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Engineering of Knitted Cotton Fabrics for Optimum Comfort in a Hot Climate

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Abstract
Cotton knitted fabrics are popular for summer-wear and outer-wear due to their comfort. The typical porous structure of knitted fabrics, however, increases the risk of exposure of human skin to UV rays, resulting in skin cancer. Therefore a trade-off is required between the comfort and UV ray resistance of the fabric. In this study, an attempt was made to engineer single jersey and 1×1 rib knitted fabrics with optimum comfort and desired UV resistance. It was found that 1×1 rib knitted fabrics could provide better comfort and UV protection with respect to single jersey fabrics manufactured on the same gauge knitting machine.

Key words: *air-permeability, optimum comfort, single objective optimization, thermal-conductivity, UPF.*

Introduction

Textiles have the key objective to protect our body, especially from harmful UV rays, by creating a shield around human skin. The shield forms a micro-climate in-between the textile inner-surface and human skin. This micro-climate is the decisive factor controlling the comfort feeling of the human body. A hot and humid micro-climatic condition is not desirable during summer, whereas a cold micro-climatic condition is unacceptable during winter. Hence it is required to maintain the micro-climate at a desired level. During the summer, heat and moisture in the micro-climate have to be dissipated through textiles, whereas during winter heat needs to be entrapped to provide warmth to the body. Hence the characteristics of textiles decide the comfort through controlling the rate of transmission of heat and moisture through it. Knitted fabrics are very popular as summer-wear and active-wear due to their high stretch-ability, breathability and comfort properties [1]. The typical porous structure of knitted fabrics provides high breathability and comfort characteristics during summer. However, high porosity increases the risk of UV ray exposure. Although UV rays are required for Vitamin D synthesis in the human body [2 - 4], over-exposure to UV rays causes erythema, sun-tanning and skin-cancer (basal cell carcinoma and melanoma) etc.[5 - 7]. Therefore a fabric with a high comfort level but with minimum UV resistance is not acceptable. Hence a trade-off is required between the UV resistance and comfort properties of knitted fabrics. Engineering an optimum comfortable fabric with the UV protection value desired thus becomes a challenging task. The UV resistance of a textile is expressed by UPF, which assesses the degree of sunburn protection provided by fabrics. Textiles can be classified under ‘good protection’ (UPF range 15 to 24), ‘very good protection’ (UPF range 25 to 39) and ‘excellent protection’ (UPF more than 40) based on their UPF values [8, 9]. The UPF of a fabric depends on the fibre type, yarn properties, tightness factor or cover factor, areal density, colour, finishing, etc. [10 - 16]. Several studies have been done on the comfort of knitted fabrics. Investigations were reported on the effect of various parameters (raw material, yarn properties and fabric parameters) on knitted comfort properties like air-permeability, thermal-conductivity, moisture management properties etc. Onfrei et al. [17] investigated the effect of the knitted fabric structure on comfort properties and concluded that the raw material type and knitted structure parameters are the decisive parameters affecting fabric comfort properties. Ramachandran et al. [18] investigated the thermal behaviour of single-jersey, rib and interlock knitted fabrics made out of ring and compact yarns and inferred that the thermal properties of knitted fabric depends on the yarn type and various fabric factors like fabric thickness, areal density, the tightness factor of the fabric etc. Oglakcioglu et al. [19] studied the thermal behaviour of various knitted structures viz. single-jersey, rib, interlock made of polyester and cotton and inferred that single-jersey fabric has the least thermal-conductivity and thermal-resistance. Ogulata et al. [20] developed a theoretical model correlating the fabric porosity and air-permeability of single-jersey fabric. An investigation was also reported on the optimisation of knitted comfort properties. Marvuz and Ogulata [21] used different experimental designs to optimise the air-permeability of interlock fabric. Prediction of the thermal properties of knitted fabrics was also studied. Fayala et al. [22] tried to predict the thermal-conductivity of knitted fabric using a soft computing technique i.e ANN. However, no attempt has been reported to engineer a knitted fabric with the desired level of comfort properties viz. air-permeability, thermal-conductivity and UV ray protection i.e UPF. It is felt that it has become an essential task to engineer a knitted fabric with optimum comfort characteristics with desired UV ray protection. In this study, an attempt was made to engineer single jersey and 1 × 1 rib knitted fabrics with optimum comfort characteristics for a hot climate that induce desired protection against UV rays.

Materials and methods

Preparation of fabric samples

Single-jersey and 1 × 1 rib knitted fabric samples were prepared using 100% cotton gas mercerised yarn of three different linear density 118.1 tex (5 Ne), 78.7 tex (7.5 Ne) and 59.1 tex (10 Ne) on a 12 gauge computerised flat knitting machine equipped with a digitised stitch control system to maintain the loop-length at the desired level. In this experiment, four variables, namely loop-length (X_1), carriage-speed (X_2), yarn-input-tension (X_3) and yarn linear density in the English system (X_4) were chosen, and for each variable three levels were considered. The coded levels and the actual values of the variables are shown in ***Table 1***.

Two types of knitted fabrics, single-jersey and 1×1 rib, each of which consisting of 36 samples, were prepared according to the 4-variables and 3-levels Box and Behnken orthogonal block design of experiments, as cited below:

$$\begin{bmatrix} \pm 1 & \pm 1 & \pm & 0 \\ \pm 1 & \pm 1 & 0 & \pm 1 \\ \pm 1 & 0 & \pm 1 & \pm 1 \\ 0 & \pm 1 & \pm 1 & \pm 1 \end{bmatrix}$$

A Washcator washing machine (China) was used to wash all 72 knitted fabric samples (36 single-jersey and 36 1 × 1 rib) according to the EN ISO 6330 standard for complete relaxation of the fabric samples. The samples were conditioned at a standard temperature of 20 ± 2 ºC and 65 ± 4% relative humidity for 48 hours. Then they were evaluated for air-permeability, thermal-conductivity and the ultraviolet-protection-factor (UPF). For each of the 72 fabric samples, 10 readings were taken for air-permeability, thermal-conductivity and UPF, and their mean values were considered.

Testing of fabric samples

Air-permeability tests were conducted according to the ASTM D737 standard using a TEXTTEST FX3300 air-permeability tester (UK). A pressure gradient of 100 Pa was maintained, in accordance with the standard. The air-permeability of a textile material is defined by the volume of air that passes through a unit area of the material, in a unit time, under a constant pressure gradient across it.

Thermal-conductivity tests were conducted according to the ISO EN 31092 standard using an Alambeta instrument (Sensora, Liberac, Czech Republic). During the measurement, the measuring head temperature and contact pressure were maintained approximately at 32 ºC and 200 Pa, respectively. The thermal conductivity of a textile material is its ability to conduct heat through it, expressed by the ***Equation 1***.

Table 1. *Actual values of the factors and corresponding coded levels.*

Variables	Coded Level					
	Single jersey			1×1 rib		
	-1	0	+1	-1	0	+1
Loop-length (X_1), mm	6.6	7.0	7.4	5.09	5.39	5.69
Carriage-speed (X_2), m/s	0.25	0.6	0.95	0.25	0.45	0.65
Yarn-input-tension (X_3), cN	6	8	10	6	8	10
Linear-density(X_4), tex (Ne)	118.1 (5)	78.7 (7.5)	59.1 (10)	118.1 (5)	78.7 (7.5)	59.1 (10)

Table 2. *Response surface equations of various parameters for single jersey knitted fabric.*

	Air-permeability	Thermal-conductivity	UPF
Quadratic regression equations	$134.25 + 22.29X_1 +$ $+ 111.49X_4 + 9.60X_1X_4 +$ $+ 10.36X_3^2 + 25.94X_4^2$	$38.85 – 0.78X_1 – 4.60X_4 +$ $+ 1.16X_4^2$	$10.05 – 1.69X_1 – 7.69X_4 +$ $+ 1.32X_1X_4 + 2.05X_4^2$
R^2	0.99	0.95	0.97

Table 3. *Response surface equations of various parameters for 1×1 rib knitted fabric.*

	Air-permeability	Thermal-conductivity	UPF
Quadratic regression equations	$48.93 + 13.05X_1 +$ $+ 42.33X_4 +$ $+ 6.26X_1X_4 + 12.28X_4^2$	$52.83 – 3.70X_1 +$ $– 10.18X_4 + 2.22X_4^2$	$59.97 – 19.45X_1 +$ $– 53.97X_4 + 17.42 X_1X_4$ $+19.97X_4^2$
R^2	0.99	0.97	0.97

$$\lambda = \frac{Qh}{A\Delta Tt}\text{, in W/mK} \qquad (1)$$

where, λ is the thermal conductivity in W/mK, Q the quantity of heat conducted in J, h the thickness of the material in m, A the area of the surface in m^2, Δt the temperature differential across the material in K and t is the time in s.

UPF tests were determined by an in-vitro method according to the AATCC 183: 2004 standard using a Labsphere 200F. The ultraviolet-protection-factor is a rating which indicates how effectively a fabric blocks UV rays. The UPF of a fabric sample was calculated using the following equation.

$$UPF = \frac{\sum_{290}^{400} E(\lambda)S(\lambda)\Delta(\lambda)}{\sum_{290}^{400} E(\lambda)S(\lambda)\mathrm{T}(\lambda)\Delta(\lambda)} \qquad (2)$$

where, $E(\lambda)$ is the relative erythemal spectral effectiveness, $S(\lambda)$ the solar spectral irradiance in W/m^{2}nm, $\Delta\lambda$ = measured wavelength interval in nm, and $T(\lambda)$ = average spectral transmittance of the sample.

Response surface equations of air-permeability, thermal-conductivity and UPF of the fabrics

To relate the independent controlled factors (loop-length, carriage speed, yarn-input-tension and linear-density) with the air-permeability, thermal-conductivity and UPF, a quadratic regression equation was developed. The general form of the model is shown below:

$$\begin{aligned} \mathrm{Y} = {} & \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \\ & + \beta_4X_4 + \beta_5X_1X_2 + \beta_6X_1X_3 + \\ & + \beta_7X_1X_4 + \beta_8X_2X_3 + \beta_9X_2X_4 + \\ & + \beta_{10}X_3X_4 + \beta_{11}X_1^2 + \beta_{12}X_2^2 + \\ & + \beta_{13}X_3^2 + \beta_{14}X_4^2 \end{aligned} \qquad (3)$$

where, Y is the dependent variables, X_1, X_2, X_3 & X_4 the inputs to the model. and β_1, β_2, β_3, ..., β_{14} are the regression coefficients. Significance tests were conducted on the regression coefficients of the quadratic regression models, where only the regression coefficients, which are significant at a 95% confidence limit, were considered. The fitted quadratic regression models along with the coefficient of determination (R^2) of the single-jersey and 1×1 rib fabrics are tabulated in Tables 2 and 3, respectively. It is observed that a higher R^2 shows a good fit of the response surface equation to the experimental data. It is obvious from ***Tables 2*** and ***3*** that while the loop length and linear density have a considerable influence on air permeability, thermal-conductivity and UPF, the yarn carriage-speed has no significant impact on these response variables. However, it is evident from ***Table 2*** that only the square term of the yarn-input-tension has a little influence on the air-permeability of single-jersey fabric; hence it is omitted from the response surface equation. Thus the modified response surface equation of air-permeability for the single-jersey fabric is given below:

$$\text{Air permeability (single-jersey)} = 134.25 + 22.29X_1 + 111.49X_4 + 9.60X_1X_4 + 25.94X_4^2 \quad (4)$$

Formulation of the optimisation problem

Cotton knitted fabric is mainly suitable for summer-wear, where a higher air-permeability value is desirable as the wearer receives certain extended comfort by means of the evaporation of sweat and transmission of heat from the body to the outer atmosphere through convection. Once again higher thermal-conductivity is also desirable for summer-wear to dissipate heat from the body through conduction. Therefore in the case of cotton knitted summer-wear fabrics, it is desirable to optimise either air-permeability or thermal-conductivity for better comfort.

Approach-1

In a first attempt, the air-permeability for both types of knitted fabrics was considered as an objective function to be maximised and the thermal-conductivity was taken as a constraint function to be retained at a desired level. The constraint boundary was set using data collected from literature and experience. The optimisation problem for single jersey fabric was formulated as follows:

Maximize $AP = 134.25 + 22.29\,X_1 + 111.49\,X_4 + 9.60\,X_1X_4 + 25.94\,X_4^2$

Subjected to TC: $38.85 - 0.78\,X_1 + - 4.60\,X_4 + 1.16\,X_4^2 \geq 40$

$6.6 \geq X_1 \geq 7.4$

$5 \geq X_4 \geq 10$

The optimization problem for double jersey fabric was formulated as follows:

Maximise $AP = 48.93 + 13.05\,X_1 + + 42.33\,X_4 + 6.26\,X_1X_4 + 12.28\,X_4^2$

Subjected to TC: $52.83 - 3.70\,X_1 + - 10.18\,X_4 + 2.22\,X_4^2 \geq 40$

$5.09 \geq X_1 \geq 5.69$

$5 \geq X_4 \geq 10$

The solution for the optimization problem above is given in ***Table 4***. In the case of single jersey fabric, the maximum value of air-permeability was obtained as 114, with a value of thermal-conductivity of 40 at a 7.4 mm loop length and 90.3 tex (6.54 Ne) linear density. Whereas for 1 × 1 rib fabric the maximum value of air-permeability was estimated as 122.85, with a value of thermal-conductivity of 41.17 at a 5.69 mm loop length and 59.1 tex (10 Ne) linear density.

Approach-2

In the second attempt, the thermal conductivity for both types of knitted fabrics was considered as the objective function to be maximized, and the air permeability was taken as a constraint function to be retained at a desired level. The optimisation problem for single jersey fabric was formulated as follows:

Maximise $TC = 38.85 - 0.78\,X_1 + - 4.60\,X_4 + 1.16\,X_4^2$

Subjected to AP: $134.25 + 22.29\,X_1 + + 111.49\,X_4 + 9.60\,X_1X_4 + 25.94\,X_4^2 \geq 80$

$6.6 \geq X_1 \geq 7.4$

$5 \geq X_4 \geq 10$

The optimization problem for double jersey fabric was formulated as follows:

Maximise $TC = 52.83 - 3.70\,X_1 + - 10.18\,X_4 + 2.22\,X_4^2$

Subjected to $AP = 48.93 + 13.05\,X_1 + + 42.33\,X_4 + 6.26\,X_1X_4 + 12.28\,X_4^2 \geq 80$

$5.09 \geq X_1 \geq 5.69$

$5 \geq X_4 \geq 10$

Table 4 depicts the solution for the optimisation problem above. In the case of single jersey fabric, the maximum value of thermal conductivity was obtained as 42.2, with a value of air-permeability of 80 at a 7.4 mm loop length and 105.1 tex (5.62 Ne) linear density. Whereas for double jersey fabric the maximum value of thermal conductivity was estimated as 48.99, with a value of air-permeability of 80 at a 5.09 mm loop length and 60.1 tex (9.82 Ne) linear density.

The fabrics with optimal comfort properties obtained from the two approaches mentioned above were evaluated for the UPF to categorise them under ‘good protection’ (15 ≥ UPF ≥ 24), ‘very good protection’ (25 ≥ UPF ≥ 39) or ‘excellent protection’ (UPF ≥ 40). The UPF values of both types of knitted fabrics were calculated with optimum solutions of the loop length and linear-density using the response surface equations given in ***Tables 2*** and ***3***. The corresponding values of UPF are tabulated in ***Table 4***.

It is evident from ***Table 4*** that in the case of single-jersey fabrics, both approaches 1 and 2 provide good comfort, with TC ≥ 40 and AP ≥ 80. However, both fabrics fail to provide ‘good protection’ against UV. Cotton knitted fabrics with UV < 15 may not provide adequate protection during summer with high solar UV radiation. However, it is always desirable to have ‘very good protection’ or ‘excellent protection’ against UV considering the intense solar UV radiation during summer. However, it is evident from the quadratic equation of UPF and boundary values of the loop-length and linear-density of single jersey fabric that ‘very good protection’ cannot be achieved. The typical porous and open structure of single-jersey fabric allows more UV rays through it.

1 × 1 rib fabrics provide the comfort level desired, with TC ≥ 40 and AP ≥ 80, and they are categorised as ‘good protection’ and ‘very good protection’ against UV for approaches 1 and 2, respectively. A rib fabric with optimal comfort and ‘very good protection’ against UV is always preferable.

In view of the fact above, a third approach to the optimization problem was formulated for cotton knitted summer fabric to have the minimum UV protection desired with optimum comfort properties (TC ≥ 40 and AP ≥ 80), as follows:

Approach-3

The optimisation problem for optimal comfort with ‘good protection’ against UV in the case of single jersey fabric for summer wear was formulated as follows:

Minimise $(\text{UPF} - 15)^2$

Subjected to TC: $38.85 - 0.78\,X_1 + - 4.60\,X_4 + 1.16\,X_4^2 \geq 40$

AP: $134.25 + 22.29\,X_1 + 111.49\,X_4 + +9.60\,X_1X_4 + 25.94\,X_4^2 \geq 80$

$6.6 \geq X_1 \geq 7.4$

$5 \geq X_4 \geq 10$

The optimisation problem for optimal comfort with ‘very good protection’ against UV in the case of 1×1 rib fabric for summer-wear was formulated as follows:

Minimise $(\text{UPF}-25)^2$

Subjected to AP: $48.93 + 13.05\,X_1 + + 42.33\,X_4 +6.26\,X_1X_4 + 12.28\,X_4^2 \geq 80$

TC: $52.83 - 3.70\,X_1 - 10.18\,X_4 + + 2.22\,X_4^2 \geq 40$

$5.09 \geq X_1 \geq 5.69$

$5 \geq X_4 \geq 10$

The optimum UPF, thermal-conductivity, air-permeability and corresponding solutions of the loop-length and linear-density using approach 3 are given in ***Table 4***. It is evident from the data that approach 3 ensures ‘good protection’ and ‘very good protection’ against UV rays with desired comfort values in the case of single and 1 × 1 rib knitted fabrics, respectively.

For the same gauge machine and linear-density, 1 × 1 rib knitted fabrics provide better comfort with more UV protection than single jersey fabrics.

It is also evident from the equations in ***Tables 2*** and ***3*** that coarser yarn and a smaller loop-length produce lower air-permeability, higher thermal-conductivity and higher UPF and vice-versa. This may be explained by the surface mass of the fabric, which is a function of the loop-length and linear-density. A higher surface mass of the fabric produces a compact structure, which resists air transmission and UV through it, and thus leads to low air-permeability and higher UV protection (UPF). Once again a compact fabric structure results in a higher fibre to pour ratio in the fabric and leads to higher thermal-conductivity. However, a relatively more porous structured fabric will lead to higher air-permeability, lower UPF and lower thermal-conductivity. A trade-off solution for air-permeability, UPF and thermal-conductivity with desired levels is possible at optimum values of the loop-length and linear-density which are found to be neither the minimum nor the maximum in the range of the present experimental set-up.

Validation of optimisation problem

The optimization problem of approach-3 was considered for validation. For this purpose, single-jersey and 1 × 1 rib knitted fabric samples were made on the same 12 gauge computerised flat knitting machine with a digitized stitch control system to acquire the desired loop length. 100% cotton gas mercerized yarns of 90.8 tex i.e 6.5 Ne (6.45 Ne ≈ 6.5 Ne) and 59.1 tex i.e 10 Ne (9.99 Ne ≈ 10 Ne), and loop-lengths of 6.8 mm (6.76 mm ≈ 6.8 mm) and 5.5 mm (5.54 mm ≈ 5.5 mm) were used for single-jersey and 1 × 1 rib knitted fabric samples, respectively. The samples were washed for complete relaxation and tested for air-permeability, thermal-conductivity and UPF according to the standard explained before. The values obtained and optimized values were compared, with the results shown in ***Table 5***. It is evident from ***Table 5*** that the values of air-permeability, thermal-conductivity and UPF obtained are very close to the optimised values (with error < 5%) for both single-jersey and 1 × 1 rib knitted fabrics.

Table 4. *Solutions for the optimization problems for three approaches*

Fabric type	Approach	Objective	Constraint	Optimum values	Solution
Single-jersey	Approach 1	Maximize *AP*	*TC* ≥ 40	*AP* = 114 *TC* = 40 *UPF* = 11.10	X_1 = 7.4 mm X_4 = 6.54 Ne (90.3 tex)
	Approach 2	Maximize *TC*	*AP* ≥ 80	*AP* = 80 *TC* = 42.20 *UPF* = 14.33	X_1 = 7.4 mm X_4 = 5.62 Ne (105.1 tex)
	Approach 3	Minimize (UPF – 15)^2	*TC* ≥ 40 *AP* ≥ 80	*AP* = 80.95 *TC* = 41.46 *UPF* = 15	X_1 = 6.76 mm X_4 = 6.45 Ne (91.6 tex)
1×1 rib	Approach 1	Maximize *AP*	*TC* ≥ 40	*AP* = 122.85 *TC* = 41.17 *UPF* = 23.94	X_1 = 5.69 mm X_4 = 10 Ne (59.1 tex)
	Approach 2	Maximize *TC*	*AP* ≥ 80	*AP* = 80 *TC* = 48.99 *UPF* = 30.33	X_1 = 5.09 mm X_4 = 9.82 Ne (60.1 tex)
	Approach 3	Minimize (UPF – 25)^2	*TC* ≥ 40 *AP* ≥ 80	*AP* = 112.7 *TC* = 43.08 *UPF* = 25	X_1 = 5.54 mm X_4 = 9.99 Ne (59.1 tex)

Table 5. *Optimised and fabric properties obtained: O = optimised value, A = achieved value.*

Fabric type	Optimised parameters	Air-permeability			Thermal-conductivity			UPF		
		O	A	Error, %	O	A	Error, %	O	A	Error, %
Single-jersey	6.76 mm and 91.6 tex (6.45 Ne)	80.95	83.4	2.9%	41.46	40.1	3.4%	15	15.3	1.96%
1×1 rib	5.54 mm and 58.1 tex (9.99 Ne)	112.7	108.2	4.2%	43.08	45.1	4.5%	25	25.9	3.5%

Conclusions

A system of fabric engineering was established to optimise comfort with desired protection against UV rays for both single-jersey and 1 × 1 rib knitted fabrics. The typical porous and open structure of single jersey and 1 × 1 rib knitted fabrics provides better comfort, but transmits more UV rays through it, thus making it challenging to engineer knitted fabrics with simultaneous high comfort and UV protection. Quadratic regression equations for air-permeability, thermal-conductivity and UV were developed and optimisation problems then formulated for knitted fabric engineering to obtain optimum comfort with desired UV protection. Optimum solutions for the loop-length and linear-density were then evaluated for knitted fabrics with optimum comfort and desired UV protection level. The newly engineered fabrics were developed using optimum combinations of the loop-length and linear density. The target and engineered fabric properties are found to be in proper harmony. The single-jersey fabric can provide TC ≥ 40 and AP ≥ 80 with 'good protection' against UV, whereas 1 × 1 rib fabric can provide similar comfort with 'very good protection' against UV. 1 × 1 rib fabric provides better protection from UV and comfort than single jersey fabrics produced on the same machine gauge. In this study, only the comfort of summer fabrics were highlighted as they were made with 100% cotton fibres, which are mainly used for summer-wear. Nevertheless, a separate similar study can be accomplished using acrylic, wool or blends of acrylic and wool for winter-wear fabrics.

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INSTITUTE OF BIOPOLYMERS AND CHEMICAL FIBRES

LABORATORY OF BIODEGRADATION

The Laboratory of Biodegradation operates within the structure of the Institute of Biopolymers and Chemical Fibres. It is a modern laboratory with a certificate of accreditation according to Standard PN-EN/ISO/IEC-17025: 2005 (a quality system) bestowed by the Polish Accreditation Centre (PCA). The laboratory works at a global level and can cooperate with many institutions that produce, process and investigate polymeric materials. Thanks to its modern equipment, the Laboratory of Biodegradation can maintain cooperation with Polish and foreign research centers as well as manufacturers and be helpful in assessing the biodegradability of polymeric materials and textiles.

The Laboratory of Biodegradation assesses the susceptibility of polymeric and textile materials to biological degradation caused by microorganisms occurring in the natural environment (soil, compost and water medium). The testing of biodegradation is carried out in oxygen using innovative methods like respirometric testing with the continuous reading of the CO_2 delivered. The laboratory's modern MICRO-OXYMAX RESPIROMETER is used for carrying out tests in accordance with International Standards.

The methodology of biodegradability testing has been prepared on the basis of the following standards:

- **testing in aqueous medium:** 'Determination of the ultimate aerobic biodegrability of plastic materials and textiles in an aqueous medium. A method of analysing the carbon dioxide evolved' (PN-EN ISO 14 852: 2007, and PN-EN ISO 8192: 2007)
- **testing in compost medium:** 'Determination of the degree of disintergation of plastic materials and textiles under simulated composting conditions in a laboratory-scale test. A method of determining the weight loss' (PN-EN ISO 20 200: 2007, PN-EN ISO 14 045: 2005, and PN-EN ISO 14 806: 2010)
- **testing in soil medium:** 'Determination of the degree of disintergation of plastic materials and textiles under simulated soil conditions in a laboratory-scale test. A method of determining the weight loss" (PN-EN ISO 11 266: 1997, PN-EN ISO 11 721-1: 2002, and PN-EN ISO 11 721-2: 2002).

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The following methods are applied in the assessment of biodegradation: gel chromatography (GPC), infrared spectroscopy (IR), thermogravimetric analysis (TGA) and scanning electron microscopy (SEM).

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