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Assessment of Polylactide Properties for Use in Knitted Clothing Products

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Abstract
The article presents the results of a study work on the assessment of selected structural and performance characteristics of weft knitted fabrics, produced from the commercial multifilament polylactide yarn PLA 6201D. The work was carried out on PLA materials with the aim of application in lightweight outerwear. The materials presented are examples of solutions used in the industrial process of the manufacturing and finishing of so-called seamlesswear products. The structure of the materials in the solutions of left-right stitch applied was determined by the indicator of the degree of filling of the knitted fabric "k", used in the filling characteristics of the linear structure of knitting materials made from the same type of yarn. The functional properties of the materials were determined in the scope of selected indicators, important in the aspect of physiological comfort and clothing's quality of wear. The PLA yarn was subjected to the assessment selected qualitative and hygroscopic indicators, which was carried out in relation to selected multifilament polyester yarns of similar linear mass.

Key words: *polylactide, multifilament yarn, weft knitted materials, physiological comfort, wear quality.*

Introduction

Polylactic acid (PLA) is currently a well-known thermoplastic polymer with scientifically proven biodegradable and bioresorbable properties, produced from renewable vegetable raw materials (e.g. corn, potatoes, reeds or beets) and increasingly used in mass production [1]. Microbial degradation of polylactide is stimulated by the presence of selected bacterial strains and proceeds relatively slowly, especially at lower temperatures [2]. Under very specific conditions of high temperatures and humidity of the composting environment, PLA products are completely decomposed, giving rise to carbon dioxide and water, while under typical conditions of use and storage they are extremely stable [3], giving the potential for ecological use of raw material also in the textile sector. Lactic acid is the final product of PLA hydrolysis, known in food application as a natural acidifying agent, preserving or improving the taste, as well as naturally occurring in food (e.g. fruit, vegetables, yoghurt, cheese or wine) [4]. In 1984, lactic acid was recognised by the U.S. government organisation FDA (U.S. Food and Drug Administration) as a GRAS (substance Generally Recognized As Safe) for use in food [5].

According to literature data, Wallace Carothers (DuPont) – an American chemist, was the discoverer of PLA, who in 1932 produced this product by heating lactic acid under a vacuum [6]. Research works on the possibility of technological application of polylactide have been undertaken since around 1960, and due to biocompatible functions and degradation to non-toxic substances, they have been directed towards biomedical products, i.e. surgical threads, implants, long-lasting drug carriers etc. [7]. The applications of polylactic acid (PLA) have also been developed in packaging materials technology (e.g. foils, bottles, trays, packaging filling materials in transport etc.) as well as in agriculture and gardening (e.g. foils supporting the cultivation of vegetables without the need to use pesticides, protective foils against pests and climatic factors, ensuring air permeability and atmospheric precipitation) [8]. Due to small scale and high production costs, polylactide and its co-polymers have been used only to a limited extent, mainly in medicine (tissue engineering, bone surgery, medicament carriers etc.). Since 2005, the development of the mass production of biodegradable products from renewable raw materials has been observed. Polylactide, due to the scale of industrial application, was recognised in 2010 as the second most important bioplastic in the world [2, 9]. The essence of the development of technologies based on this biodegradable polymer is a green alternative to synthetic raw materials, the production of which consumes fossil fuel resources (i.e. oil) and contributes to the storage of waste. However, the ability to depolymerise PLA by hydrolysis can find use in the chemical recycling of waste from this polymer [10].

PLA polymer brands currently known on the global production and trade market include, among others, Ecodear®PLA of the Japanese company Toray Industries, Inc., Weforyou Pure PLA of Weforyou GmbH, Resomer®L of the German concern Evonik Industries AG, Terramac® of the Japanese company Unitika Ltd., as well as Purac® PF and Luminy® PLA of the Dutch manufacturer Total Corbion PLA [11]. Currently, the American company Cargill Dow LLC (NatureWorks, LLC) is the world's largest producer of commercial plastic resins from renewable natural sources, which in 2002 introduced to the market polylactide polymer under the trade name *NatureWorks™* PLA and fibres from this polymer under the brand *Ingeo™* [12]. It should be emphasised that poly(lactic acid) fibres are the first produced in a molten state from renewable sources [6]. The technological application of *NatureWorks™* polylactide *PLA* has been focused on the packaging industry, flooring materials, the fillings of quilts/pillows as well as textiles. Currently, *Ingeo™* fibres are also offered by the manufacturer for use in 3D printing technology, hygienic products, clothing and decorative textiles [13].

On the basis of a public review of scientific literature in the area of research and application of polylactide and lactide-based co-polymers in the textile sector [14-25], it is observed that activities are focused primarily on the properties and technology of fibres, where work includes, among others studies on the impact of parameters of the finishing process on strength properties and fibre morphology [14], modifications of fibre properties, e.g. in the range of antibacterial activity using silver [15] or strength indicators with the application of carbon nanotube (CNT) nanocapsules in PLA matrix [16], shaping the cross-section of fibres for applications in the carpet industry [3] or thermal and mechanical indicators for the use of fibres in the technology of textiles for protective clothing [17], as well as modification of lactide with polymers from bio- or petroleum sources to improve the processing capabilities of PLA (i.e. yarn texturing, dyeing, finishing), difficult due to the high rigidity and brittleness of PLA after long-term storage [18]. The mechanical properties of PLA are determined as similar to those of conventional polyethylene terephthalate (PET) [10]. Among the properties of PLA fibres that can find use in textiles, the following are listed: elasticity and strength, controlled shrinkage, resistance to UV radiation, as well as favourable features in relation to PET, i.e. higher surface hydrophilicity and better moisture transport, lower density, and also reduced flammability and smoke production (three times shorter burning time at six times lower smoke generation) [3, 19, 20].

The first research work in the area of the applicability of polymers and aliphatic copolymers in yarns and textiles was undertaken at the Textile Research Institute in 2005 under the international project Eureka E! Initiative 3420 BIOTEXTIL. Experimental activities of these works were focused on the development of a method for manufacturing a medical knitted fabric from yarns, produced under the project, based on a biodegradable PLLA polymer. Polymers were produced by the Project Partner – Centre for Polymer and Carbon Materials of the Polish Academy of Sciences in Zabrze, using the method of atactic poly synthesis developed by this institution [(R, S)-3-hydrobutyrate] (a-PHB). The process of forming the fibre was achieved by the classical polymer melt method for a multifilament structure of yarn with an assumed linear mass in the range from 50 to 110 dtex. The basis for shaping the parameters of the polymer and fibre production process were the results of the assessment of the quality indicators of yarns (i.e. linear mass, breaking strength, elongation at break), planned for application in the process of producing knitted fabrics using the weft knitted technique. An important issue in the attempts to produce knitted fabrics were primarily: the structure of the yarn with a protective twist (up to approx. 10 turns/m), low yarn tensile strength (approx. four times lower compared to classic polyester yarn with a similar linear weight and number of filaments) and tendencies toward yarn defibring on the friction barriers on the technological stand and then the cracking of fibres and yarn breakages. As a result of experimental work undertaken, the conditions for the production of knitted fabrics from multifilament PLLA yarns with a linear weight of approx. 55 and 75 dtex and the number of filaments 17 on circular knitting machines of small diameter (Φ4″) and needle gauge 34E, were developed [21]. Research works in the field of application of (bio)degradable (co)polyester yarns, among others in textile technology, produced by the weft knitting technique were continued at the Textile Research Institute under the key project POIG.01.03.01-00-007/08-00 Biogratex. Multifilament yarns with a linear mass in the range of 40-150 dtex and number of filaments of 12, 17 and 24 produced under the project, among others, from the commercial polymer *NatureWorks^{TM} PLA* were tested. In the design and technological works, new solutions were introduced for polylactide yarns in the field of the construction of knitting stitches and product structures designed for dressings and hygienic materials [22-24]. Technological development of raw materials and fibres based on (bio) degradable synthetic polymers creates new possibilities for the use of commercially available yarns of this type in the area of textiles.

The material presented in the article is the result of research work conducted by the Textile Research Institute (actual name: Łukasiewicz Research Network – Textile Research Institute), which was undertaken to assess the applicability of polylactide in the clothing sector. Experimental work focused on knitting technology called seamless wear, implemented in the weft knitting technique on seamless machines and a finishing technique using the extraction method. The PLA multifilament yarn selected, recommended by the manufacturer for apparel application, currently offered on the global production and trade market, was evaluated. The research materials were knitted fabrics in selected structural solutions of clothing material intended for lightweight outerwear, e.g. blouses, shirts or T-shirts. A test program was established for assessment of the materials in relation to selected hygiene comfort indicators and the quality of the performance of the clothing product.

Materials and methods

The research works used multifilament non-textured polylactide yarn with the technological structure of FDY (fully drawn yarns) and trade name *Radyarn® CornLeaf* of the Italian sector Radici-Group by Noyfil SpA, well-known in the European market of raw materials and synthetic yarns [25]. According to the manufacturer's data, yarn was made from PLA fibres under the trade name *Ingeo^{TM}* of the American company NatureWorks LLC. The areas of technological application of *Radyarn® CornLeaf* yarn include clothing products (i.e. sports, underwear, socks) and engineering (i.e. decorative, geo-textiles). The use direction of PLA filament yarns in weaving and knitting techniques for textile products is defined in NatureWorks® Ingeo^{TM} specifications for Poly-D-lactide types 6201D and 6204D [26]. According to the manufacturer's data, the density of this type of PLA polymer is 1.24 g/cm^3, the glass transition 55-60 °C, melting temperature 160-170 °C, and the basic physical properties of fibres made from it are similar to those of PA6 and PET [27]. An undyed yarn – PLA 6201D with a linear density of 192 dtex f 48 was selected for the knitted fabrics, the properties of which were assessed in relation to selected multifilament polyester yarns of similar linear density and number of filaments – 48. Metrological testing of yarns was performed in terms of selected qualitative and hygroscopic indicators according to the following standards: PN-P-04653:1997 (linear mass; test conditions: number of bobbins: 1, length of the measuring section: 500 mm, initial pressure: 3.5 cN), ISO 2061 (twist in yarns; test conditions: number of bobbins: 1, distance between the holders: 250 mm, initial pressure: 3.7 cN), ISO 2062 (breaking force and elongation; test conditions: testing machine: Zwick 1120, number of bobbins: 2, initial pressure: 9.5 cN, test speed: 250 mm/min, distance between the holders: 250 mm), PN-84/P-04656 (indicators at extension of knot and loop; test conditions: testing machine: Zwick 1120, number of bobbins: 1, initial pressure: 19 cN, test speed: 250 mm/min, distance between the holders: 250 mm), PN-84/P-04667 (elasticity level; test conditions: testing machines: Zwick 1120, number of bobbins: 1, initial pressure: 3.8 cN, test speed: 50 mm/min, distance between the holders: 500 mm), PN-80/P-04635 (hygroscopicity; test conditions: drying temperature 100 °C), PN-72/P-04734 (water absorptivity; test conditions: time of immersion in water: 5 minutes, waiting time: 2 minutes), and PN-77/P-04735 (drying speed; test conditions: soaking time of a sample: 5 minutes, time between weightings: 30 minutes).

The knitted fabrics were made under industrial conditions on a selected model of an electronically controlled knitting machine – SM8 TOP2 of the seamless type, with a needle gauge 28E and cylinder diameter ∅ 20″, made by Santoni, Italy. The materials were made from single PLA yarn using a basic construction of left-right weft stitch (knitted fabric variant marked as "LR") and two selected solutions of left-right derived stitch, where one is a tuck derived stitch on the base of once-tucked loops (knitted fabric variant marked as "TLR") and second one – a derived stitch with once – held loops (knitted fabric variant marked as "HLR"). For the solutions of derived stitch selected, tucked or held loops were introduced in every second column after the course of basic left-right loops. Further courses of knitted fabric with tucked or held loops were formed by shifting the derived loops to the neighbouring column. The left-right derived stitches used in this work were solutions 3.1.19 and 3.1.24 for knitted fabrics manufactured under industrial conditions according to the standard ISO 8388.

The modifications of the basic structure of the left-right weft stitch adopted in the work are examples of structural solutions of knitted fabrics that, through the introduction of tucked or held loops, change the filling of the material structure, thus affecting the functional properties and material appearance. Solutions of this type can be used in shaping a material's hygienic comfort features, e.g. for underwear or lightweight outerwear. The actual appearance of the right and left side of knitted fabrics for specified solutions of the left-right stitch is presented in pictures 1-3. A Nikon Eclipse 50i biological microscope, equipped with a digital camera and NIS-ELEMENT AR software, was used to take pictures. The pictures were taken using the magnification lens x2.

In this work, the knitted fabrics were tested in their raw state and after processes of industrial finishing, carried out by the exhaust method, as used in seamlesswear technology. After the production process, the knitted fabrics were subjected to dry relaxation (in an unfolded state) for 48 hours under normal climate conditions (air temperature 20 °C ± 2 °C & relative air humidity 65% ± 4%, according to the standard ISO 139). Properties of the PLA knitted fabrics were presented in this paper for certain thermal conditions of finishing processes performed for selected variants of seamlesswear technology containing Polyamide – which has a similar glass transition temperature (47-70 °C) to PLA polymer. The materials were finished in two variants, one of which was conducted at 35 °C-60 °C-35 °C and included washing and the application of softening and anti-bending agents (the finished version was marked as "W/60"). And the second variant included the dyeing of knitted fabrics and application of hydrophilizing agents and was carried out at 35 °C-95 °C-35 °C (the finished version was marked as "D/95"). The washing process of the knitted fabrics was conducted at 35 °C using non-ionic washing detergent. After the finishing processes, the knitted fabrics were subjected in a unfolded state to wet relaxation and drying in climatic ambient conditions. The actual appearance of the right and left side of the knitted fabrics in the selected finish variant ("W/60") is illustrated in photographs ***Figures 1, 2*** and ***3***.

In the basic research on the properties of PLA materials in a raw state (***Figures 1.a, 1.b, 2.a, 2.b*** and ***3.a, 3.b***) and after the finishing processes (***Figures 1.c, 1.d, 2.c, 2.d*** and ***3.c, 3.d***), parameters of the knitted fabrics were determined using the methodology of the following standards for textiles: PN-EN 14971:2007 (loop density; test condition: measuring length: 2.5 cm), PN-EN ISO 5084:1999 (thickness; test conditions: surface of the foot: 20 cm^2, pressure: 1 kPa) and PN-P-04613:1997 (surface mass; test conditions: surface of the samples: 0.01 m^2).

In order to compare the state of filling up the structure of the fabrics analysed with yarn, the filling-up degree indicator of the knitted fabric *k* was determined, calculated by the following ***Equation (1)*** [28]:

$$k = \frac{\sqrt{Tt}}{l} \qquad (1)$$

where:
Tt – yarn linear mass, tex
l – length of yarn in the loop, mm

The k – indicator is a parameter that can be used in the characteristics of linear filling-up of the structure of knitting materials made from the same type of yarn. It also allows to specify the length of yarn in the loop – l depending on the linear weight of yarn – *Tt* in order to obtain knitted fabrics with a similar structure.

The length of yarn in a loop – *l* was calculated on the basis of a relationship connecting the indicators metrologically determined in this work, i.e. indicators of the loop density and surface mass of knitted fabric made from yarn with a determined linear mass [29]:

$$l = \frac{M_S 10^4}{P_c P_W Tt} \qquad (2)$$

where:
M_s – surface mass of kitted fabric, g/m^2
P_r – density of courses, number of courses/cm
P_w – density of wales, number of wales/cm

The program for testing finished PLA knitted fabrics' performance properties was defined for garment direction of use, including products having direct contact with the user's skin. The tests included selected indicators of knitted fabrics important in the aspect of physiological comfort, which were determined according to the following standards: ISO 9237 (the permeability of fabrics to air; test conditions: field of surface tested: 20 cm^2, pressure drop: 100 Pa), PN-80/P-04635 (hygroscopicity; test conditions: relative humidity 100%, drying temperature 107 °C), PN-72/P-04734 (water absorption; test conditions: time of immersion in water: 5 minutes, waiting time: 2 minutes) and PN-77/P-04735 (drying speed; test conditions: soaking time of the sample: 5 minutes, time between weightings: 1 hour).

Hygroscopic properties of the knitted fabrics after the finishing processes were also determined in the range of sorption indicators according to the Tegewa Drop Test [30].

PLA knitted fabrics after finishing processes were also subjected to tests important in terms of the functional quality of a clothing product. In this area the work program included tests of indicators of resistance to domestic washing at 40 °C, acid and alkaline sweat, dry and wet friction, as well as artificial light.

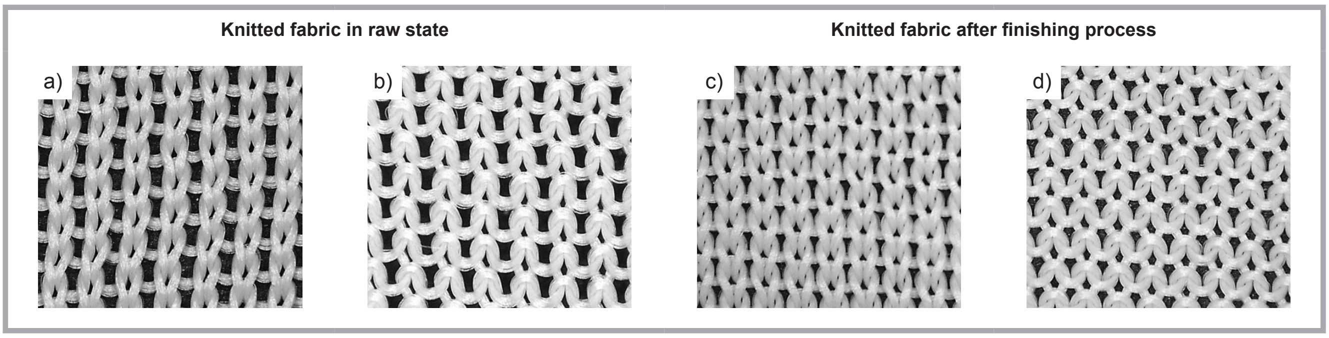

Figure 1. *Real look of right (a, c) and left (b, d) side of PLA knitted fabric with basic left-right weft stitch – variant "LR".*

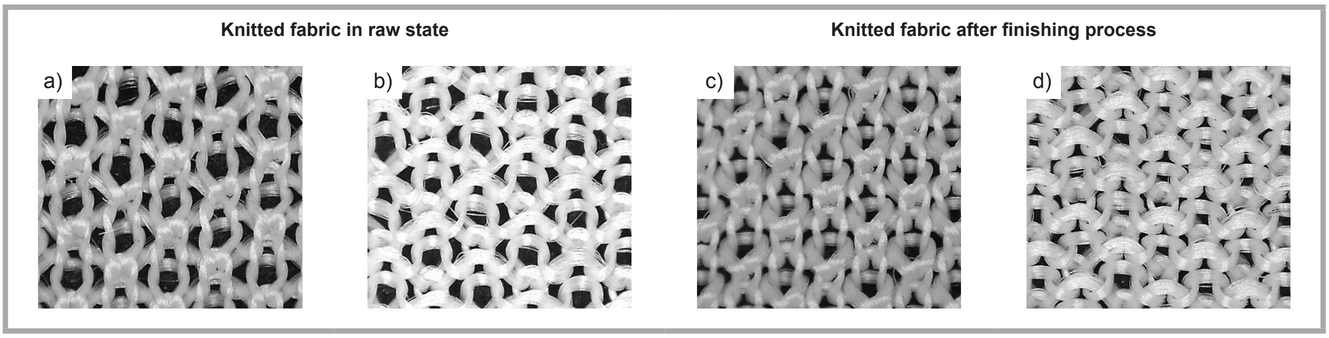

Figure 2. *Real look of right (a, c) and left (b, d) side of PLA knitted fabric with derived weft stitch left-right tucked variant "TLR".*

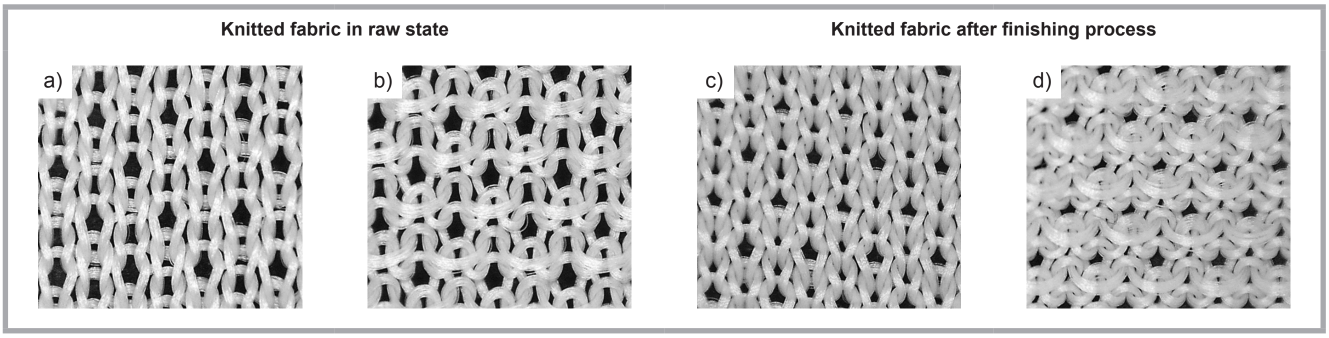

Figure 3. *Real look of right (a, c) and left (b, d) side of PLA knitted fabric with weft derived stitch, including once held loops – variant "HLR".*

The colour fastness of the materials to certain factors was the subject of the assessment. The resistance of the materials to washing, alkaline and acidic sweat was evaluated on the basis of the colour change of the PLA knitted fabric tested and the soiling of associated white fabric – which was wool, acrylic, polyester, polyamide, cotton and acetate materials. The colour fastness to dry and wet friction was determined on the basis of the assessment of the white of cotton rubbing fabric, while the colour fastness to artificial light was determined in a Multilight chamber (light D65). The tests were carried out according to the methodology of the following standards for textiles: ISO 105-C06 (colour fastness to domestic laundering; test conditions: washing detergent recommended by ECE (European Colourfastness Establishment), number of steel balls: 10), ISO 105-E04 (colour fastness to perspiration), ISO 9237 (colour fastness to rubbing; test conditions: friction arbour: $\varnothing 16 \pm 0.1$ mm, pressure: 9 ± 0.2 N, moisture level of friction fabric: 100%), ISO 105-B02 (colour fastness to artificial light; Xenon arc fading lamp test; test conditions: visible light (wavelength of radiation: 380-750 nm, temperature: 45 ± 3 °C, humidity: 40%).

Properties of the knitted fabrics after the finishing processes were also evaluated in terms of resistance to UV using accelerated aging tests in a UV Atlas®Test chamber according to the methodology of the ISO 4892-3 standard. Plastics. Methods of exposure to laboratory light sources. Part 3: Fluorescent UV lamps. In the tests, the knitted fabric was exposed to UV light with a wavelength of 340 nm. The materials were irradiated for 8 hours under conditions of a so-called dry cycle and for 4 hours in a so-called wet cycle in condensed water vapour. The effect of UVA radiation on the PLA materials was determined after 100 and 200 hours of exposure. The ball penetration index was used to evaluate the properties of the materials. The tests were carried out in accordance with Research Procedure No. 59: 2009, Edition 1, dated 09.05.2009. Determination of material's resistance to ball puncture, developed on the basis of the standard for flat and confectioned textile products used in knitted fabrics tests: PN-P-04738: 1979. Methods of testing textile products. Determination of puncture strength (measurement conditions: ball diameter: 20 mm, testing machine Zwick 1120, speed of head movement

Table 1. Characteristics of qualitative and hygroscopic indicators of PLA yarn and PET yarns. ***Note:*** *[1)] Batch Test Report. Technical features. PLA FDY 167/48. RadiciGroup Noyfil SpA. 24.07.2017; * FDY- Fully Drawn Yarns; ** POY – Partially Oriented Yarn.*

Raw material (type of fibre)	PLA (FDY*)[1)]	PLA (FDY*)	PET (FDY*)	PET (POY**)
Actual linear density, dtex V,% (n)	192 –	191 ± 1 0.7 (10)	176 ± 0 0.4 (10)	168 ± 1 0.8 (10)
Twist direction, – Twist number, rotation/m V, % (n)	– 10 –	protective twist 0-5 (10)	S 128 ± 3 4.0 (10)	protective twist 0-3 (10)
Breaking force, cN V, % (n)	536 –	553 ± 5 2.0 (20)	523 ± 24 10.4 (20)	560 ± 8 3.1 (20)
Extension at breaking force, % V, % (n)	28.5 –	28.4 ± 0.1 1.1 (20)	19.2 ± 1.7 19.1 (20)	21.8 ± 0.8 1.9 (20)
Breaking tenacity, cN/tex	2.8	28.9	29.7	33.3
Relative resistance in the loop, % V, % (n)	–	82.5 6.2 (10)	92.3 6.3 (10)	97.0 2.4 (10)
Breaking tenacity in the loop, cN/tex	–	23.9	27.4	32.3
Elasticity degree, % V, % (n)	–	49.5 1.8 (20)	60.5 0.4 (5)	69.5 0.8 (5)
Total elongation, mm Elastic elongation, mm Permanent extension, mm	– – –	65.0 32.2 32.8	45.0 27.3 17.7	40.0 27.8 12.2
Hygroscopicity, % V, % (n)	–	1.0 ± 0.2 20 (5)	1.5 ± 0.2 13.3 (5)	1.2 ± 0.2 16.7 (5)
Water absorption, % V, % (n)	–	163.8 ± 6.8 4.7 (5)	145.3 ± 6.3 4.9 (5)	195.7 ± 15.8 9.0 (5)
Drying time, min V, % (n)	–	31 ± 2 8.1 (5)	30 ± 3 10.3 (5)	29 ± 4 16.6 (5)

Table 2. Results of the basic structural parameters and surface mass of PLA knitted fabrics in a raw state and after finishing processes.

Marking of knitted fabric variant	Density of courses P_c, number of courses/cm V, % (n)	Density of wales P_w, number of wales/cm V, % (n)	Thickness T, mm V,% (n)	Surface mass M_s, g/m² V, % (n)	Degree of knitted fabric cover k, – (length of yarn in the loop, mm)
Knitted fabrics in raw state					
LR	16.0 ± 0.3 1.6 (5)	13.3 ± 0.2 1.2 (5)	0.45 ± 0.02 1.1 (10)	124 ± 1 1.0 (5)	1.43 (3.05)
TLR	14.7 ± 0.3 2.1 (5)	13.3 ± 0.1 0.7 (5)	0.47 ± 0.02 1.6 (10)	138 ± 8 6.6 (5)	1.18 (3.70)
HLR	20.0 ± 0.1 0.2 (5)	10.3 ± 0.1 1.0 (5)	0.98 ± 0.03 1.8 (10)	162 ± 9 6.1 (5)	1.06 (4.12)
Knitted fabrics after finishing process in variant 'W/60' (temperature 35-60-35 °C)					
LR	16.7 ± 0.2 1.5 (5)	14.2 ± 0.2 1.5 (5)	0.42 ± 0.02 1.2 (10)	133 ± 3 2.4 (5)	1.49 (2.94)
TLR	14.8 ± 0.3 1.8 (5)	15.2 ± 0.2 1.2 (5)	0.51 ± 0.03 3.3 (5)	160 ± 2 1.5 (5)	1.17 (3.72)
HLR	20.7 ± 0.7 3.3 (5)	11.8 ± 0.2 1.7 (5)	0.87 ± 0.03 1.9 (6)	188 ± 2 1.1 (5)	1.08 (4.03)
Knitted fabrics after finishing process in variant 'D/95' (temperature 35-95-35 °C)					
LR	16.2 ± 0.2 1.3 (5)	15.0 ± 0.2 1.7 (5)	0.45 ± 0.01 0.9 (6)	151 ± 2 1.7 (5)	1.34 (3.25)
TLR	15.6 ± 0.2 1.6 (5)	15.1 ± 0.1 0.6 (5)	0.53 ± 0.01 1.5 (5)	163 ± 2 1.3 (5)	1.21 (3.62)
HLR	22.5 ± 0.3 1.0 (5)	11.8 ± 0.2 1.7 (5)	0.89 ± 0.02 1.1 (5)	197 ± 4 2.1 (5)	1.12 (3.88)

with the ball: 100 ± 5 mm/min, number of samples tested: 10).

The tests of the yarn and knitted materials were carried out in accredited laboratories of the Textile Research Institute. The materials were acclimatised for 48 hours under normal climate conditions before testing according to the standard ISO 139.

Research results

Evaluation of selected qualitative and hygroscopic indicators of PLA yarns

Table 1 presents the test results of selected parameters of PLA yarn – used in the work, and parameters of PET yarns adopted for comparison. The test results of indicators determined in the work are the average value of *n* measurements, the uncertainty of measurement (expanded uncertainty of measurement at a confidence level of 95%, the extension coefficient k = 2), and the coefficient of variation of the mean value (V, %).

The classical multifilament PET yarns accepted for the comparative assessment had approx. 10% lower actual density in relation to the PLA yarn used in this work (***Table 1***). On the basis of the average values of breaking force and relative resistance in the loop, it was observed that PLA yarn had a similar breaking strength to that of PET yarns. However, in the tests of elongation indicators, PLA yarn compared to PET yarn showed significantly higher permanent elongation and elongation at break, where on the basis of mean values obtained, the differences were 45-65% and 25-30%, respectively. The elasticity degree in the values presented determines the relative elasticity of the yarn as the ratio of total elongation to elastic elongation. The test results showed that PLA yarn had an approx. 20-30% lower elasticity than the PET yarns used for comparison.

Hygroscopic properties of the yarns depended mainly on the type of raw material, but they were also affected by the type and content of spinning preparations, oil impurities and yarn structure. In the assessment of indicators examined, PLA yarn was characterised by similar hygroscopicity and drying time compared to PET yarn in this work. However, PLA and PET yarns of the FDY type were characterised by similar values of the water absorption indicator, lower than for PET yarn of the POY type.

Characteristic of structural properties and surface mass of PLA knitted fabrics

Table 2 presents the results of basic tests of the structural parameters and surface mass of raw and finished knitted fabrics (***Figures 1, 2*** and ***3***). The test results are the mean value of measurements (number of "n" measurements), the uncertainty of measurement (expanded uncertainty of measurement at a confidence level of 95% and extension coefficient k = 2), and the coefficient of variation of the mean value (V, %). The table also presents the values of indexes for the degree of knitted fabric cover – *k* and length of yarn in the loop – *l*, marked on the basis of ***Equations (1)*** and ***(2)***.

In the accepted designs of the left-right stitch in weft knitted fabrics (***Figures 1, 2*** and ***3***) – manufactured from the given PLA yarn under industrial technological conditions, carried out on the selected knitting machine model with a 28E needle gauge, the materials being in a raw state, the surface mass was in the range of 124-162 g/m^2, the thickness – from 0.45 mm to 0.98 mm (***Table 2***), and surface loop density – from approx. 195 to approx. 213 loops/cm^2 (values calculated as a product of indicators of weft y and warp density). For the research material analysed in this work, the knitted fabrics in the accepted constructions of the LR derived stitch ("TLR" – ***Figures 2.a*** & ***2.b***, and "HLR" – ***Figures 3.a*** & ***3.b***) in a raw state were characterised by a higher surface mass than the material with a basic LR stitch ("LR" – ***Figures 1.a***, ***1.b***), which is important in the economic aspect of the production process of PLA materials. The differences in mean values of the surface mass indicator for the knitted fabric with a tucked stitch ("TLR") amounted to approx. 10%, and for knitted fabrics with unprocessed loops ("HLR") approx. 25%. In the evaluation of raw PLA materials, the knitted fabric with the specified tucked stitch construction ("TLR") was characterised by a similar thickness and lower loop density per unit area (by approx. 10%) to those of the basic stitch of knitted fabric ("LR"), whereas knitted fabric with a structure containing unprocessed loops ("HLR") was characterized by a similar density of loops per unit area to, but with a greater thickness (by approx. 55%) than, the fabric with a basic structure ("LR").

The graphs present the dependencies of surface mass indicators (***Figure 4.a***) and thickness (***Figure 4.b***) on the degree of knitted fabric cover *k* (the ***Equation (1)***) in the applied constructions of the left-right weft stitch. The reduction in the indicator of the surface mass observed on graph 4.a, with an increase in the cover level of the knitted fabrics resulted from the reduction in yarn length in the loop (the ***Equation (2)***), at which the thickness of the material was also reduced (***Figure 4.b***). For the research material specified in this work, the highest degree of knitted fabric cover *k* occurred in the variant with the basic structural solution – left right stitch ("LR"– ***Figure 1***). The design solutions of the left-right derived stitches ("TLR"– ***Figure 2*** and "HLR"– ***Figure 3***) used in this

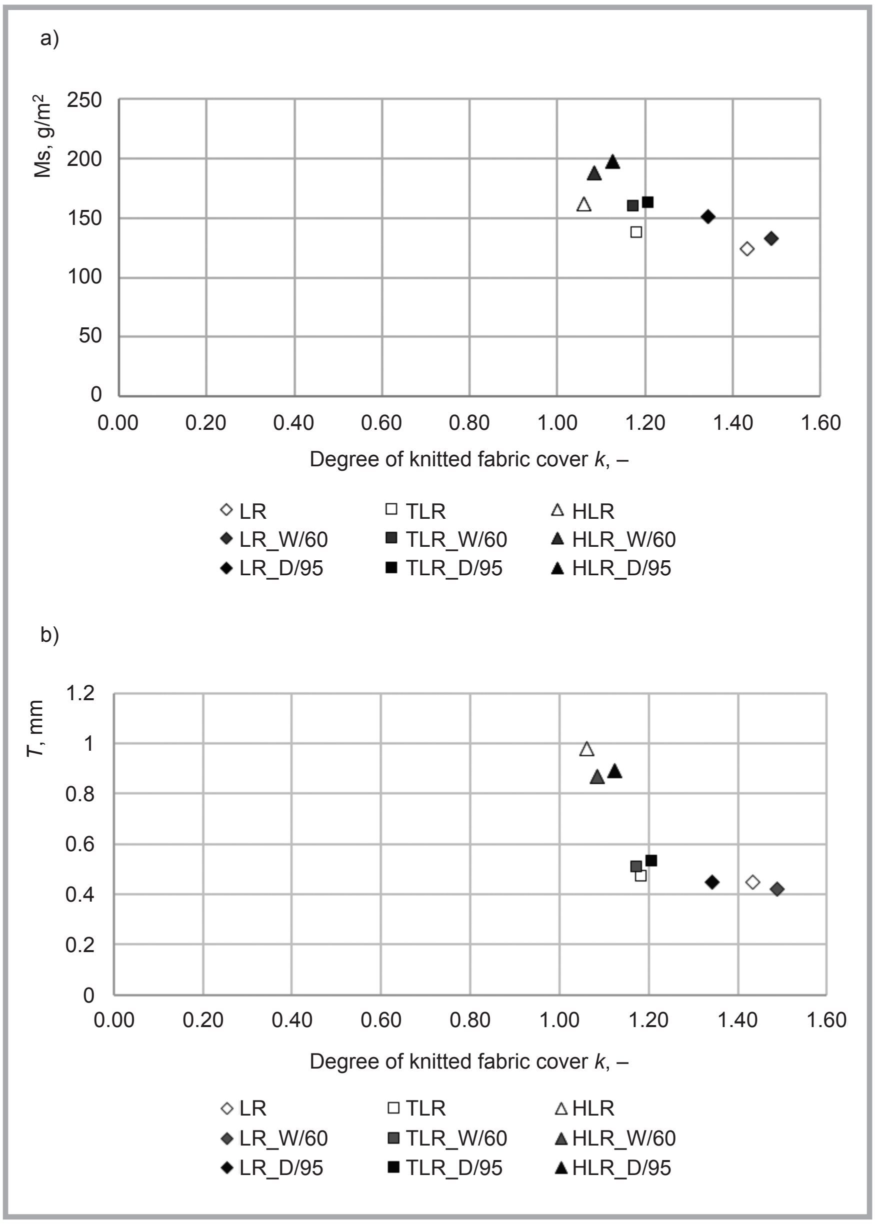

Figure 4. *Characteristics of indicators of the surface mass M_s (a) and knitted fabric thickness T (b) depending on the degree of knitted fabric cover k.*

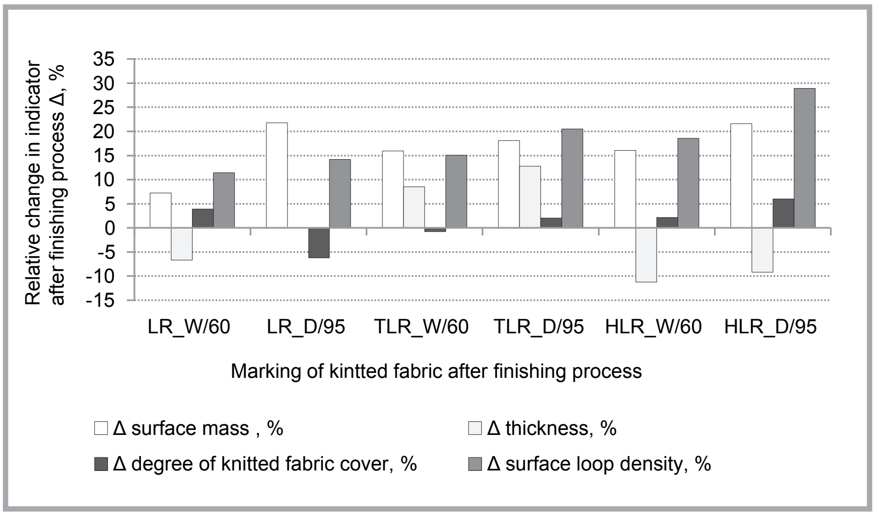

Figure 5. *Characteristic of the relative change in structural indicators and surface mass after finishing processes of PLA knitted fabric at 60 °C ("W/60") and 95 °C ("D/95").*

Table 3. Test results of physiological comfort indicators for PLA knitted fabrics.

Indicator	LR W/60	LR D/95	TLR W/60	TLR D/95	HLR W/60	HLR D/95
Air permeability $\mathbf{A_p}$, mm/s V, % (n)	3605 ± 87 3.8 (10)	3192 ± 102 3.6 (5)	2901 ± 60 3.2 (10)	2542 ± 54 2.4 (5)	4429 ± 78 2.8 (10)	3804 ± 104 3.1 (5)
Hygroscopicity **H**, % V,% (n)	0.69 ± 0.08 10.1 (4)	0.69 ± 0.10 15.9 (3)	0.79 ± 0.10 12.1 (3)	0.53 ± 0.16 18.4 (3)	0.81 ± 0.07 9.6 (3)	0.70 ± 0.04 7.1 (3)
Relative water absorption $\mathbf{W_a}$, % V% (n)	122.7 ± 2.5 2.5 (5)	136.3 ± 2.1 3.2 (3)	128.1 ± 4.3 2.9 (3)	136.9 ± 2.8 4.1 (3)	129.9 ± 1.9 2.9 (3)	130.5 ± 2.6 2.9 (3)
Drying time $\mathbf{T_d}$, min V,% (n)	58 ± 8 14.6 (5)	54 ± 3 7.1 (3)	66 ± 1 0.7 (3)	66 ± 1 0.8 (3)	67 ± 8 10.0 (3)	70 ± 7 12.1 (3)
Time of absorption of a drop of water $\mathbf{T_a}$, s V, % (n)	635 ± 61 10.7 (5)	5 ± 1 12.8 (5)	558 ± 35 7.0 (5)	1 ± 0 19.6 (5)	292 ± 54 10.3 (4)	0.5 ± 0 21.5 (4)
Size of drop of water absorbed **A**, mm^2 V, % (n)	210 ± 16 6.6 (5)	473 ± 22 14.3 (5)	370 ± 40 10.8 (5)	360 ± 44 10.8 (5)	293 ± 21 6.2 (4)	208 ± 27 14.2 (5)

***Table 4.** Test results of PLA knitted fabric‘s strength indicator for puncturing by a ball, daN.*
***Note:** * n = 8; W(α; n) = 0.818.*

Marking of knitted fabric (Shapiro-Wilk test)	Sample without light exposure	Sample after light exposure – time of exposure, *hr*	
		100	200
LR W/60 (W; p-value)	30.0 ± 0.5 (0.963; 0.875)	33.0 ± 1.0 (0.979; 0.987)	33.0 ± 1.0 (0.898; 0.213)
LR D/95 (W; p-value)	26.5 ± 0.0 (0.949; 0.713)	29.0 ± 1.0 (0.919*; 0.466*)	29.5 ± 1.0 (0.891; 0.176)
TLR D/95 (W; p-value)	31.0 ± 0.5 (0.958; 0.816)	32.0 ± 1.0 (0.902; 0.236)	30.5 ± 1.0 (0.976; 0.978)
HLR D/95 (W; p-value)	27.0 ± 0.0 (0.940; 0.588)	27.5 ± 1.0 (0.919; 0.364)	28.0 ± 1.0 (0.951; 0.730)

***Table 5.** Empirical values of F Fisher-Snedecor’s statistics and results of the Student’s t test.*
***Note:** * marking of population: 0-material before ageing test; A, B – material after 100 and 200 hr light exposure with UV A, respectively; a) $F_{kr}(α;7;9) = 3.293$; b) $F_{kr}(α;9;7) = 3.677$; c) $t_{0,95} = 2.12$.*

Marking of knitted fabric	Empirical values of statistics for populations* compared					
	F(0,A) (p-value)	F(0,B) (p-value)	F(A,B) (p-value)	t(0,A) (p-value)	t(0,B) (p-value)	t(A,B) (p-value)
LR W/60	2.020 (0.189)	2.660 (0.138)	1.317 (0.281)	**7.08** **(< 0.001)**	**8.56** **(< 0.001)**	1.48 (0.156)
LR D/95	1.868[a)] (0.205)	3.124 (0.111)	1.67[b)] (0.237)	**14.30[c)]** **(< 0.001)**	**14.29** **(< 0,001)**	1.59[c)] (0.131)
TLR D/95	1.062 (0.330)	1.154 (0.311)	1.087 (0.325)	**4.03** **(0.001)**	1.63 0.121	**5.57** **(< 0.001)**
HLR D/95	1.679 (0.228)	1.761 (0.218)	1.049 (0.333)	1.18 (0.253)	0.68 (0.505)	**2.40** **(0.027)**

work, as compared to the basic structure of left-right stitch, reduced the degree of cover of the knitted fabrics and increased the thickness of the material. The specified direction of changes in the cover of these knitted fabric variants resulted from the greater length of yarn in the tucked loop (“TLR”) and unprocessed loop (“HLR”) than in the basic left-right loop, and the changes in thickness resulted from the occurrence of stitch construction elements in the form of a tucked loop (“TLR”) and extended floats loop (“HLR”).

The shrinkage of polylactide fibres in boiling water is 8-15% according to literature data [27]. However, the shrinkage of PLA yarn determined at work was 9.4 ± 2%. After the finishing processes used in this work (“W/60” and “D/95”), the knitted fabrics were characterised by approx. 5-20% higher surface mass and approx. 10-30% higher density of loops per unit area compared to raw knitted fabrics. In the analysis of changes in the average values of these indicators, the influence of the temperature applied in the finishing process was mainly observed. However, the influence of the stitch used in the fabric was also observed in the analysis of changes in the average values of the filling up/cover and thickness of the knitted fabric. ***Figure 5*** presents the relative change in the surface area and structural indicators after the finishing processes performed for PLA fabric.

Characteristics of selected performance properties of PLA fabrics

Table 3 presents the test results of physiological comfort indicators specified in this work. The test results are the average of measurements (number of measurements “n”), the uncertainty of measurement (expanded uncertainty of measurement at a confidence level of 95% and extension coefficient k = 2), and the coefficient of variation of the mean value (V %).

The average values of the air permeability indicator A_p of knitted fabrics with the specified construction of a left-right weft stitch were in the range of 2500-4500 mm/s. Such values are characteristic for knitted fabrics made from continuous non-textured synthetic yarns, and provide the high-airy characteristics of the material.

The hygroscopicity indicator H – marked in the work, determined the material’s capacity to sorb water vapour from the air with a relative humidity of 100%, while the water absorption indicator W_a is the water absorption capacity of the material immersed in water. After the exemplary finishing processes carried out in this work for PLA fabrics, the materials showed hydrophobic properties at average values of the hygroscopicity indicator H in the range of 0.53-0.81% and water absorption W_a in the range of 122.7-136.6%. The hygroscopic properties of the textiles depended mainly on the type of raw material and could be improved in hydrophilising finishing processes with the use of various types of physical methods (e.g. corona discharge, plasma, laser) or chemical (e.g. enzymatic modification grafting of different monomers, enzymatic hydrolysis, alkaline hydrolysis) [31].

Studies on the surface sorption properties of the knitted fabrics, made with the use of the Tegewa Drop test, showed the ability to transport moisture of the hydrophobic fibres. The properties of PLA knitted fabrics were, in this respect, similar to those of knitted fabrics made of continuous polyester and polypropylene fibres. On the basis of research on the indicator of the water drop absorption time T_a, the influence of the finishing processes applied on the surface sorption properties of PLA knitted fabrics was observed. While the test results of the size of the absorbed water drop indicator *A* showed that the structure of the material was also an important factor affecting the surface sorption properties. PLA knitted fabrics did not show any change in colour and dirt of the supporting fabric in the assessment of colour fastness to domestic washing at 40 °C, nor in acid and alkaline sweat or dry and wet friction. According to the five-level grey scale, the materials achieved the highest value in the assessment of colour durability, which determines the highest resistance of the material to specific utility factors. In the studies on colour durability to artificial light, materials received scores 7-8 according to the eight-point blue scale of woollen standards, according to which the highest durability is given by grade 8 and the lowest by grade 1.

Assessment of the resistance of PLA knitted fabrics to UV radiation

Table 4 presents the test results of PLA knitted fabric‘s strength indicator for puncturing by a ball, which is the indicator for the assessment of material resistance to UVA radiation in accelerated aging tests, used in this work. The test results were presented in the form of the mean value of n = 10 measurements with measurement uncertainty (expanded uncertainty of measurement at a confidence level of 95% and extension coefficient k = 2).

Test results of the ball puncture index carried out for two variants of PLA material (“LR W/60” and “LR D/95”) showed an approx. 10% increase in the mean value of the index after UVA radiation.

To demonstrate the significance of the impact of the ageing test on the knitted fabric’s strength indicator, the measurement results were statistically evaluated using Student’s t-test for independent groups. The measurement data were analysed in the terms of the normality of distribution of the random variable and the equality of variances of the groups of results compared in order to ensure the conditions of the test. The measurement results were interpreted with the probability of the materiality of error while rejecting assumed conditions of p-value ≥ 0.05. To verify the hypothesis of the normal distribution of measurement data, the Shapiro-Wilk test was used, which is effective in the case of a small number of measurements (n < 20) [32]. The normalcy of distribution of the measurement values tested for the number *n* was determined for the significance level α = 0.05. For the number of measurements *(n = 10)* of the strength indicator performed and analysed in this work, the critical value of the W (α; n) test was 0.842. The results of the *W* statistic presented in ***Table 4*** showed higher values than the tabular critical value of the test with a probability of making a mistake when rejecting the hypothesis of the normality of distribution from 17.6 to 98.7%, which indicates a statistically insignificant difference between the distribution of the data analysed and the normal distribution. The hypothesis of the equality of variances of the groups of results compared was verified using the Fisher-Snedecor test (***Table 5***). In the results analysed, the critical value of F statistics for the significance level α = 0.05 was 3.179. The test analysis showed for each of the compared groups the lower empirical values of the F statistics with respect to the tabular critical F_{kr} (α; v_1; v_2), where v1 and v2 was the number of degrees of freedom n_1-1 and n_2-1 for n_1 and n_2 the number of measurements in groups of knitted fabrics compared. These results allowed to accept the hypothesis about the equality of variance and were statistically significant based on the value of probability of the p-value test statistic < 0.05.

A comparative analysis of mean values with the use of Student’s t-test was carried out in population samples, which were the above-mentioned groups of PLA knitted fabrics before UVA treatment and after the radiation process. Interpretation of the test results was made at the statistical significance level p = 0.05, while tabular values of t were determined with a probability of 0.95 for the number of degrees of freedom $k = n_1 + n_2 - 2$, where n_1 and n_2 were the number of measurements of the indicator in the data group studied (value t (α, 18) for the populations compared, where the number of measurements n1 = n2 = 10 was 2.10). The t test results summarised in ***Table 5*** showed that for statistically significant results (p < 0.05), the empirical statistic values *t* were greater than the tabular value t (α, k), which allowed to accept the significant differences between the average values of the indicator in the groups of knitted fabrics compared. In the groups selected, there was no significant difference between the mean values compared, and the results in this case were statistically insignificant (p-value > 0.05).

On the basis of statistically significant values, the test results indicated for PLA materials tested in this work that there was an increase in the average value of the ball penetration strength index after the accelerated ageing tests. These results indicated that, after having tests, the materials underwent the first phase of degradation, where the degradation factors affected the improvement of the mechanical strength, and only then did they lower it [33]. Moreover, on the basis of test results of the ball penetration indicator (***Table 4***), it was also observed that the material structure might have an impact on the degradation time of PLA fabrics. These results indicated the need to expand research in this area, which will be the subject of further activities in the area of PLA applications in clothing products.

Summary

The research results presented characterised the selected properties of knitted fabrics made from commercially selected multifilament PLA yarn – *Radyarn® CornLeaf.* The materials in the examples of structure and industrial finishing processes proposed were characterised by a surface mass of approx. 130-200 g/m^2 and thickness of approx. 0.5-1.0 mm. In the assessment of the impact of thermal conditions of the finishing process on the structure of the PLA knitted fabrics tested, an increase in the density of the loop in the surface unit was observed with an increase or decrease in material thickness, depending on the stitch construction used. For the changes in the fabrics’ structural indexes after the finishing processes specified in this work , an increase in surface mass was demonstrated, which was up to approx. 15% for the finished variant at 60 °C (“W/60”) and up to approx. 20% for the finished variant at 95 °C (“D/95”). In the examples presented, PLA knitted fabrics showed the functional properties of clothing material, which in the designs of knitting stitch construction adopted (***Figures 1, 2*** and ***3***) and structural properties determined, proved favourable in the aspect of hygiene comfort due to its high air permeability index values. In the tests of hygroscopic properties, hydrophobic properties of the materials similar to polyester materials were demonstrated. In the aspect of sensory comfort, PLA knitted fabrics had properties characteristic for materials made of continuous non-textured synthetic fibres.

In the tests of knitted fabric resistance to washing, sweat (acid and alkaline), rubbing (dry and wet) and artificial light, the materials showed colour durability. However, in the assessment of the ball penetration index, the test results showed that after the accelerated ageing tests, there were changes in the materials indicating the first phase of degradation of PLA under the influence of specific physical factors.

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