna svojstva*

**Paper presented at the *18th Scientific-Professional Symposium Textile Science and Economy*, Jan 27, 2026, Zagreb, Croatia

1. Introduction

In today's circumstances, where sustainability and environmentally responsible material selection are coming to the forefront, the textile industry is facing increasing demands for the development of structures that combine high quality with enhanced functional properties. Achieving such goals requires a thorough understanding of the interaction between fiber type, yarn properties, and the construction of the fabric structure, since these factors significantly shape the final behavior of textile products. Among natural fibers, wool has once again emerged as a material of particular interest. After a period of reduced use, mainly due to the dominance of synthetic fibers, wool is being re-evaluated for its advantages, such as biodegradability, thermal regulation capability, elasticity, and effective moisture management. This renewed interest has encouraged more intensive research into its potential for the development of advanced and functional textile solutions.

A review of the literature shows that wool knitted fabrics have significant potential in the field of functional textile structures due to their ability to manage moisture and heat. Hu et al. [1] investigated wool knitted fabrics that respond to increased moisture levels by opening pores, enabling faster sweat transport and contributing to a cooling sensation, while in dry conditions they provide thermal insulation. The structural adaptability of such knitted fabrics highlights wool as a suitable material for garments intended for variable climatic conditions. Similarly, Zhou et al. [2] demonstrated that moisture transport and distribution properties depend on the construction and composition of the knitted fabric. A comparison of 100% wool knitted fabrics and blends of wool with polyester and cotton confirmed that certain fiber combinations improve moisture management capability, which directly affects wearer comfort. Research by Nawaz et al. [3] further emphasized the importance of thickness, porosity, and knitted fabric construction in the transfer of heat and water vapor. Wool knitted fabrics and their blends proved to be the most favorable for maintaining thermal comfort, confirming the importance of proper fiber selection and structural parameters of knitted fabrics when designing functional textile layers. Troynikov and Wardiningsih [4] found that blending wool fibers with polyester or bamboo fibers significantly improves moisture management compared to fabrics made exclusively from wool fibers. In this study, wool/bamboo combinations showed the most balanced properties on both the skin-facing and outer surfaces, and five out of nine analyzed samples were classified as effective moisture-management knitted fabrics. Kejkar and Dhore [5] point out that wool fibers can be successfully integrated into multilayer constructions but emphasize that functionality does not depend solely on the type of fiber; rather, it results from the combination of fibers, knitted fabric structure, and applied finishing processes.

In this context, the aim of the research presented in this paper is to examine the relationship between the structure and properties of knitted fabrics produced exclusively from 100% wool yarn. Therefore, a series of knitted structures was produced and subjected to a comprehensive evaluation of their physical and mechanical properties, part of which is presented in this paper. A systematic comparison of the results obtained for different structures provides insight into the influence of changes in knitted structure design on the properties of the final product in practical application.

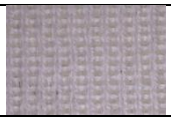
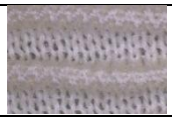
2. Experimental part

2.1. Materials and methodology

For the purpose of the research, six knitted samples were designed and produced on a Shima Seiki SES 122 RT knitting machine, gauge 12E. All samples were made from 100% wool with a linear density of 66 tex in six different knitted structures, as presented in Table 1. All samples were produced under the same conditions.

As part of the experimental section of the study, the thickness, surface roughness, wetting and drying dynamics, air permeability, and elasticity of the knitted fabrics were examined.

Tab.1 Sample description

Sample	KF1	KF2	KF3	KF4	KF5	KF6
Knitted structure	Double jersey	Single jersey Mock rib 3+3	Double jersey - wave	Rib double jersey 2+2	Rib double jersey 2+2 with double tuck stiches	Double jersey circular
Photo						

The thickness of the knitted fabrics was measured using a DM-2000 thickness gauge manufactured by Wolf Messtechnik GmbH, Germany, following the method described in the ISO 5084:1996 standard [6]. During testing, the samples were subjected to a pressure of 0.5 kPa, and a total of 10 measurements were taken at different locations on the horizontally positioned sample.

Surface roughness was measured using a PCE-RT 2000 roughness tester manufactured by PCE Instruments, UK. The measurements were carried out on both the face and the back side of the knitted fabric, as well as in the wale and course directions.

The investigation of wetting and drying dynamics was conducted on samples measuring 100 × 100 mm. Due to the pronounced tendency of knitted fabrics to curl at the edges, the samples were stabilized during testing using two circular metal frames, between which the material was fixed. Onto the prepared sample, 0.5 ml of distilled water was applied using a micropipette, and the time required for the liquid to distribute within the knitted fabric was recorded.

The area of the wet region was determined by analyzing digital images taken with a Kodak PixPro FZ45 compact digital camera using the Photo-Measure software. The wetting rate was calculated based on the measured area and time.

The drying time was determined using an infrared thermographic camera TESTO 872, manufactured by Testo SE & Co. KGaA, Germany. By monitoring temperature differences, the device enables a clear distinction between wet and dry areas. The dry state was defined as the moment when thermal homogeneity of the sample was achieved, allowing for an objective and reliable determination of the end of the drying process.

Air permeability was measured using an Air-Tronic B air permeability testing device (MESDAN, Italy), as prescribed by the standard [7]. The measurement area was 20 cm² and the pressure drop was 100 Pa. Ten measurements were performed for each sample of air flow in l/min. The air permeability was calculated according to equation 1:

$$R = \frac{\overline{q_v}}{A} \times 167 \quad (1)$$

Where:
R – air permeability [mm/s]
$\overline{q_v}$ – average air flow [l/min]
A – sample area [cm^2].

The elasticity of the knitted fabrics was tested using a multiaxial test on an Instron 5566 dynamometer (Instron, UK) in accordance with the adapted standard SIST EN 14704-2:2007. The specimens were clamped into a fixed ring with a diameter of 45 mm and stretched with a ball with a diameter of 40 mm. The clamp speed was 500 mm/min, and the maximum load on the tested samples was 10 N. The samples were loaded five times; in the first stretching cycle, the deformation – elongation at a load of 0.2 N was measured. In the fifth cycle, the specimen was loaded with 10 N, the load was held for 60 s, the test piece was unloaded and held in an unloaded state for 60 s, then a control cycle was performed and the deformation – elongation at a load of 0.2 N – was recorded. Five measurements were performed for each sample. For each measurement, a graph was plotted. The values, such as extension under a load of 0.2 N in the first stretching cycle [mm] (l), reduction of force in the fifth stretching cycle, after 60 seconds of rest [N] (F), and remaining extension in the control cycle under a load of 0.2 N [mm] (x), were read from the graph, and permanent elongation (TR) was calculated according to equation 2:

$$TR = x - l \quad (2)$$

Where:
TR permanent elongation [mm]
x remaining extension in the control cycle under a load of 0.2 N [mm]
L extension under a load of 0.2 N in the first stretching cycle [mm].

3. Results and discussion

The results of the knitted fabric thickness measurements are presented in Fig.1. As can be seen from the figure, the differences in thickness between the designed structures are significant, ranging from 1.958 to 4.195 mm. This range of thicknesses, achieved through the design of different structures, ensures diversity within the observed group, which significantly affects their physical and mechanical properties, as discussed further in the paper. In addition, it enables precise adjustment of the designed and produced knitted structures to specific applications.

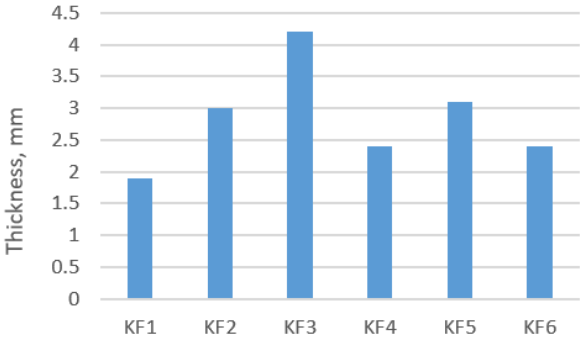


Fig.1 Thickness

Tab.1 Results of surface roughness measurements of knitted structures

Sample												
	KF 1		**KF 2**		**KF 3**		**KF 4**		**KF 5**		**KF 6**	
Direction	course	wale	course	wale	course	wale	course	wale	course	wale	course	wale
Face	25.51	13.07	21.81	13.71	12.55	17.67	20.66	16.75	21.14	20.58	13.93	19.32
Back	26.22	16.28	11.33	15.73	27.20	4.27	22.38	17.09	29.21	16.63	14.46	22.48

The results of the surface roughness measurements are presented in Table 2 and indicate considerable differences between measurements taken on the face and the back side of the material, as well as between the different designed structures (KF1–KF6) and the measurement directions (course and wale). The analysis of the results indicates that the back side shows significantly greater variability and a wider range of surface roughness values compared to the face of the knitted fabric.

Unlike the face, whose roughness values fall within the interval of 12.55 to 25.51 µm, the back side exhibits more pronounced extreme values, with a minimum of 4.27 µm (KF3–wale) and a maximum of 29.21 µm (KF5–course). The analysis of the different designed structures shows that the relationship between face and back roughness changes significantly depending on the measurement direction and the specific designed structure.

In structures KF1, KF2, and KF6, the differences are more moderate and mainly relate to variations between the horizontal and vertical directions, whereas structures KF3, KF4, and especially KF5 exhibit the largest deviations, including very low or very high roughness values on the back side.

Analysis of the results of the wetting and drying dynamics tests (Figure 2) shows pronounced differences among the fabric samples, confirming that the fabric structure strongly influences the observed dynamics. The wool knitted fabrics generally have a high absorption capacity but also exhibit slower drying compared to materials made from synthetic fibers.

The wetting time among the samples ranged from 6.86 s to 54.05 s. The shortest wetting time was recorded for sample KF3, which has the greatest thickness and the highest wetting rate along both axes. This sample has a more open and porous structure with pronounced pores, allowing rapid penetration of liquid into the fabric and efficient moisture transfer through the material. Consequently, it also exhibited relatively fast drying (2.02 h).

In contrast, sample KF4 showed the longest wetting time and the lowest rate along both axes, due to its very dense structure with small pores that slow the initial liquid penetration. Despite its larger wetting area, this results from prolonged contact with the liquid rather than effective capillary transfer, leading to slow moisture movement through the structure and longer drying.

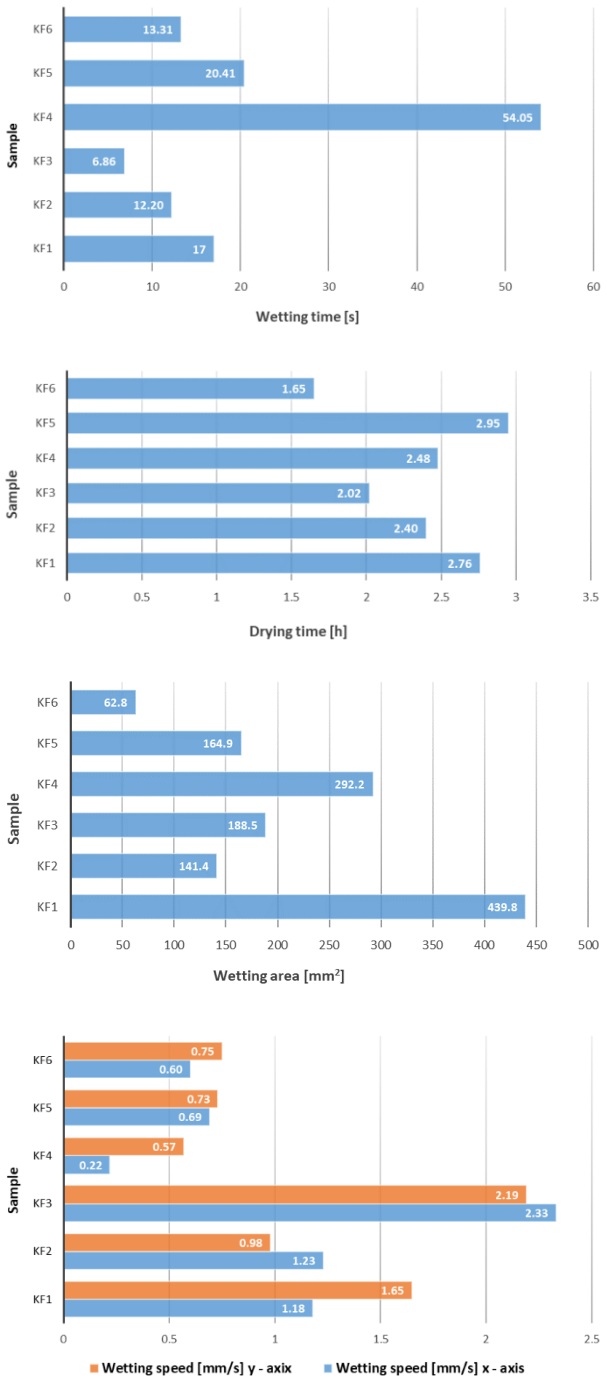


Fig.2 Results of wetting and drying of knitted structures

Sample KF1 has the largest wetting area and relatively higher wetting rate, but dries more slowly (2.76 h), indicating retention of a larger amount of liquid within the fabric. Sample KF5 also exhibits a longer wetting time and the longest drying time (2.95 h), which is related to its thickness. The fastest drying was observed for sample KF6 (1.65 h), which has smaller thickness and mass. Among all samples, KF3 stands out as the most balanced, with the fastest wetting and relatively short drying time.

Analysis of air permeability (Fig.3) showed significant differences between samples with different knitted structures. The highest air permeability was observed in structures KF3 and KF6, indicating that these two have the most open surface area. KF3 consists of a simple single jersey structure with added waves, while KF6 is knitted as a tubular structure with floated threads. KF4 and KF1 structures have the lowest air permeability; these two are simple double jersey and rib double jersey structures, which are denser.

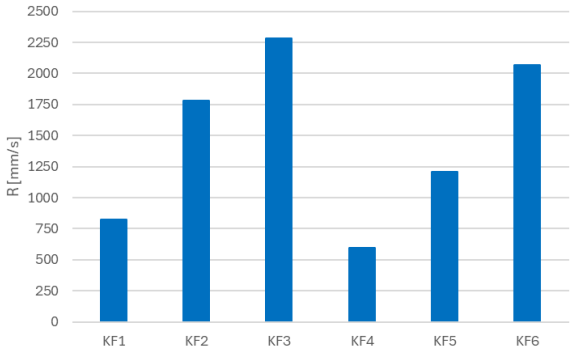


Fig.3 The results of air permeability of knitted structures

Table 3 shows that the KF5 knitted structure, rib double jersey 2+2 with double tuck stitches, exhibits the greatest elongation at a load of 0.2 N in the first stretching cycle, measuring 4.99 mm. The smallest elongation at a load of 0.2 N in the first stretching cycle is observed in the KF1 knitted structure, a double jersey knitted structure.

The smallest permanent multiaxial deformation TR (0.68 mm) was found in the simple double jersey structure KF1, while the largest permanent multiaxial deformation TR was found in the rib double jersey 2+2 with double tuck stitches, structure KF5 (3.84 mm). The greatest reduction in force in the fifth stretching cycle, after 60 seconds of rest, is observed in samples KF3 and KF5, which are the wave structure and rib double jersey 2+2 with double tuck stitches, respectively. The smallest reduction in force in the fifth stretching cycle is observed in sample KF1, the double jersey structure.

Tab.3 The results of the elasticity of knitted structures

Knitted structure	*l* at 0.2 N, 1. cycle [mm]	*F* [N]	*x* at 0.2 N, 6. cycle [mm]	*TR* [mm]
KF1	2.54	1.50	3.22	0.68
KF2	2.86	1.86	5.51	2.65
KF3	3.58	2.01	6.89	3.30
KF4	2.99	1.64	5.20	1.28
KF5	4.99	2.00	8.82	3.84
KF6	4.38	1.79	6.01	1.63

The results of the elasticity analysis of the knitted structures confirm that the double jersey has the smallest permanent multiaxial deformation and the smallest reduction in force after the fifth stretching cycle and 60 seconds of rest. Knitted structures with tuck stitches, on the other hand, have the greatest permanent elongation and the greatest reduction in force after the fifth loading cycle.

4. Conclusion

From the analysis of six different knitted structures made from 100% wool, it can be concluded that the structure of knitted fabrics significantly influences their physical, mechanical, and functional properties. The results showed that the thickness of the knitted fabrics varied considerably depending on the structure, ranging from 1.96 mm to 4.20 mm, which enables different functionality of the knits. Surface roughness varies greatly between the front and back, as well as between different structures, affecting comfort and interaction with the skin. The dynamics of wetting and drying confirm that more open structures (KF3) allow faster wetting and relatively shorter drying times, while compact structures (KF4) have lower moisture transfer. Air permeability also varies greatly between samples; those with a more compact structure have lower air permeability, while samples with a more open structure have higher air permeability. Permanent multiaxial deformation of knitted fabrics is greatest in structures with tuck stitches (KF5), which show the highest elongation and permanent deformation, whereas the simple double jersey structure (KF1) exhibits the least deformation and the greatest elasticity.

Based on these findings, it can be concluded that with appropriate design of the knitted structure, it is possible to specifically adapt the properties of the material, which is crucial for the development of functional and sustainable textile products. Wool knitted fabrics are proving to be a promising material for sports and technical clothing, as they combine thermal regulation, breathability, and comfort.

This work is a result of the implementation of the bilateral project between Croatia and Slovenia, "Development and Structural Functionalization of Knitted Sportswear from Natural and Comparative Synthetic Fibers," funded by the Ministry of Science, Education and Youth of the Republic of Croatia and the Ministry of Higher Education, Science and Innovation of the Republic of Slovenia; the project of the Programme P2-0213 Textiles and Ecology and Infrastructural Centre RIC UL-NTF of the Slovenian Research Agency, Slovenia; as well as the implementation of the institutional research project "Research and development of sustainable, functional textile components for next-Generation composites ", FUNK-TEX, TTF-IIP-06, funded by the European Union - NextGenerationEU.

Funded by the European Union
NextGenerationEU

Statement on the Use of AI Tools: AI tools were not used to define the scientific research, design the methodology, or present and analyze measurement results. Given the international composition of the authors, AI tools were used solely for linguistic correction of the content.

References:

[1] Hu, J.; Irfan Iqbal, M.; Sun, F.: Wool Can Be Cool: Water-Actuating Woolen Knitwear for Both Hot and Cold, *Advanced Functional Materials* **2020**, 30 (51), p. 2005033. https://doi.org/10.1002/adfm.202005033

[2] Zhou, L.; Feng, X.; Du, Y.; Li, L.: Characterization of Liquid Moisture Transport Performance of Wool Knitted Fabrics, *Textile Research Journal* **2007**, 77 (12), pp. 951–956. https://doi.org/10.1177/0040517507083518

[3] Nawaz, N.; Troynikov, O.; Watson, C.: Thermal Comfort Properties of Knitted Fabrics Suitable for Skin Layer of Protective Clothing Worn in Extreme Hot Conditions, *Advanced Materials Research* **2011**, 331, 184–189. https://doi.org/10.4028/www.scientific.net/AMR.331.184

[4] Troynikov, O.; Wardiningsih, W.: Moisture Management Properties of Wool/Polyester and Wool/Bamboo Knitted Fabrics for the Sportswear Base Layer, *Textile Research Journal* **2011**, 81 (6), pp. 621–631. https://doi.org/10.1177/00405175103924

[5] Kejkar, V.; Dhore, R.: Active Sportswear Fabrics, *Trends in Textile Engineering & Fashion Technology* **2019**, 5 (2), pp. 603-605. https://doi.org/10.31031/TTEFT.2019.05.000606

[6] ISO 5084:1996 Textiles — Determination of thickness of textiles and textile products

[7] ISO 9237:1995 Textiles — Determination of the permeability of fabrics to air

[8] ISO 20932-2:2018 Textiles — Determination of the elasticity of fabrics, Part 2: Multiaxial tests