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Overview on infrared spectra of textile products with a focus on fiber blends and special fiber materials

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ABSTRACT

The IR spectroscopy is a versatile analytical method to identify chemical compounds and analyze their composition. This spectroscopic method is fast and provides a non-destructive analysis of the investigated materials. By this, the IR spectroscopy is an excellent tool for investigation of consumer textile products which are often produced from different types of synthetic and natural fibers. The current overview supports a broad overview of IR spectra from textile products from mono-materials and fiber blends. Further, a view on selected special and high-performance fibers is provided. The determined IR spectra are structurally discussed under consideration of the related chemical structures of polymers building up the fiber materials. The advantages but also the limits of this method for analysis of fiber materials, commercial fiber-based products and special fibers are presented. Overall, valuable spectroscopic data on polymers and fiber materials are supported. These data are helpful for people working in quality control, fiber identification and analytics. Finally, this current overview paper, is a useful educational tool to teach the composition of fiber materials, the chemical nature of fibers and related analytical methods.

Keywords
textile products,
fiber blends,
IR spectroscopy,
cotton,
polyester
polyamide,
acrylics,
polyolefins,
polyvinyl alcohol,
chlorinated fiber materials

1 Introduction

The absorption of infrared radiation by chemical compounds leads to acceleration of vibrations of molecules [1-3]. This molecular vibration can be understood as a collection of vibrations from different functional groups and their presence in different covalent bonds. By this, different parts of a molecule are responsible for the absorption of a certain type of IR radiation containing the specific energy responsible for the acceleration of a specific vibration [3-5]. In IR spectroscopy the amount of IR radiation absorbed by a chemical component is determined and recorded as wavenumber (unit 1/cm). The wavenumber is the reciprocal value of the wavelength of absorbed IR radiation. By evaluation of absorption peaks determined in such an IR spectrum, functional groups and related vibrations can be identified, which can be used for qualitative analysis of the investigated material and its composition [4-6]. Further, the pattern of IR absorption spectra can be used as kind of fingerprint to identify a chemical compound by comparison to earlier reported IR spectra [4,7,8]. Based on this, the IR spectroscopy developed to a powerful analytical tool for investigation and analysis of compounds from organic chemistry, macromolecular chemistry and material science [4]. In the field of textile materials, IR spectroscopy is established for analysis and identification of natural and synthetic fibers [9-12]. This statement is valid for conventional fibers but also for special fibers and high-performance fibers [13,14]. The IR spectroscopy is used as analytical tool on a broad range of different fiber materials also beyond textile as composite materials, artificial leather and leather [15-19].

In recent years a special focus was set on the use of IR spectroscopic devices for fast detection of textile materials in sorting processes for fiber recycling [20-25]. Without a doubt, there is a broad range of different IR spectroscopic data on textile and fibers available in literature [9-12]. However, often the reported IR spectra are of medium quality and a structural discussion of measurement data is done only partly [9]. The discussion of IR spectra from fiber blends of textile consumer products is present only in view reports [26,27]. Recently an interesting study on the identification and classification of blended fibers is published focusing on the IR spectroscopy in combination with chemometric analysis [28]. IR spectroscopy is especially valuable for investigation of textile products made from different types of fiber, because it is a non-destructive and fast measurement method. This method is powerful for fast control of material quality and composition. However, often reported data do not cover the broad range of different textile consumer products available on the market. With this background, the current overview is dedicated to the IR spectra of textile consumer products made from different fiber blends. Such products made from different types of fibers exhibit several advantages and are broadly used in clothing and other textile products. The main aim for using of fiber blends is the combination of the different advantageous properties of different fibers combined in the blend. For clothing roughly three different types can be categorized. First, by using of fiber blends the textile comfort should be improved. Examples for this case are the combination of polyester fibers with cotton fibers, combining the water up-take capacity of cotton with the mechanical stability of polyester fibers [29-32]. Second, by using fibers with a special functional property, functional textile products can be realized. A prominent example are antimicrobial products containing small amounts of antimicrobial fibers [33-35]. Such antimicrobial fibers are e.g. silver-plated polyamide fibers [36]. Also, flame-retardant textile can be realized by blending with fibers containing flame retardant properties [37, 38]. Such flame-retardant fibers are e.g. co-polymers from acrylic and chlorinated units [39]. Third, by blending with elastane fibers the personal fit of the clothing product is improved [40]. Working and safety gloves are together with socks products which contain typically a blend of a broad range of different fiber materials [41,42].

To guide a structural discussion, first typical textile mono-materials are presented as references to discuss especially the occurrence of distinct IR signals to vibrations of functional groups in the fiber materials. On base of these references, a broad range of textile consumer products and their related IR spectra are presented and a structural discussion of spectral data is performed. In an additional section, IR spectroscopic data for special fibers are reported and structurally discussed. The reported data cover a broad range of various textile products and fiber types and are valuable offering a helpful tool for people working in textile analytics, material science, quality control and with textile recycling processes. Finally, this current overview paper can be also used as educational tool to teach the composition of fiber materials, the chemical nature of fibers and related spectroscopic methods.

2 Fiber materials and infrared spectroscopic methods

2.1 Fiber materials

A various number of different fiber materials are chosen for the current infrared spectroscopic measurements. First, reference materials made only from one type of fiber are considered. Second, textile consumer products with different composition used for a broad range of different applications are investigated. Third, a selection of several special fibers is considered to broaden the value of IR spectroscopic data and the structural discussion.

2.1.1 Mono-material references

For first reference measurements, materials are analyzed which are built up by one type of fiber material. An overview on those so-called mono-material references is presented in Table 1. The mono-material references MR1 to MR6 are gained as test fabrics used for determination of staining properties during washing procedures. These fabric samples are supplied by Wfk Testgewebe GmbH (Brüggen, Germany). The mono-material reference MR7 is a cotton umbel directly taken from a dried cotton plant. With a Dralon fiber from the year 1959 also a historical polyacrylic fiber is considered as reference. Two types of silk materials (fiber and cocoon) are investigated as mono-material references. Hair samples for reference measurements are taken for two different species – human and dog. The human hair is taken from the author himself. The dog hair is freshly cut from a brown Labrador. Two regenerated fibers are considered – regenerated from protein (casein) and from alginate. The regenerated protein fiber is especially chosen for comparison with the other protein-based fiber samples from wool or silk. The alginate fiber is chosen for comparison with other carbohydrate-based fiber samples. Both casein and alginate fiber samples are gained from the fiber collection of the Chemistry Faculty of the Hochschule Niederrhein. Finally, a sea grass ball (Pillae marinae) is used for IR spectroscopic investigation. This sea grass ball was kindly supplied by Prof. Textor (Hochschule Reutlingen).

Table 1. Mono-material references – investigated materials.

Reference No.	Material
MR1	Cotton fabric
MR2	Polyester / PET fabric
MR3	Polyamide / Nylon fabric
MR4	Wool fabric
MR5	Polyacrylic fabric
MR6	Cellulose acetate fabric
MR7	Cotton umbel
MR8	Polyacrylic fibers / historical (Dralon 1959)
MR9	Silk fibers
MR10	Silk cocoon
MR11	Human hair
MR12	Dog hair
MR13	Casein fiber
MR14	Alginate fiber
MR15	*Pilae marinae* / sea ball

2.1.2 Textile products

For IR spectroscopic investigations textile consumer products from a broad range of different applications are considered. Some of these products are made from only one type of fiber. However, most of them are built up by two or more different fiber types. An overview on the investigated products is given in Table 2, which lists also the fiber composition, the appearance and the main purpose of these textile products.

Table 2. Investigated textile products listed with their material composition and short description of purpose

No.	Composition	Appearance	Purpose
TP1	100% cotton	White yarn	For knitting handcraft
TP2	100% cotton	White fabric	Conventional T-Shirt
TP3	100% cotton	Orange woven fabric	For UV-protective applications
TP4	98% cotton / 2% elastane	Light colored fabric	Conventional T-Shirt
TP5	90% cotton / 10% viscose	Blue colored fabric	Pajama / children cloth
TP6	100% cotton	Blue woven fabric	Blue jeans
TP7	100% polyester	Black fabric	T-shirt for sport purposes
TP8	84% polyester / 16% elastane	Green fabric	T-shirt for sport purposes
TP9	100% polyester / Trevira CS	Dark colored fabric	Flame retardant applications
TP10	90% polyester / 10% polyamide	Light colored fabric	Towel
TP11	100% polyester	White fibers	Artificial imitation of cotton umbel
TP12	76% polyester / 18% viscose / 6% cotton	Grey fabric	Bag for handy craft tools
TP13	64% polyester / 36% Tencel	Orange fabric	T-shirt for UV protective purposes
TP14	100% polyamide	Black fabric	Light ladies socks
TP15	96% polyamide / 4% elastane	Black fabric	Pullover for children
TP16	84% polyamide / 14% elastane	Light blue fabric	T-shirt for UV protective purposes
TP17	75% wool / 25% polyamide	Colored yarn	For knitting handcraft
TP18	100% polyacrylic	Colored yarn	For knitting handcraft
TP19	100% polyacrylic	Orange knitted fabric	Working hat
TP20	98% polyacrylic / 2% polyester	Colored yarn	For knitting handcraft
TP21	60% cotton / 40% polyacrylic	Colored yarn	For knitting handcraft
TP22	58% cotton / 33% polyacrylic / 9% polyamide	Colored yarn	For knitting handcraft
TP23	72% polyacrylic / 18 wool / 10% polyamide	Colored yarn	For knitting handcraft
TP24	90% polyacrylic / 10% polyamide	Colored yarn	For knitting handcraft
TP25	58% modacrylic / 37% cotton / 3% elastane / 2% antistatic	Black fabric	Scarf for flame retardant purposes
TP26	60% modacrylic / 39% cotton / 1% other fibers	Black fabric	T-shirt for flame retardant purposes
TP27	58% polyester / 23% modacrylic / 19% cotton	Black textile belt	Textile belt for flame retardant purposes
TP28	100% polypropylene	White woven material	Shopping bag
TP29	100% polypropylene	Red non-woven material	Shopping bag
TP30	100% polypropylene	Colored rope	For fixation
TP31	100% polyethylene	White woven material, laminated	For outdoor covering
TP32	100% polyethylene, LD-PE	Uncolored polybag	Packaging of samples and goods
TP33	Polyethylene, HPPE	Grey rope	Rope with high strength
TP34	High performance polyethylene	Grey glove	Cut-resistance glove
TP35	Polyvinyl alcohol	White sewing yarn	Water soluble sewing yarn

2.1.3 Special fiber materials

To broaden the base of reported IR spectroscopic data on fiber materials, also special fibers and high-performance fibers are considered. The scope of the actually reported samples on special fibers goes beyond the earlier reported data on IR spectra of high-performance fibers [14]. An overview on the now reported special fibers is shown in Table 3. Product names are summarized together with related polymer composition. Mainly these fibers are based on chlorine containing polymers and are also dedicated to flame-retardant applications [43]. All these fibers are gained from the fiber collection of the Chemistry Faculty of the Hochschule Niederrhein.

Table 3. Investigated special fiber materials listed with their name and polymer composition

No.	Product name	Polymer composition
SP1	Isovyl	Polyvinylchloride / PVC
SP2	Rhovyl	Polyvinylchloride / PVC
SP3	Thermovyl	modified PVC
SP4	Saran PV	Polyvinylidenchloride / PVDC
SP5	VinyonN	Copolymer of acrylonitrile and vinyl chloride / PAN-PVC
SP6	Dynel	Copolymer of acrylonitrile and vinyl chloride / PAN-PVC
SP7	Yinylon	Polyvinylalcohol / PVAl

2.2 Infrared spectroscopy

All reported IR-spectra are recorded with a FT-IR spectrometer IRTracer-100 from Shimadzu (Japan) equipped a Specac Golden Gate ATR unit. The ATR crystal is made from diamond. The number of scans is set to a minimum of 20 for each measurement. The IR spectroscopic measurements are done on the samples as received without any further pretreatment, cleaning or modification. This is done following the purpose of investigating textile products as they are offered and supplied on the market. The textile and fiber samples are investigated without special treatment and are pressed as they received in the ATR unit on the ATR crystal.

3 Fiber materials and their IR spectra

3.1 Mono-material references

Polyester and cotton are the most important and the most used fiber materials worldwide [44,45]. For this, the presentation of the mono-material references starts with these both materials. The IR spectra of cotton and polyester are presented in Figure 1. Both IR spectra are in good agreement to the spectra of these materials reported in literature [11, 20, 46-49]. The IR spectrum of the cotton reference sample is mainly based on the cellulosic molecular structure building up the cotton fiber in high ratio. Other cellulose based fiber materials like hemp or regenerated fibers like viscose exhibit quite similar pattern in the IR spectra [50]. However, a detailed view in the fingerprint area of the IR spectra can offer the possibility for fiber identification based on non-cellulosic components in the natural fibers [51].

To explain the main signals in the IR spectrum of cotton by view on the cellulosic structure, it can be simplified by discussion only the vibrations on distinguished structural units (compare Fig. 2). The medium signals at 2857 cm^{-1} and 2900 cm^{-1} can be assigned to the stretching vibration of C-H bonds [4]. The signal 2900 cm^{-1} is here related to symmetric stretching vibration, while the signal at 2857 cm^{-1} stands for antisymmetric stretching vibration of -CH_2- units. The signal at 1426 cm^{-1} can be assigned to C-H deformation vibration of -CH_2- units [4]. The broad signal at around 3300 cm^{-1} is related to the O-H stretching vibration of the hydroxy groups of cellulose. Additionally, water absorbed from these natural fibers contributes also to this broad signal with O-H vibrations. The strongest peak at 1128 cm^{-1} is related to C-O stretching vibration of hydroxy groups and acetal units [11]. The weak signal at 1637 cm^{-1} is related to absorbed water [5].

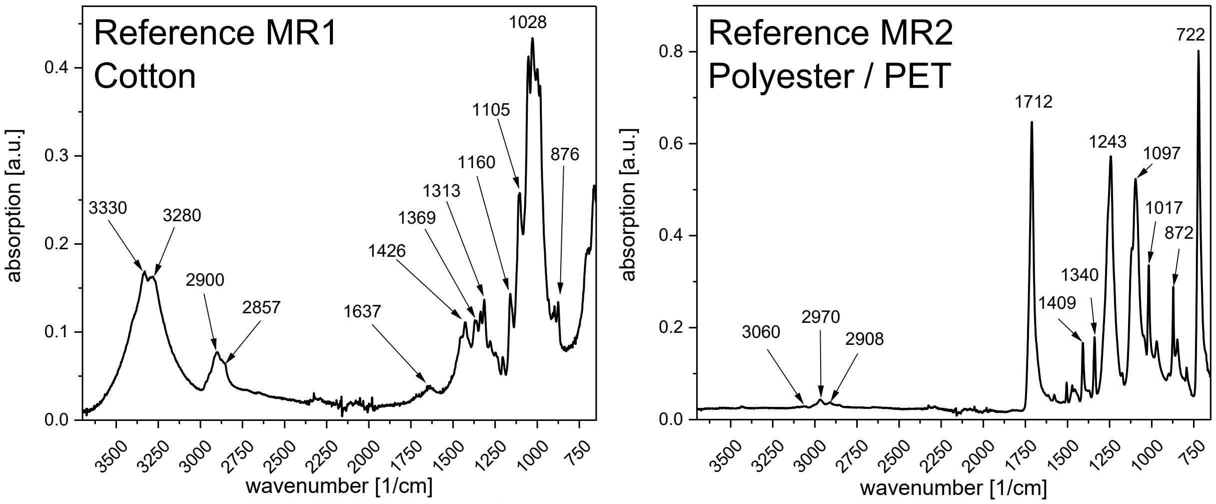

Fig. 1 Infrared spectra of cotton and polyester mono-material references.

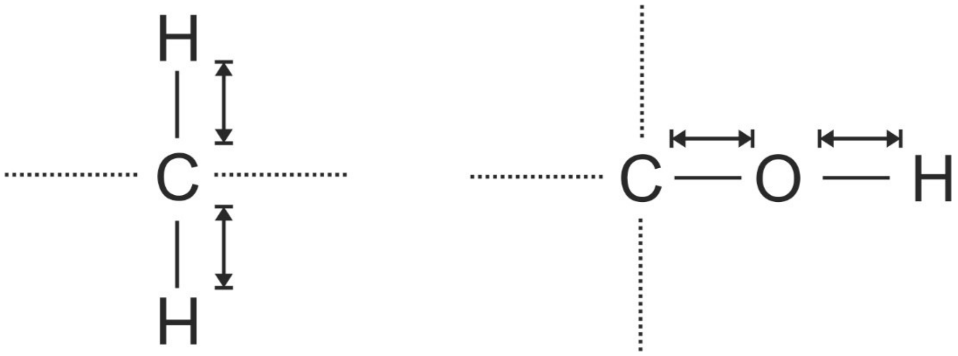

Fig. 2 Structural units of cellulose responsible for main signals in the related infrared spectrum – left: C-H stretching vibrations; right: stretching vibrations of C-O and O-H bonds.

The IR spectrum of polyester fabric is totally different to the spectrum of cotton (Fig. 1). The signals related to C-H stretching vibrations detected from polyester are very weak. Additional to the two signals at 2908 cm^{-1} and 2970 cm^{-1}, also an extremely weak signal can be determined at 3060 cm^{-1}. The both signals at 2908 cm^{-1} and 2970 cm^{-1} are related to C-H stretching vibrations of the aliphatic ethylene unit $-CH_2-CH_2-$ in the polyester structure (polyethylene terephthalate, PET). In contrast, the signal at 3060 cm^{-1} is related to C-H stretching vibration of carbon atoms which are part of the aromatic ring system [4,48]

The three signals of polyester at 1097 cm^{-1}, 1243 cm^{-1} and 1712 cm^{-1} can be assigned to different vibrations from the from the ester group of polyester (compare Fig. 3). The signal at 1712 cm^{-1} is the most typical signal for polyester and is related to the C=O stretching vibration of the ester group. The two signals at 1097 cm^{-1} and 1243 cm^{-1} are assigned to C-O stretching vibrations in the ester unit but differing, because one C-O bond is neighboring the C=O unit and is a conjugated part of the aromatic ring system [5]. The signal at 1243 cm^{-1} is also assigned to an asymmetric C-C-O stretching vibration involving one carbon atom from the aromatic ring system. Following, the signal at 1097 cm^{-1} is assigned to an asymmetric O-C-C stretching vibration [52]. The strongest peak at 722 cm^{-1} is assigned to a C-H wagging vibration as part of the aromatic ring system of polyester PET polyethylene terephthalate [52]. This signal is typical for a polyester containing an aromatic unit. Non-aromatic polyester materials like PLA do not exhibit this peak [53,54].

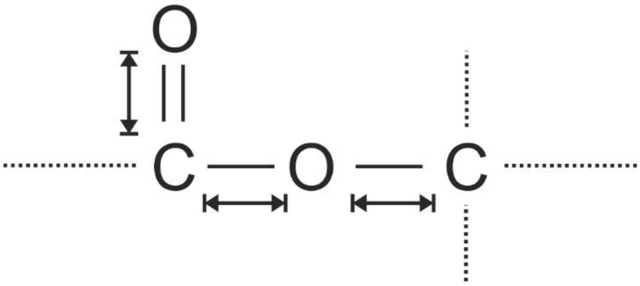

Fig. 3 Schematic drawing of an ester unit responsible for main signals in the related infrared spectrum of polyester – C=O stretching vibration and stretching vibrations of C-O bonds.

As second cotton reference material a cotton umbel directly taken from a dried cotton plant is investigated (Fig. 4). The IR spectrum of this material is nearly identical to the IR spectrum of the woven cotton reference fabric, even if it is directly taken from the plant without further processing steps. By this, it can be stated that the reference materials MR1 and MR7 are mostly identical from there chemical composition.

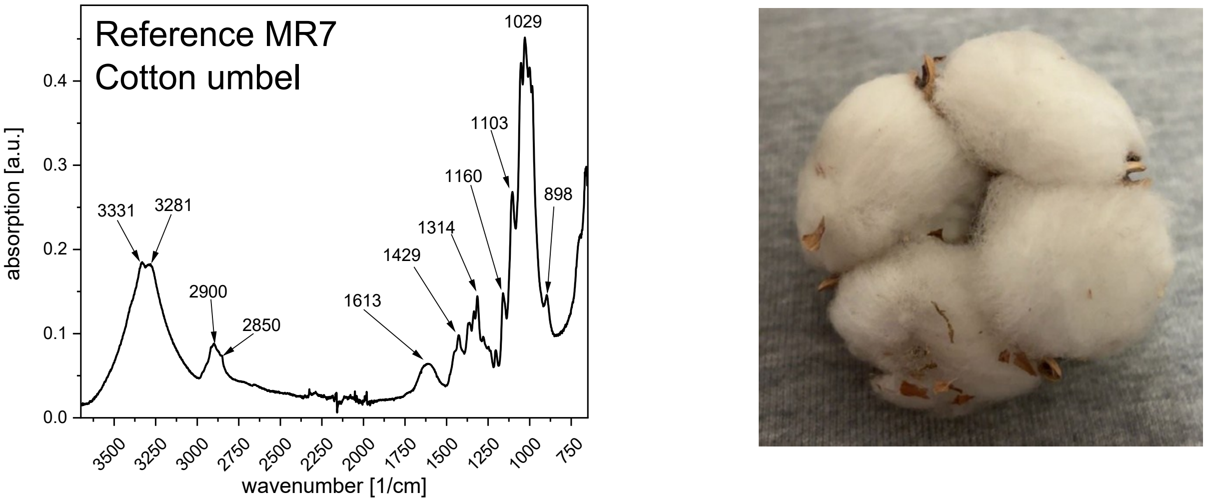

Fig. 4 IR spectrum and photograph of cotton umbel – sample MR7.

The IR spectra of polyamide (Nylon) and wool mono-materials are presented together in Fig. 5, because both fabric materials are mainly dominated by the functional group amide (see Fig. 6). The measured IR spectra of both fabrics are quite similar to spectral data reported for wool and polyamide fiber materials in literature [11, 20, 55]. The amide group can perform several different vibrations and is therefore responsible for several typical signals in the IR spectra of polyamide and wool. For polyamide, the two signals at 2860 cm^{-1} and 2932 cm^{-1} can be assigned to C-H stretching vibrations of aliphatic -CH$_2$- units. The signal at 2932 cm^{-1} is related to symmetric stretching vibration, while the signal at 2860 cm^{-1} is related to antisymmetric stretching vibration [4]. Most other signals in the IR spectrum of polyamide can be related to the amide group. The signal at 3294 cm^{-1} is assigned to N-H stretching vibration. The strongest peak at 1632 cm^{-1} is assigned to the stretching vibration of C=O double bond from the amide group. This signal is also named as Amide I [5,56]. The second strongest peak at 1533 cm^{-1} can be assigned to a combined vibration of a C-N stretching vibration with a deformation vibration of C-N-H. This signal is also named as Amide II [5,57]. The medium signal at 3076 cm^{-1} can be assigned to an overtone of the Amide II signal [4]. The signal at 1274 cm^{-1} can be related to an Amide III signal with combined deformation vibrations of NH and OCN units [5]. The both signals at 1464 cm^{-1} and 1416 cm^{-1} are assigned to scissoring vibrations of -CH$_2$- units [56].

For the IR spectrum of the wool fabric, the main signal related to the amide group can be identified – Amide I at 1628 cm^{-1} and Amide II at 1515 cm^{-1} [5]. These signals are not exactly at the same positions as in the IR spectrum of polyamide, because different chemical surroundings of the amide groups and different side chains in the protein structure are present in the wool fiber. The signal at 3270 cm^{-1} is much broader for wool compared to polyamide, because in wool additional to N-H vibrations also O-H vibrations from amino acids containing hydroxy groups are contributing – as well as water absorbed by the hydrophilic wool fibers [4]. Wool as protein fiber is built up by a broad range of different amino acids carrying different functional groups [58, 59]. For this reason, a more detailed discussion of signals in the fingerprint area of the IR spectrum of wool should not be supported to avoid misleading interconnections.

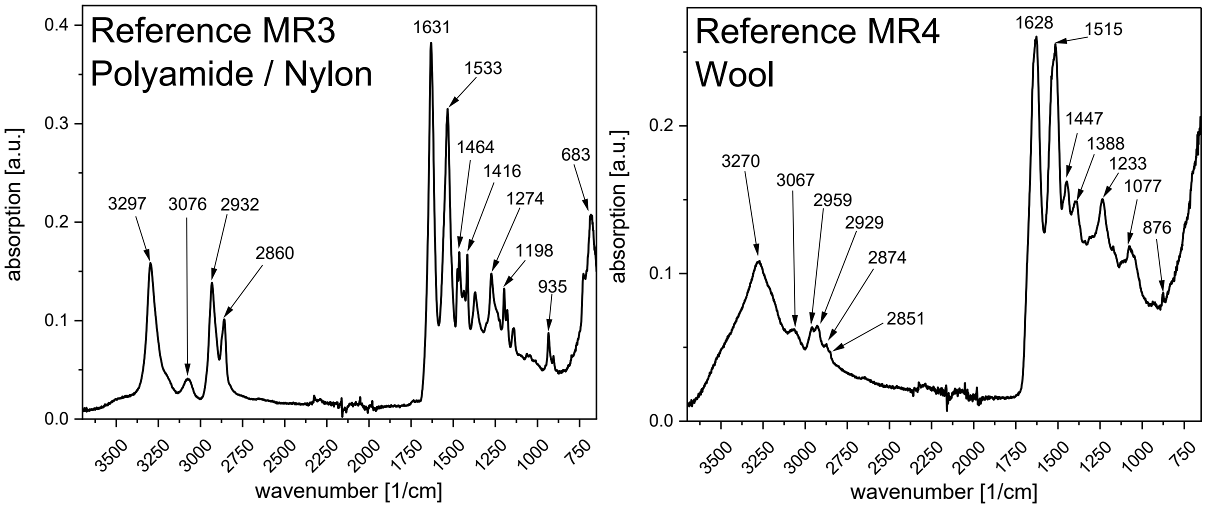

Fig. 5 Infrared spectra of polyamide and wool mono-material references.

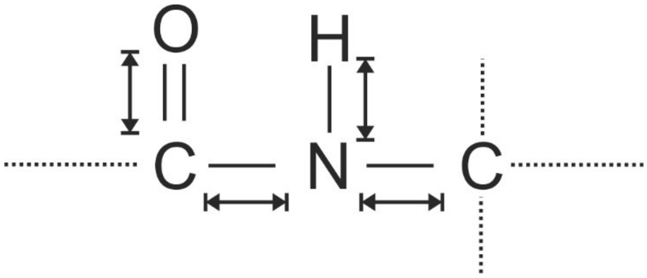

Fig. 6 Schematic drawing of an amide unit responsible for main signals in the related infrared spectrum of polyamide and protein based fibers – N-H stretching vibration, C=O stretching vibration and stretching vibrations of C-N bonds.

The IR spectra of polyacrylic and cellulose acetate reference materials are presented in Figure 7. The IR spectrum of the polyacrylic mono-material fabric exhibits a quite good similarity to spectral data reported in literature [11,60-65]. Also, for the IR spectrum recorded from the cellulose acetate reference fabric a good similarity to spectral data from literature is determined [11,66]. The IR spectrum of polyacrylic exhibits a typical peak at 2242 cm^{-1} which is assigned to the CN triple bond from the nitrile unit (compare Fig. 8) [4]. Remarkable is that this IR spectrum exhibit also a signal at 1730 cm^{-1} which is typical for an ester group [4]. Reported IR spectra for homo-polymeric polyacrylonitrile (homo-PAN) do not contain such a signal [12,63]. However, usually polyacrylonitrile fibers and modacrylic materials are built up by PAN co-polymers and the co-units often contain also ester groups. An example for a chemical structure of such a PAN co-polymer is shown in Fig. 9. The IR spectrum of polyacrylic material MR5 exhibits also a weak signal at 1666 cm^{-1}. Such a signal is assigned to the solvent dimethylformamide DMF [65]. DMF is used as solvent during fiber production of polyacrylic fibers. Due to the high boiling point of DMF, residues of this solvent can be found in the polyacrylic fibers [67]. The molecular structure of DMF exhibits an amide group, so this signal at 1666 cm^{-1} is related to the Amide I signal of DMF (C=O stretching vibration from the amide group). The IR spectrum recorded from cellulose acetate is dominated by three strong peaks at 1031 cm^{-1}, 1214 cm^{-1} and 1734 cm^{-1} which are related to the vibration of the ester group of the acetate unit attached to the cellulose molecule [66]. However, in comparison to the polyester material, for cellulose acetate a weak and broad signal around 3495 cm^{-1} is observed, which can be assigned to O-H stretching vibrations from hydroxy groups. The typical peak at 722 cm^{-1} determined for conventional polyester fibers is not determined for polyacrylic fibers or cellulose acetate fibers, because this signal at 722 cm^{-1} is related to a wagging vibration at an aromatic ring system and both polyacrylic fibers or cellulose acetate fiber do contain aromatic structures.

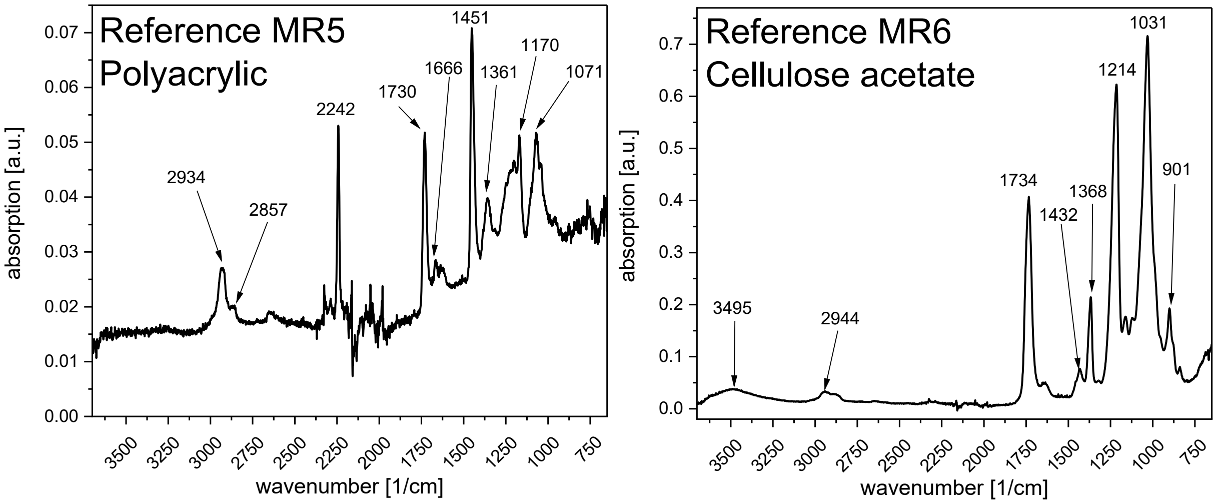

Fig. 7 Infrared spectra of polyacrylic and cellulose acetate mono-material references.

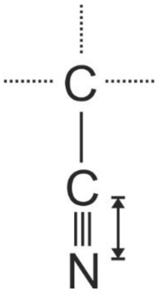

Fig. 8 Schematic drawing of a nitrile unit responsible for the typical signal in the related infrared spectrum of polyacrylonitrile – stretching vibration of CN triple bond.

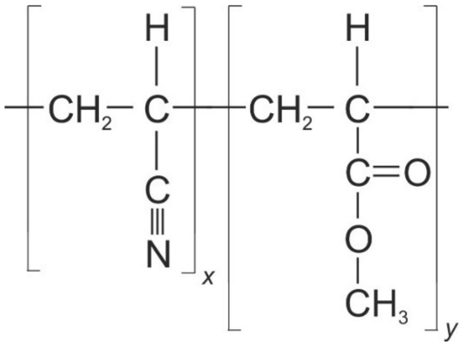

Fig. 9 Example for a chemical structure of a PAN-copolymer with an ester group containing co-unit.

Fiber sample MR8 is chosen as special mono-material reference for polyacrylic fibers. This fiber sample is distributed under the brand name Dralon (Bayer, Germany) and produced several decades ago in year

1959. The IR spectra of both polyacrylic fiber materials MR5 and MR8, even if sample M8 is produced more than 50 years ago. The chemical structures of both fibers are quite similar even if they are produced in different decades and even also under respect of long storage duration.

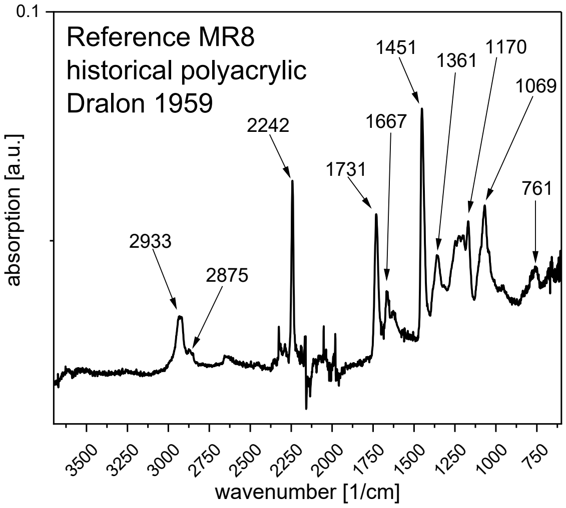

Fig. 10 IR spectrum of a historical polyacrylic fiber sample prepared in the year 1959.

Beside wool, silk is the second important natural protein fiber. For that reason, in the current overview also two reference samples related to silk are reported. Here, silk fibers and a complete untreated silk cocoon are considered. For comparison, photographs of both samples are presented in Fig. 11.

Fig. 11 Photographs from silk fibers and silk cocoons (mono-material references MR9 and MR10.

The IR-spectra of both silk related reference materials are compared in Figure 12. The main patterns of the IR-spectra are related to the protein structure of silk and here mainly determined by the signals related to the vibrations of the amide group as dominating chemical unit. For this, there is a certain similarity to the IR spectrum of the wool reference material. However, the composition of amino acids building up silk protein are different to the composition for wool. Silk protein mainly contain the quite simple structured amino acids Glycin and Alanin [68,69]. Additional to the main Amide signals, several different signals are determined in the spectral fingerprint range below 1500 cm^{-1}. Those signals can be used for identification and classification of silk from different origin [70]. The IR-spectra recorded from samples MR9 and MR10 are in quite good similarity with literature data and difference between silk fibers and silk cocoon can be explained by degumming processes [69].

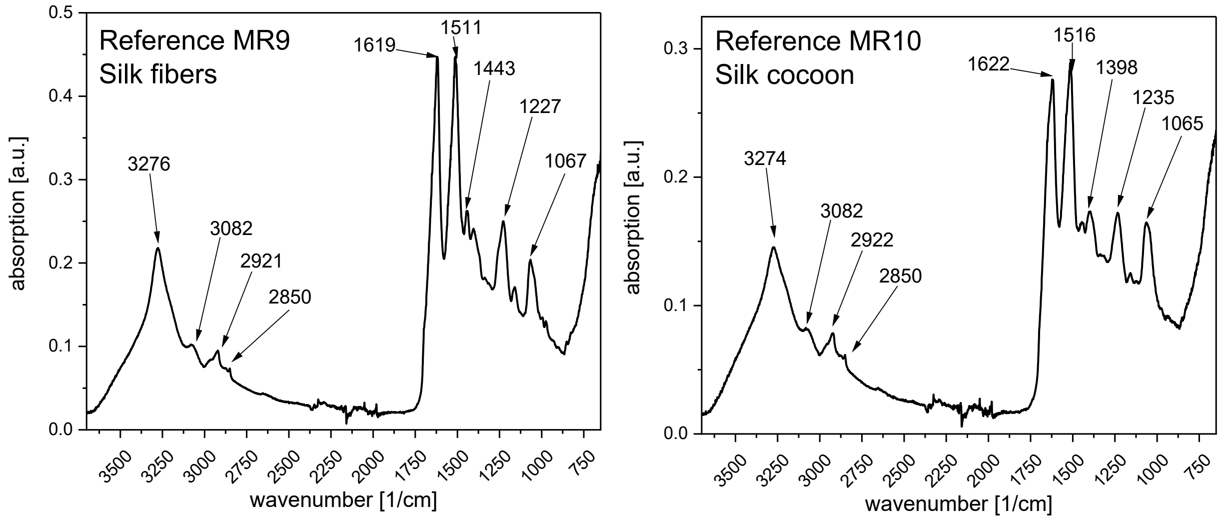

Fig. 12 IR spectra recorded from silk fibers and a silk cocoon.

As further animal-based reference fiber materials, two hair samples are taken into account (Figure 13). One hair sample is from a human and the second hair sample is from a dog. The IR spectra of both hair samples are quite similar to each other and also quite similar to the IR spectrum of the wool reference. The patterns of these IR spectra are mainly related to the protein structure of these hairs and especially to the different vibrations caused from the amide groups. IR-spectra from several human hair samples are well reported in literature. However, the quality of those spectroscopic data varies in a broad range. These literature IR spectra exhibit high similarity to the actually measured IR spectra [71-73]. Nevertheless, from these reported IR spectra an evaluation of the signals in the fingerprint range is done, to provide a correlation to the age of humans or certain hair treatment procedures. These are obviously interesting approaches and investigations but based on the reported quality of spectroscopic data also quite speculative.

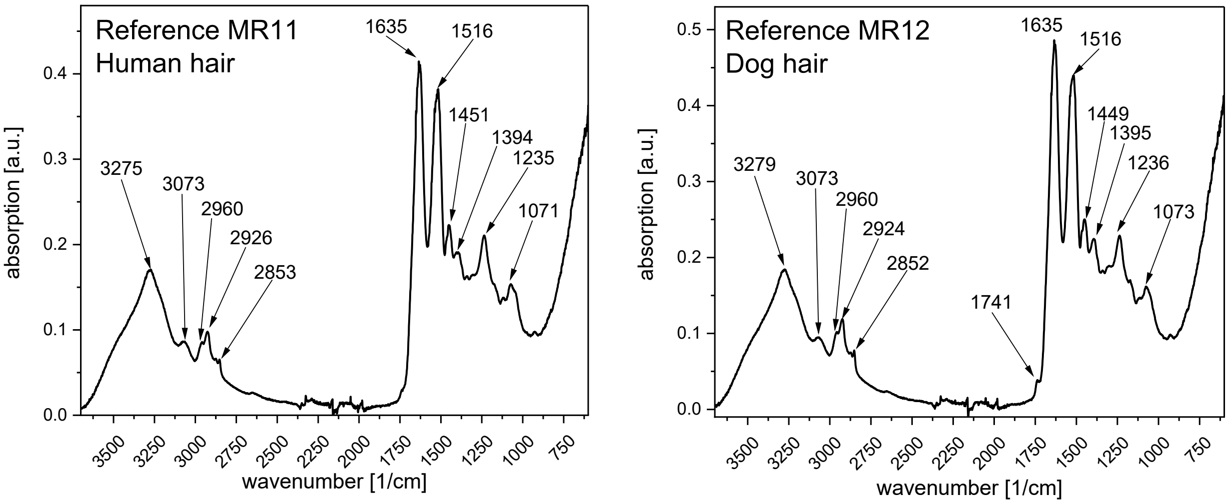

Fig. 13 IR spectra recorded from hair of different origin (human and dog).

Another interesting approach is related to the IR spectroscopic investigation of dyed and non-dyed human hair by comparison of the fingerprint range [74]. However, the reported data do not justify a clear detection of the dye on the hair [74]. A comparison of IR spectra from different dog and sheep species is supported in literature [75]. One remarkable difference in the actually presented IR spectra is the determination of a weak shoulder signal at 1741 cm^{-1} in the IR spectrum recorded from dog hair (Figure 13). This signal is probable related to a C=O stretching vibration of an ester group and can be part of a fatty acid on the hair sample. In fact, this signal fits quite well to the occurrence of diester waxes from hair lipids [76] This signal does not appear for the wool reference, because the fats are removed during degumming procedures. Further on human hair, this signal does not appear, because of daily hair washing procedures.

Casein fibers are protein regenerate fibers which are also named and distributed as milk fiber. Even if these fibers are nowadays presented as new innovation, the production of casein fibers and yarn was already reported in the years around 1945 [77, 78]. In literature several IR spectra of regenerated protein fibers are reported but often the spectroscopic data is of medium quality [79, 80]. An IR spectrum recorded from a casein fiber MR13 is presented in Figure 14. This IR-spectrum of reference material M13 exhibits clearly the main signals related to the proteinic nature of the fiber material. However, there are two signals at 1045 cm^{-1} and 3619 cm^{-1}, which are quite extraordinary and not detected for the other protein based fibers reported here. The strong signal at 1045 cm^{-1} is typical for a C-O stretching vibration as it is observed for cellulose based fibers. Eventually the present casein fiber is produced from a blend containing also a certain amount of cellulose. The weak signal at 3619 cm^{-1} is typical for an O-H stretching vibration from a carboxylic acid group -COOH [4, 5]. Amino acids units carrying -COOH groups as part of the protein structure can be responsible for this weak signal [81].

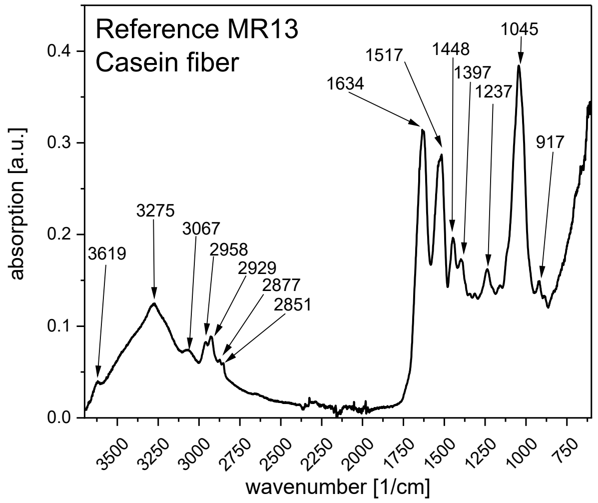

Fig. 14 IR spectrum recorded from casein fibers.

As final two reference materials, fibers from alginate and a sea ball (*Pillae marinae*) are chosen. The related IR-spectra are presented in Figure 15. Alginates are the salts of alginic acid, which is a hetero polysaccharide found in the cell walls of brown algae. Alginate fibers are produced by spinning from aqueous solutions of sodium alginate [82]. Sea balls are natural fiber-based objects with spherical shape found on the beach [83, 84]. As origin of the fibers is described in different sources to be from different water-based plants or algae [85-87]. The IR spectrum of the alginate fiber sample MR14 fits quite well to several in literature reported IR spectra from different alginate fibers [88-91] (Figure 15). However, the shape of the IR spectrum recorded from alginate fiber strongly depends of the type of counter cations [91]. The signals in the IR spectrum of alginate fiber MR14 can be assigned as followed. The broad signal at around 3257 cm^{-1} is assigned to O-H stretching vibrations of hydroxy groups. Both average signals at 2926 cm^{-1} and 2855 cm^{-1} are related to C-H stretching vibrations of aliphatic units. The both signals at 1590 cm^{-1} and 1420 cm^{-1} are assigned to C=O stretching vibrations of carboxylate units. The signal at 1590 cm^{-1} symmetrical and the signal at 1420 cm^{-1} for asymmetric vibration [91]. Especially the position of these both signals is determined by the type of counter cation in the alginate fiber [91]. The strongest peak at 1021 cm^{-1} is assigned to C-O stretching vibrations. The IR spectrum of the sea ball sample MR15 is depicted in Figure 15. In comparison to IR spectra recorded from different sea grass materials and other ocean-based biomass there are significant differences in the spectroscopic signatures reported in literature [92-94]. However, a certain similarity to an IR spectrum from sea balls can be stated [94]. The signals in the IR spectrum of reference sample MR15 can be mainly related to the cellulosic content of this organic material. However, the both signals determined at 1608 cm^{-1} and 1507 cm^{-1} might be caused from vibrations of amide group as a result of a certain protein content in this ocean-based biomass [95]. Also, C=O stretching vibrations caused by other by-component in this mainly cellulose based material might be responsible for the signal at 1608 cm^{-1} [94].

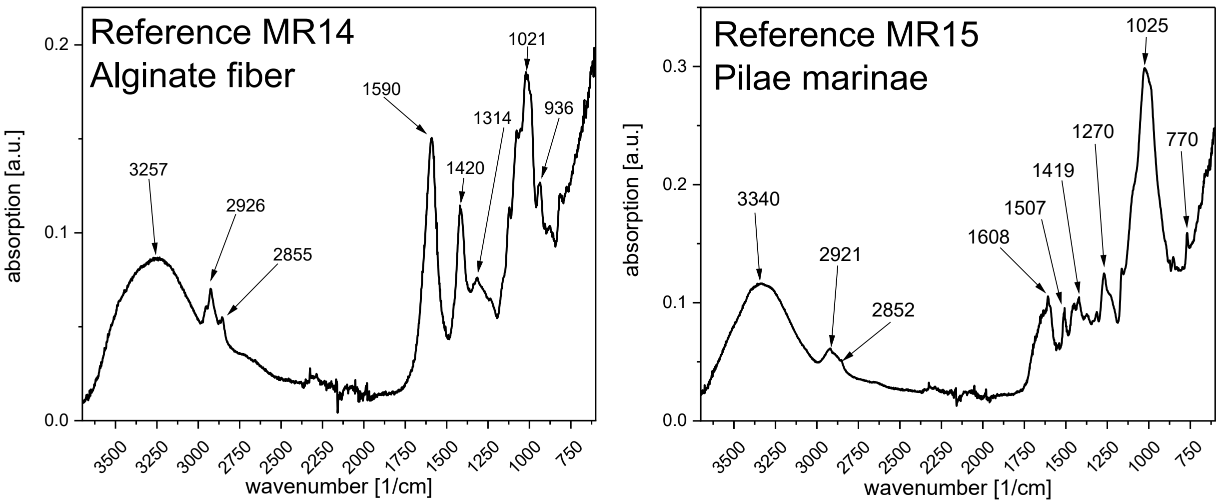

Fig. 15 IR spectra recorded from alginate fibers and a sample of Pillae marinae.

3.2 Cotton containing materials

In this section several consumer products mainly based on cotton fibers are presented. Several of these cotton products are modified to achieve a certain property. Often elastane fibers are added to improve elasticity and fit of the products. The Figure 16 exhibits the IR spectrum of the product TP1, which is a white yarn sold for the purpose of knitting handcraft. The IR spectrum of product TP1 is nearly identical to the spectrum of the cotton reference MR1.

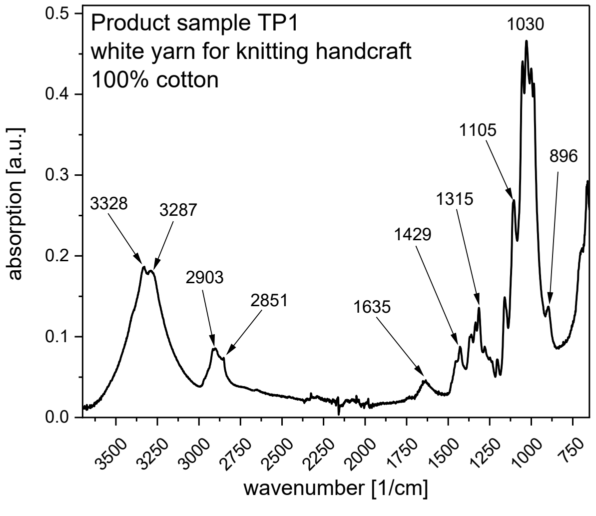

Fig. 16 Infrared spectrum of a white cotton yarn for handcraft knitting purposes.

The IR spectra of four different cotton containing fabrics are compared in Figure 17. Product sample TP2 is a conventional white cotton T-shirt, which exhibits the similar IR spectrum as the other presented cotton products MR1, MR7 and TP1. Slightly different results are gained for product TP3, which is also made from 100% cotton fibers. However, this product TP3 is intensively dyed with an orange coloration to support UV-protective effects. The IR spectrum recorded from TP3 exhibits an additional medium signal at 1558 cm^{-1}. A signal at this area can be related to a stretching vibration of a C=O bond from a keto group which can be part of the chromophore of the applied orange dye [96]. This product is an example that also an intense coloration can influence the IR spectrum – not by the absorption of visible light of the applied dye but by its absorption of IR radiation. The product TP4 contains additionally to cotton fiber only a small amount of 2 % elastane fibers. The IR spectrum of TP4 clearly differs from the IR spectra of the pure cotton samples. For product TP4, two additional weak signals at 1738 cm^{-1} and 1525 cm^{-1} are determined. Elastane fibers are often polyurethane based and the related polyurethane functional group can contribute to the IR spectrum with several different vibrations (compare Fig. 18) [97, 98]. Especially dominate is the stretching vibration of the C=O double bond leading to the signal at 1738 cm^{-1}. Product sample TP5 is a blended material from 90% cotton and 10% viscose. These both fiber materials are based on cellulose, so the related IR spectrum is nearly identical to the IR spectra taken from the other pure cotton materials reported here. This is also in good agreement with earlier reports [11, 50, 51]. In fact, additionally to signals related to the cellulosic structure of both fiber types (cotton and viscose) often additional signals are determined and reported, e.g. a signal around 1732 cm^{-1} determined on a cotton sample [11]. Such signals are related to C=O stretching vibrations of ester groups and can be caused by applied dyes, finishing agents or spinning oils [99-102].

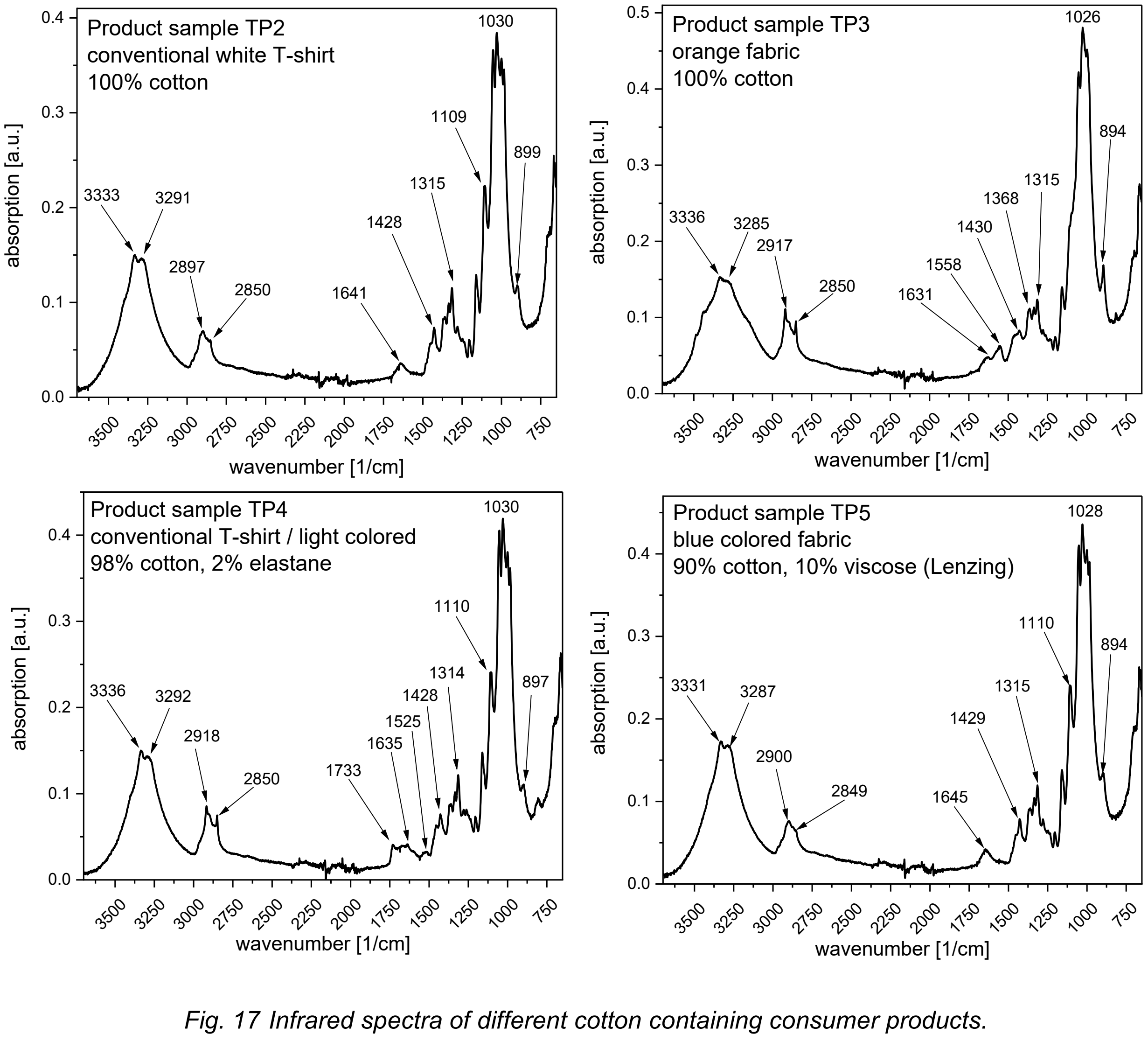

Fig. 17 Infrared spectra of different cotton containing consumer products.

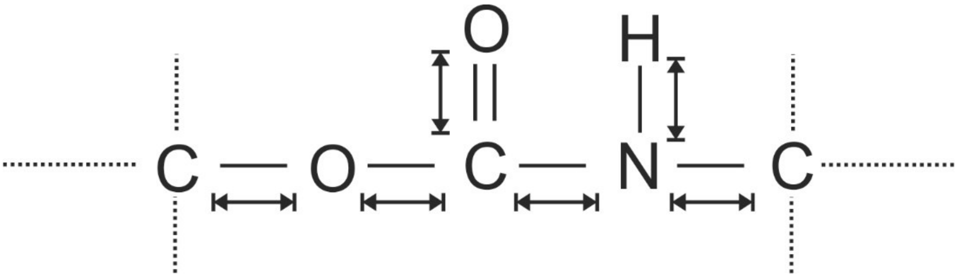

Fig. 18 Schematic drawing of a urethane unit responsible for main signals in the related infrared spectrum of polyurethane based elastane fibers.

Product TP6 can be best described as deep blue jeans fabric. The related IR spectrum recorded from product TP6 is presented in Figure 19. It is a thick cotton fabric with dark blue coloration. Compared to white cotton material, the IR spectrum of TP6 exhibits two clear peaks at 1462 cm^{-1} and 1630 cm^{-1}. Also, a shoulder at 1735 cm^{-1} can be identified. All these three features can be assigned to IR signals from blue indigo dye typically used for the production of blue jeans [103, 104].

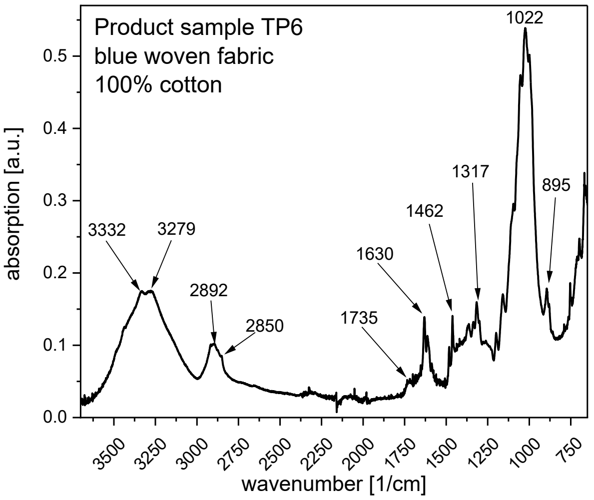

Fig. 19 Infrared spectrum of a cotton based blue jeans fabric.

3.3 Polyester containing materials

In this section products mainly made from polyester fibers are reported together with their IR spectra. In Fig. 20, the IR spectra of four polyester based consumer products are compared. The IR spectra of the products TP7, TP8 and TP9 are nearly identical to the IR spectrum of the polyester mono-material reference. This similarity is especially surprising for product TP8 with content of 14% elastane and for product TP9 which is a dark colored flame-retardant fabric with a component of phosphorous containing copolymeric units. However, even if there are these significant amounts of other materials additionally to polyester, it is not possible to identify them clearly by the current IR-spectroscopic measurements.

A different result is gained for the product TP10, which as a towel containing additionally to polyester also 10% polyamide fibers. For the product TP10, the typical amide related signals at 3291 cm^{-1}, 3075 cm^{-1}, 1637 cm^{-1} and 1539 cm^{-1} can be observed additionally to the typical pattern for polyester, so the 10% polyamide fiber content can be clearly determined additionally to the main component polyester.

With product TP11 a polyester fiber-based product is presented, which purpose is the imitation of a cotton umbel and it is used for decorative purposes. Even if the optical imitation of the cotton umbel is nearly perfect, by IR spectroscopy the polyester fibers can be clearly identified (see Figure 21). The IR spectrum of product TP11 is nearly identical to the polyester mono-material reference. Only at around 3300 cm^{-1} a broad weak signal can be observed, which is not originated by polyester fibers. This broad signal might be caused by applied hydrophilic or antistatic finishing agents [105, 106]. Hydrophilic finishing agents often contain hydroxy or amino groups and the related O-H or N-H stretching vibrations would be detected in the spectral area around 3300 cm^{-1}.

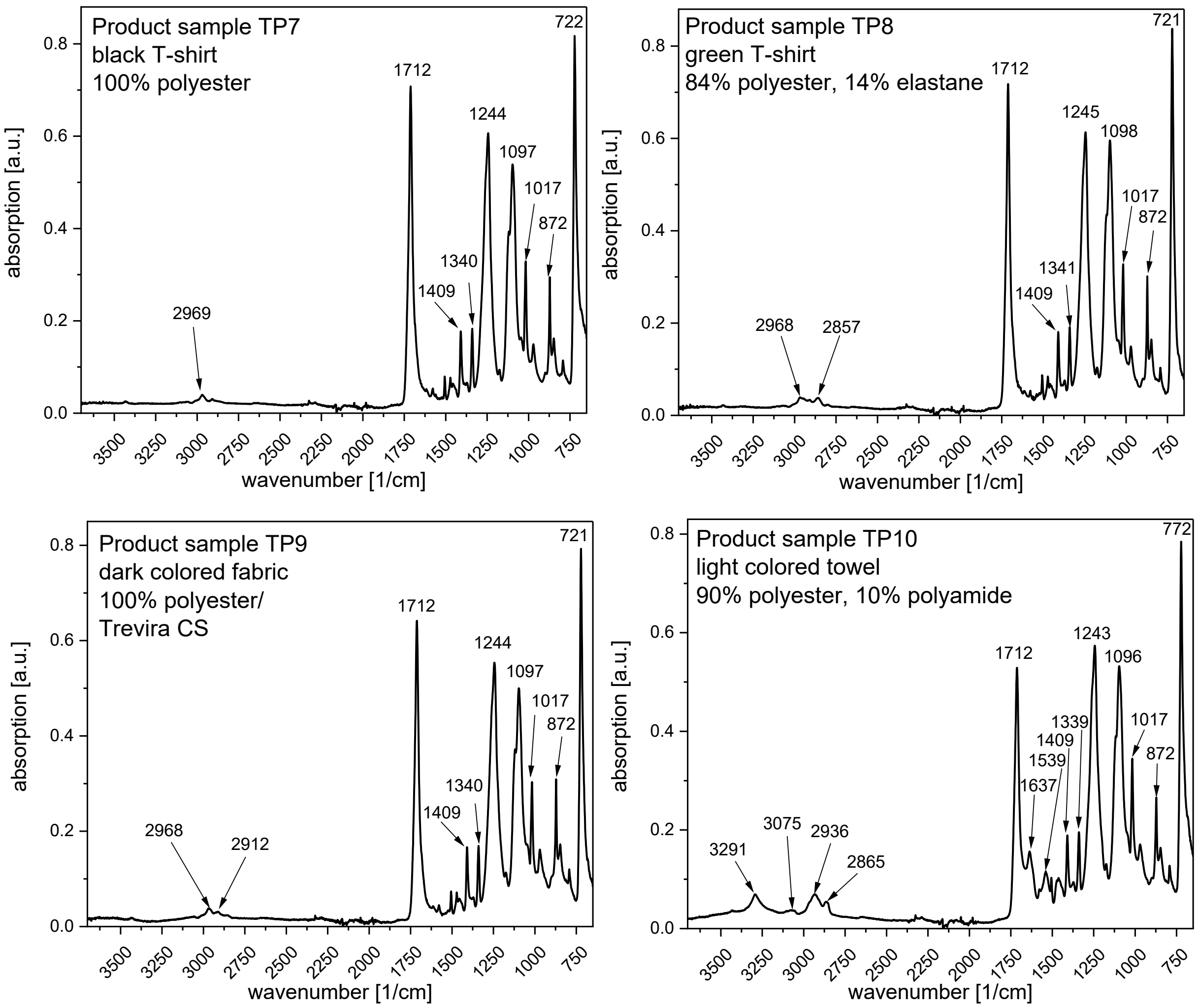

Fig. 20 Infrared spectra of different polyester based consumer products.

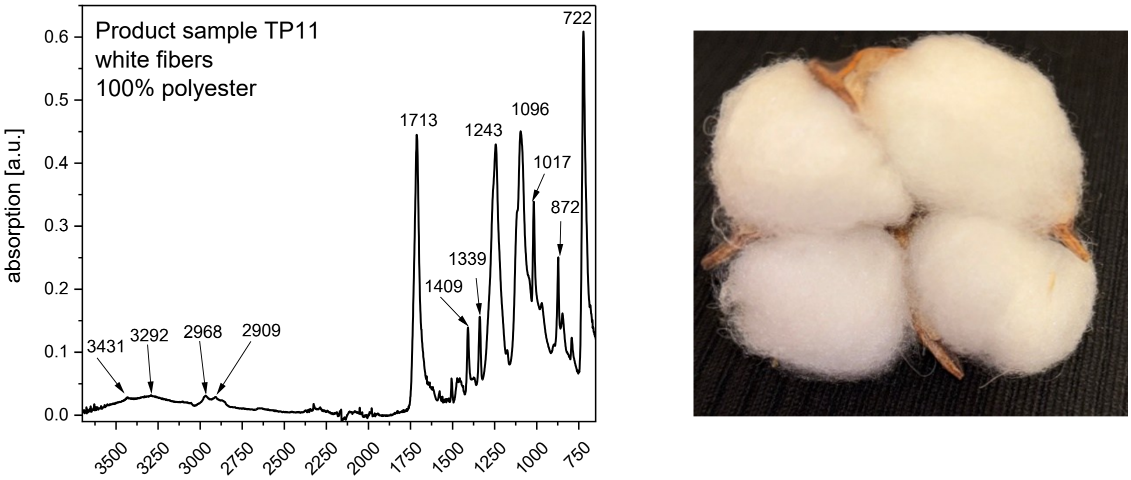

Fig. 21 IR spectrum and photograph of cotton umbel imitation made from polyester fibers.

3.4 Polyester / Cellulosic blended materials

This section is dedicated to products made from blended materials with polyester and cellulosic based fibers. The cellulosic based fibers are here the natural fiber cotton and fibers from regenerated cellulose as viscose fibers. Product TP12 is a textile bag for storage of handicraft tools. It is made from 76% polyester fibers and 24% cellulosic fibers (viscose & cotton). The IR spectrum of product TP12 exhibits signals from both fiber material components (Figure 22). The cellulosic component is especially responsible for the broad signal at around 3300 cm^{-1} which is related to the O-H stretching vibration of the hydroxy groups in the cellulose molecule.

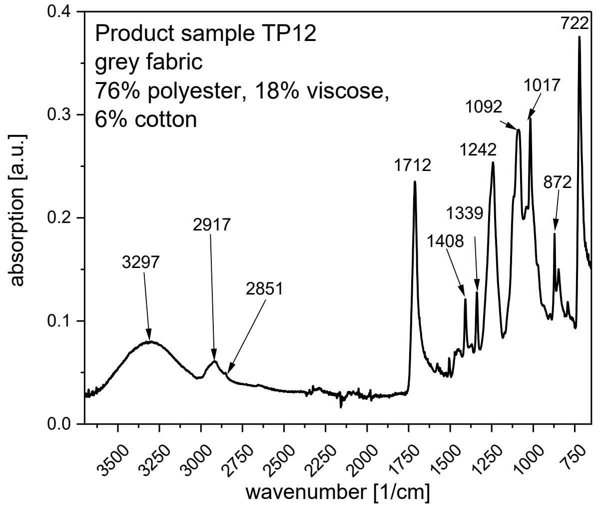

Fig. 22 Infrared spectrum of a textile-based bag made from polyester, viscose and cotton fibers.

Product TP13 is a knitted T-shirt especially promoted for its UV protective properties [107]. This knitted fabric is made from polyester fibers and Tencel fibers, which is regenerated cellulose. Both fiber types are not equally distributed in the fabric. Due to the knitting construction, the polyester fibers are placed outside of the T-shirt and the Tencel fibers are placed inside. For this, the outside and inside of the T-shirt exhibit a different fiber composition. The IR absorption of this fabric is measured from both different directions resulting in different IR spectra (Figure 23). The measurement from outside only shows signals related to polyester. In contrast, the IR spectrum taken from the inner side of the T-shirt exhibits both signals typically for polyester fibers and cellulosic fibers.

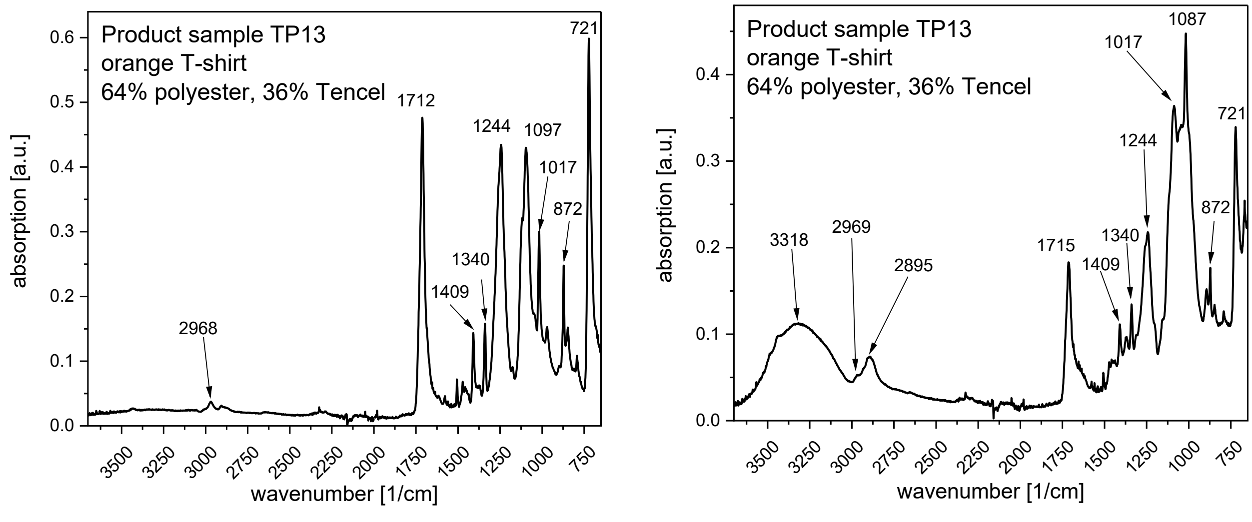

Fig. 23 Infrared spectra of a T-shirt knitted from polyester and Tencel yarns. The IR spectra are recorded from different sides of the fabric (left – from outside; right – from inside).

3.5 Polyamide containing materials

This section presents different typical polyamide containing consumer products. Product TP14 is a typical Nylon sock from 100% polyamide. The products TP15 and TP16 are typical clothing products from polyamide and elastane. The IR spectra of these three products are mainly identical to each other and to the IR spectrum of the polyamide mono-material reference fabric (Figure 24). Here the elastane component cannot be identified in the samples by IR spectroscopy. In comparison, product TP17 is from different composition with only 25% polyamide and 75% wool fibers. The presence of wool fibers is referring to three signals in the fingerprint area of the IR spectrum at 1099 cm^{-1}, 1026 cm^{-1} and 799 cm^{-1}. Additionally, the signal around 3200 cm^{-1} appears in broader shape with a shoulder around 3450 cm^{-1}, which is in good agreement with the IR spectrum of the wool mono-material reference (compare section 3.1) and literature [11].

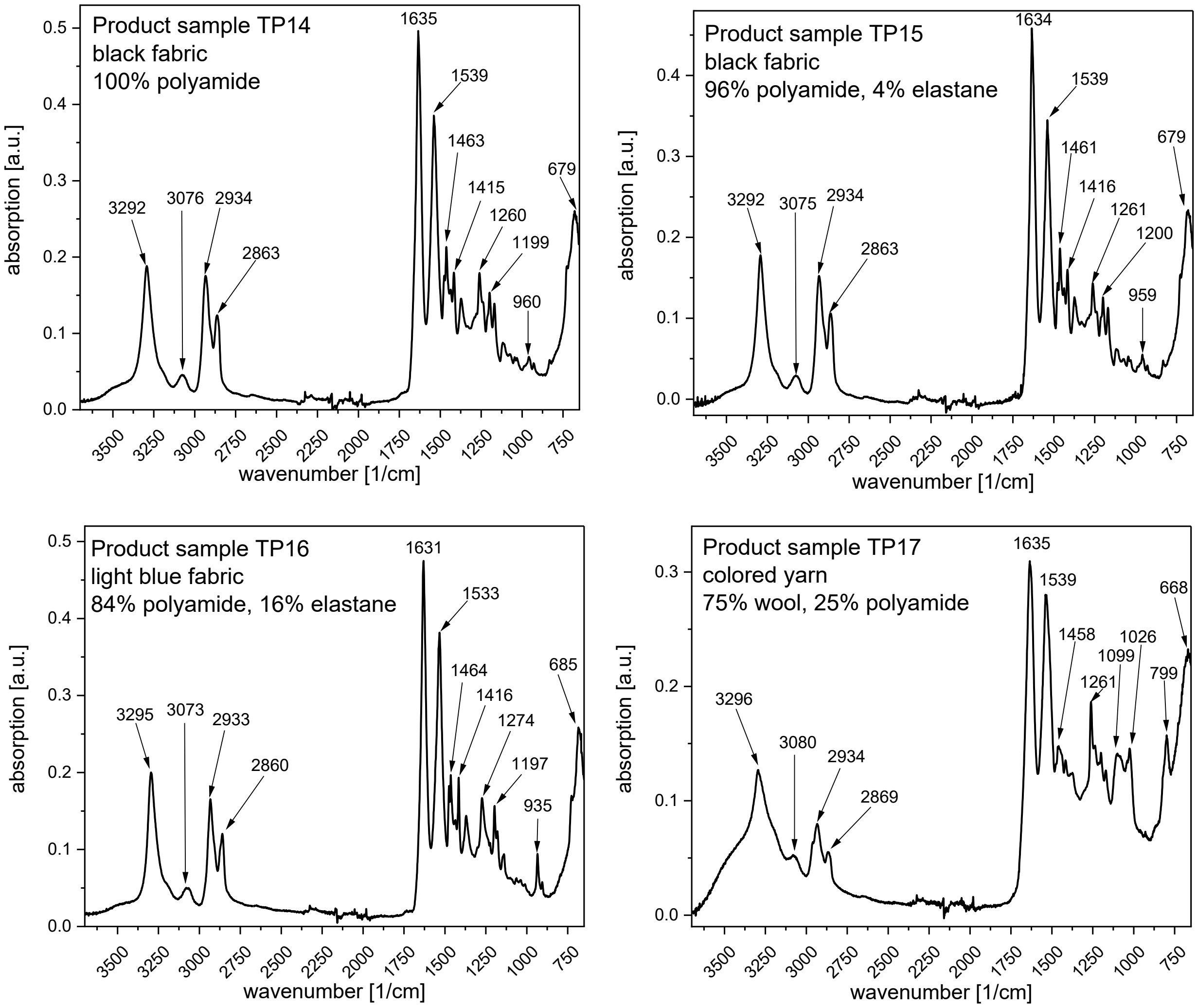

Fig. 24 Infrared spectra of different polyamide containing consumer products.

3.6 Acrylic containing materials

This section on polyacrylic fiber materials presents mainly two types of products. First discussed are conventional acrylic materials used mainly for knitted clothing products. Second, the view is set on products containing special flame-resistant acrylic fibers. Figure 25 shows the IR spectra of two typical consumer products made from 100% polyacrylic fibers. Product TP18 is a colored yarn offered for handcraft purposes, while product TP19 is a knitted hat containing a high visible luminescent orange coloration. The IR spectra of both products are nearly identical to each other and also to the IR spectrum of the polyacrylic mono-material reference fabric. The applied dye stuffs cannot be detected on these materials by the current IR spectroscopic measurements.

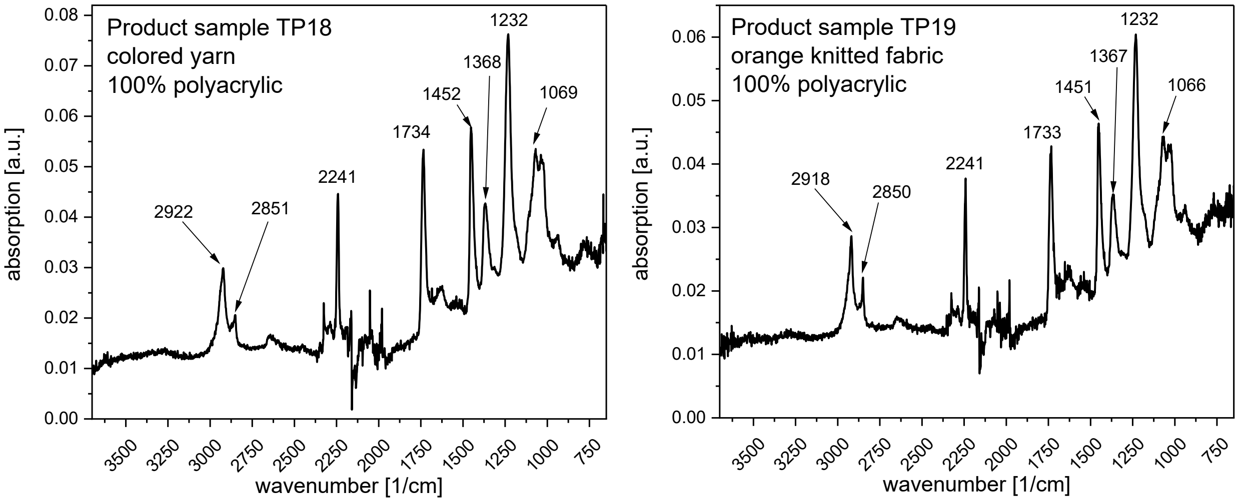

Fig. 25 IR spectra of two products made from 100% polyacrylic fibers.

Acrylic fibers are often used in yarns offered for handcraft knitting purposes, probable because acrylic fibers exhibit wool-like characteristics and are quite cost competitive against wool fibers [108]. For that reason, many different handcraft yarns are available containing acrylic fibers in various combinations with other types of fibers. In figures 26 and 27, the IR spectra of several handcraft yarns containing polyacrylic fibers in different ratio are presented and compared. The product TP20 contains additionally to acrylic fibers only 2% polyester fibers and its IR spectrum is nearly identical to the IR spectra recorded from 100% polyacrylic materials (Figure 20). The detected signal at 1734 cm^{-1} is related to the stretching vibration of C=O double bonds from an ester group. However, this ester group can be also found in the polyacrylic co-polymer structure, so it is not exclusively related to the ester group from the present polyester fibers. The products TP21 and TP22 contain mainly cotton and acrylic fibers. Product TP22 contains additionally also a small amount of polyamide fibers. The IR spectra of both products are clearly dominated by the signals related to cotton. Even if acrylic fibers are present with a significant content of 40%, they are hardly to detect. The peak at 2240 cm^{-1} related to the stretching vibration of the nitrile group CN appears very weak. However, the peak at 1738 cm^{-1} related to the ester group of acrylic co-polymer can be clearly identified. Finally, the presence of acrylic fibers in these blended yarns is better detectable from the ester group of the acrylic co-polymer instead of detecting the peak for the typical stretching vibration of the nitrile group. For the IR spectrum of product TP22, the small content of polyamide can be determined by a stronger signal at 1638 cm^{-1} and a new signal at 1541 cm^{-1}. These two signals are related to Amide I and Amide II vibrations and allow the identification of polyamide in these blended yarns even if the polyamide content in the yarn is only 9%. Product T23 is a blended yarn from acrylic fibers with wool and polyamide fibers. The IR spectrum recorded from T23 exhibits clearly the typical signals from the polyacrylic component and the amide groups of polyamide and wool. In this product the polyacrylic fibers can be clearly identified. However, it is difficult to distinguish between the polyamide and wool component, because both fibers mainly contribute to the IR spectrum by several vibrations of their amide groups.

Product TP24 is a blended yarn offered for knitting handcraft purposes. The main component is polyacrylic and polyamide fibers are present with 10%. Main signals from both fibers are clearly present in the related IR spectrum of product TP24 (Figure 27). The intensities of the signals from different fiber components are on the same level even if the ratio of both materials is with 9:1 strongly indifferent. Finally it can be stated, that for blended yarns and fabrics the sensitivity of the IR spectroscopy is lower for acrylic fibers compared to fibers of other chemical structure.

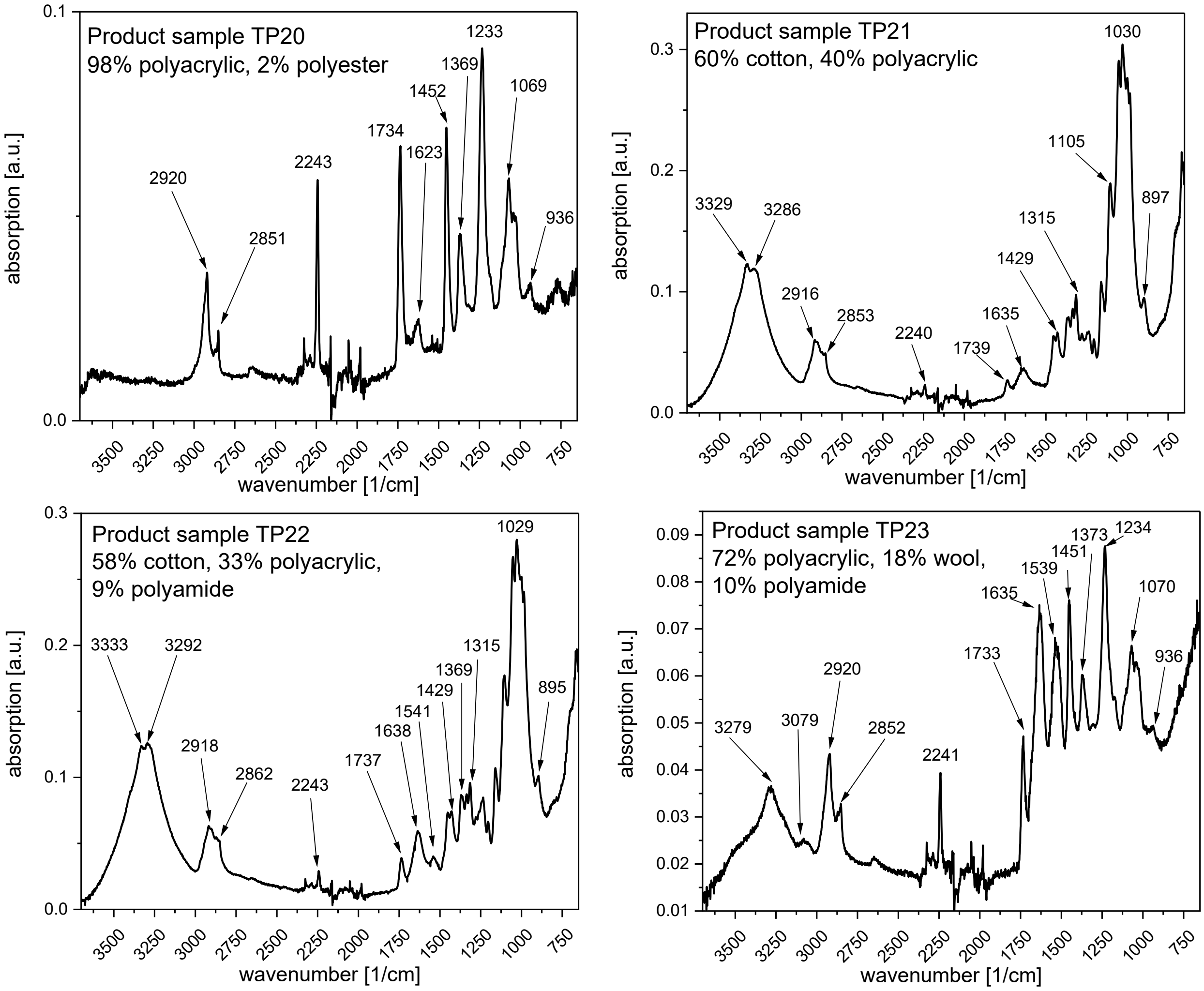

Fig. 26 IR spectra from four different yarns with acrylic fiber component for handcraft knitting purposes.

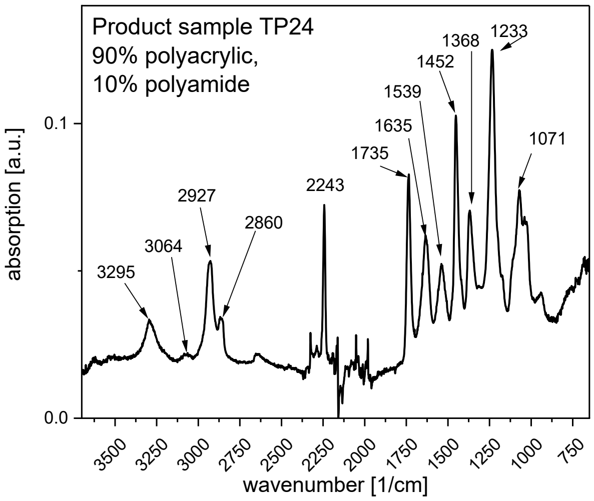

Fig. 27 IR spectrum of a polyacrylic/polyamide yarn for handcraft knitting purposes.

The products TP25 and TP26 are textile products dedicated to flame retardant applications. According to supplier information, both products contain around 60% modacrylic fibers and nearly 40% cotton fibers. In a previous study it was reported, that the modacrylic fibers contain the chemical element chlorine, which is typical for acrylic fibers with inherent flame-retardant properties [109]. In these fibers a chlorinated copolymer unit supports the flame-retardant properties to the acrylic fibers [110, 111]. The IR spectra of both products TP25 and TP26 are nearly identical to the IR spectrum of the cotton mono-material reference, even if the cotton content is content is only 40% or less (Figure 28). The peak at 2244 cm^{-1} related to the nitrile group of acrylic fibers is only detected with very weak intensity even if the modacrylic fibers are with 60% the main component in these two products. For product TP25 also a weak signal at 1719 cm^{-1} can be observed which could be caused by the elastane component in this product. Another signal related to C=O stretching vibrations from ester groups is not detected, probable because the flame retardant modacrylic fibers do not contain ester groups in their co-polymer units.

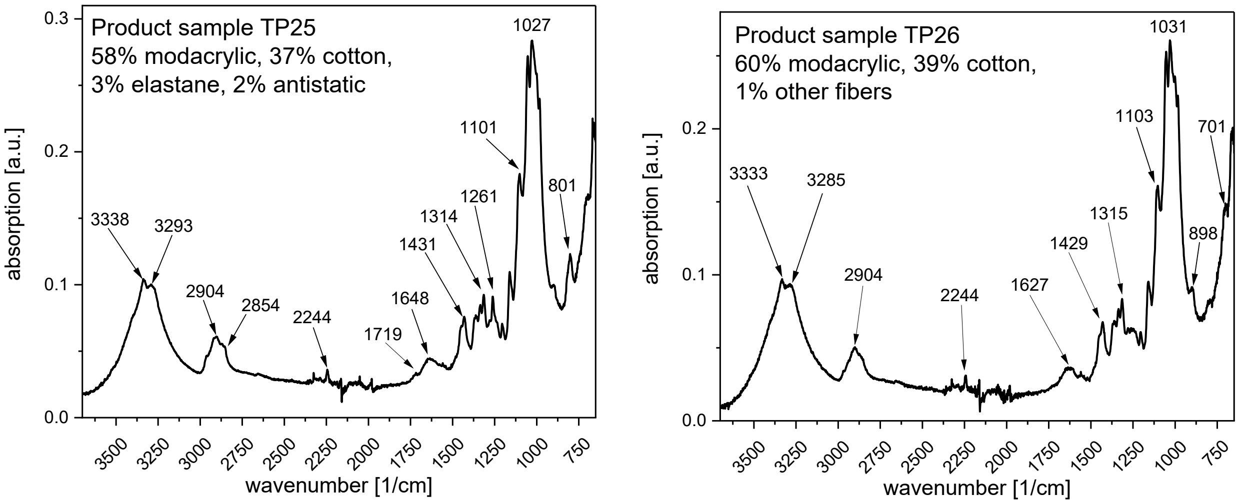

Fig. 28 IR spectra of two modacrylic fibers containing flame retardant products.

The product TP27 is offered for flame retardant applications and its main component is polyester, followed by flame retardant modacrylic and cotton fibers. The IR spectrum of product TP27 shows the typical pattern for a polyester/cotton blended material (Figure 29). Here, it is not possible to detect the modacrylic component by the performed IR spectroscopic measurements.

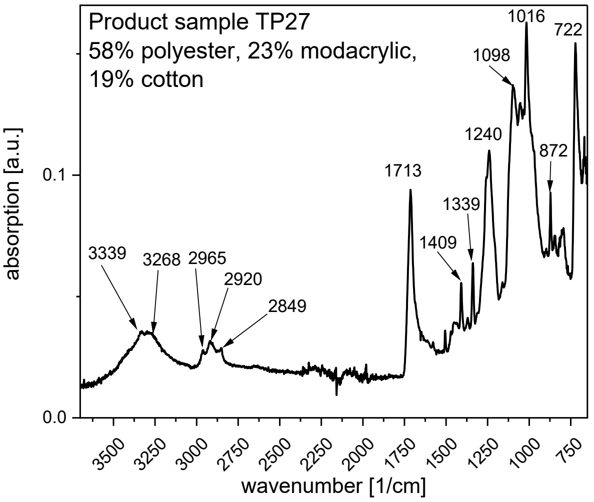

Fig. 29 IR spectrum of a flame retardant belt containing modacrylic fibers.

3.7 Polypropylene materials

The product TP28 is a white shopping bag made from woven and laminated polypropylene material. The IR spectrum of product TP28 is similar to reported IR-spectra for polypropylene materials reported in literature [112, 113] (Figure 30). The main signals at 2952 cm^{-1}, 2917 cm^{-1} and 2850 cm^{-1} are assigned to stretching vibrations of C-H bonds [4, 112]. These stretching vibrations are mainly related to the unit $-CH_2-$ and the methyl group $-CH_3$ of the polypropylene structure. The signal at 2952 cm^{-1} can be assigned to symmetric stretch vibration of the methyl group, while the signal at 2917 cm^{-1} is related to an asymmetric vibration of the ethylene fragment. Finally, the signal at 2800 cm^{-1} can be assigned to a symmetric stretch vibration of the unit $-CH_2-$ [5]. The both signals at 1376 cm^{-1} and 1458 cm^{-1} can be assigned to different deformation vibrations of the ethylene unit and the methyl group. The medium peak at 718 cm^{-1} is assigned to a rocking vibration of the ethylene unit [5].

The second polypropylene product TP29 is an intensively red colored non-woven material. The IR spectrum of TP29 exhibits the main signals for polypropylene as the product TP28. However, the IR spectrum of TP29 shows several additional small and weak signals, which either can be related as result of aging processes of polypropylene, leading to surface oxidation [112]. Also, dyes or finishing agent present on this product can contribute to these additional signals.

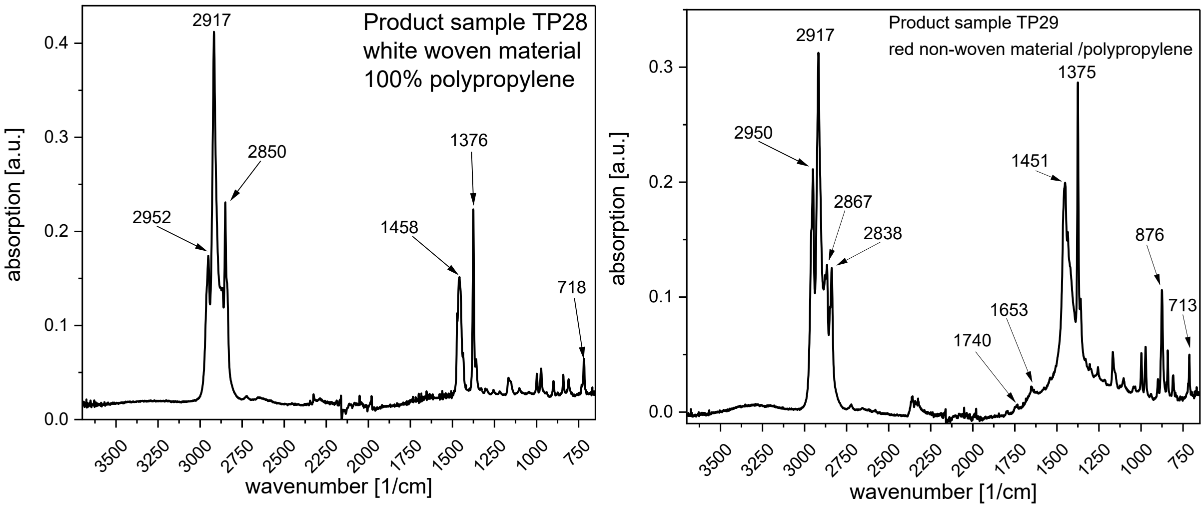

Fig. 30 IR spectra recorded from two shopping bags made from a polypropylene fiber material.

The product TP30 is a typical rope made from polypropylene with yellow/blue coloration (Figure 31). According to supplier information, this rope is produced from 100% polypropylene fibers. The related IR spectrum is mainly determined by the signals related to the different vibrations of polypropylene. However, some additional weak signals can be determined. The weak signal at 1734 cm^{-1} is probable caused by a stretching vibration of a C=O bond from an ester unit. This ester unit can be the result of an oxidation process on the fiber surface or also a part of the chromophore of the dyes used for coloration of the rope.

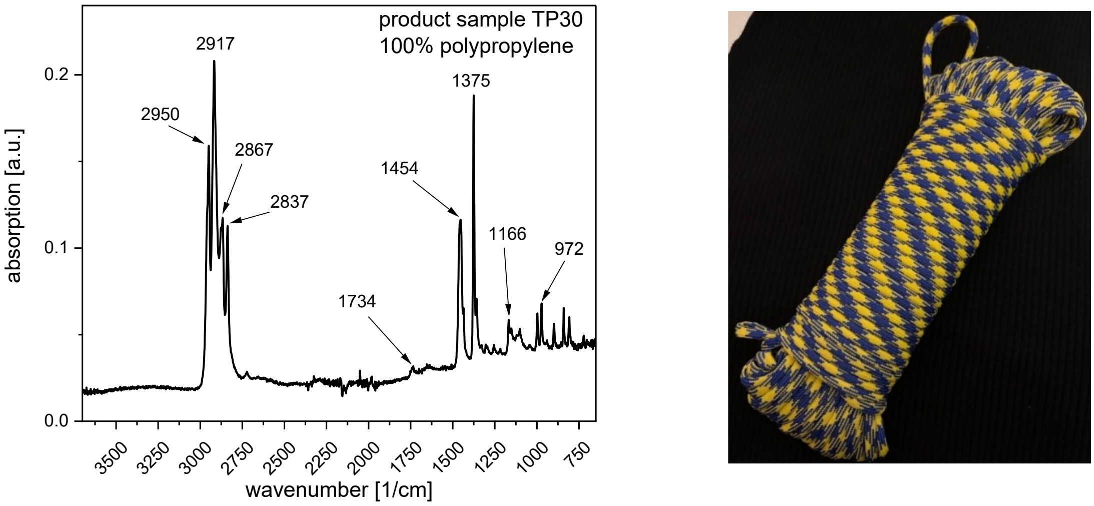

Fig. 31 IR spectrum and photograph of a rope made from polypropylene fibers.

3.8 Polyethylene materials

The product samples TP31 and TP32 are polyethylene-based products. Product TP31 is a laminated woven polyethylene fabric offered for outdoor applications. Product TP32 is a LD-PE polybag measured here as a mono-material reference for polyethylene. The IR spectra of both products are presented in Figure 32. The IR spectrum of product TP32 is nearly similar to IR spectra reported for different polyethylene materials in literature [114, 115]. The four detected signals can be assigned to different vibrations of the -CH_2- unit building up polyethylene – 2914 cm^{-1} / asymmetric stretch vibration, 2848 cm^{-1} / symmetric stretch vibration, 1472 cm^{-1} / deformation vibration and 718 cm^{-1} / rocking vibration [5]. Additional to these four peaks, the IR spectrum of product TP31 exhibits an additional medium peak at 875 cm^{-1}. Such a peak is reported for weathered polyethylene samples and assigned to a stretch vibration of a C-O-C unit, which appears on polyethylene surfaces as result of oxidation processes [115].

The products TP33 and TP34 are made from high-performance polyethylene HPPE and are offered for two different mechanically demanding purposes. TP33 is a grey colored rope with high strength. TP34 is a cut resistant glove. The IR spectrum of product TP33 is presented in figure 33 and it exhibits the main four signals related to the polyethylene structure. These four peaks are similarly reported for unmodified HPPE fibers of the brand Dyneema [116]. However, the IR spectrum of product TP33 contains three signals at 1720 cm^{-1}, 1239 cm^{-1} and 1117 cm^{-1} which are probable related to different vibrations of ester groups. Here it could be assumed that the grey coloration of the rope results from carbon black pigment bonded on the fiber surface by using an acrylate binder system. Such material modifications or surface coating applications might sometimes complicate the fiber identification by IR spectroscopy, especially if the material history is unknown.

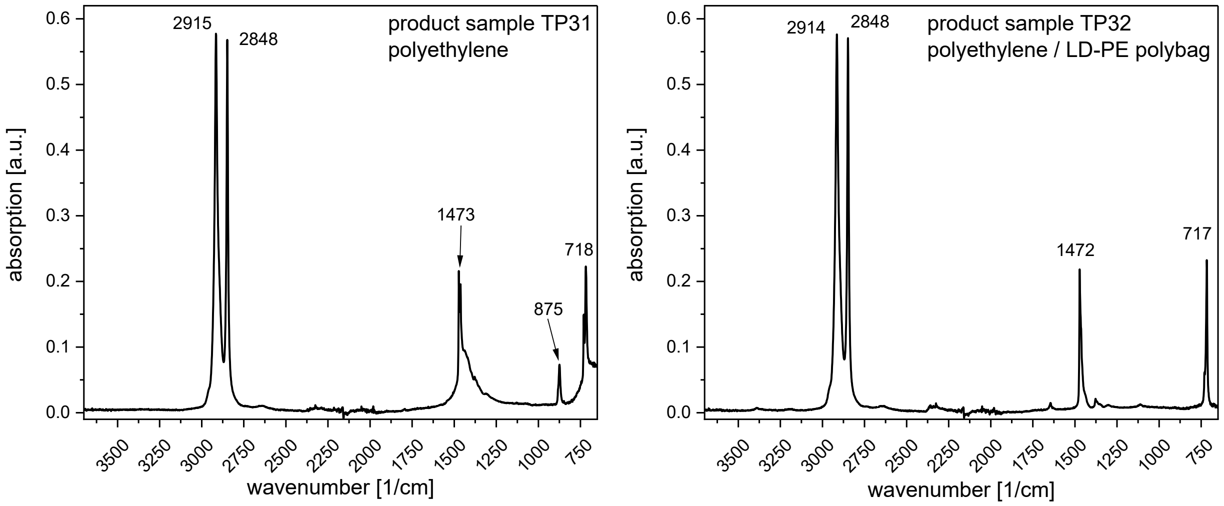

Fig. 32 IR spectra recorded from two different consumer products from polyethylene.

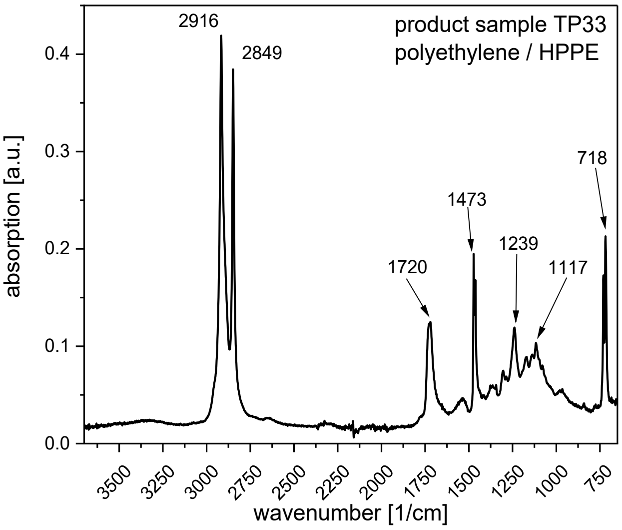

Fig. 33 IR spectrum recorded from a grey rope made from high-performance polyethylene HPPE.

The IR spectrum of the cut resistant glove (product TP34) exhibits the four typical peaks related to polyethylene (Figure 34). However, several other signals are observed, which are related to other polymeric materials. The three peaks at 1712 cm^{-1}, 1244 cm^{-1} and 1096 cm^{-1} can be assigned to vibrations from the ester group of polyester. The four signals at 3294 cm^{-1}, 3064 cm^{-1}, 1636 cm^{-1} and 1534 cm^{-1} can be assigned to vibrations from the amide group of polyamides. For this, it can be concluded that this glove contains additionally to the cut resistant HPPE fiber also polyester and polyamide fibers.

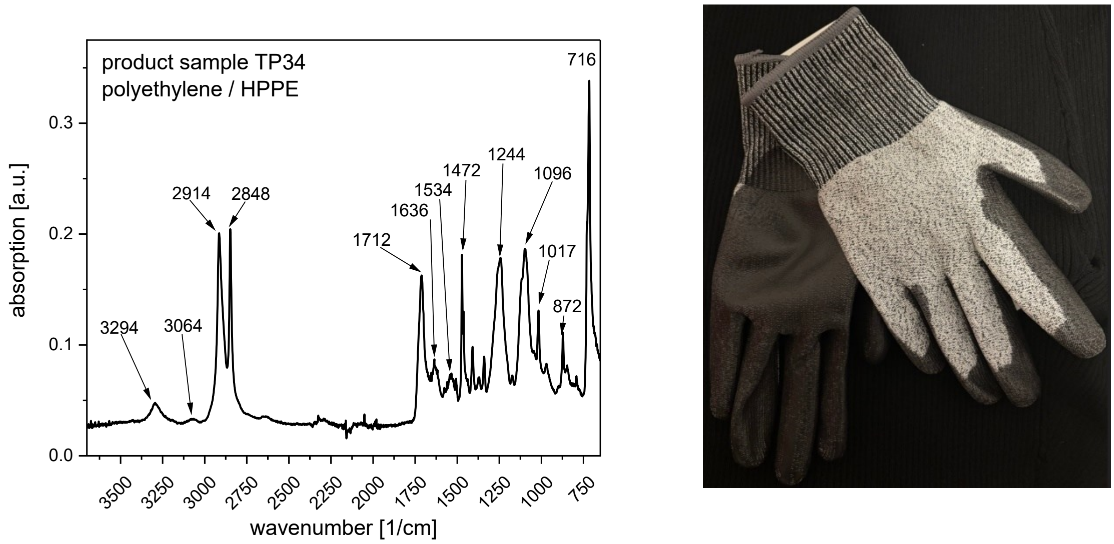

Fig. 34 IR spectrum and photograph of cut resistant gloves made from HPPE fibers (high performance polyethylene HPPE).

3.9 Polyvinyl alcohol materials

Product TP35 is a water-soluble white sewing yarn made from polyvinyl alcohol fibers. The IR spectrum of product TP35 is presented in Figure 35. However, this IR spectrum is not in agreement with several IR-spectra reported in literature earlier. The reported IR spectra of polyvinyl alcohol do not exhibit the peak at 1715 cm^{-1}, which is determined for product TP35 [117-119]. Usually polyvinyl alcohol is produced by hydrolysis of polyvinyl acetate and the result of this hydrolysis is a polymer containing both polyvinyl alcohol units and polyvinyl acetate units [120]. The ratio of these both units depends on the progress of hydrolysis. The chemical structure of such a co-polymer contains hydroxy and ester as functional groups

(Figure 36). Related to these both groups the main signals in the IR spectrum of product TP35 can be assigned. For the alcohol group, these are mainly the signals 3314 cm^{-1} (O-H stretching vibration) and 1018 cm^{-1} (C-O stretching vibration). For the ester group, these are mainly the signals 1715 cm^{-1} (C=O stretching vibration) and 1084 cm^{-1} (C-O stretching vibration).

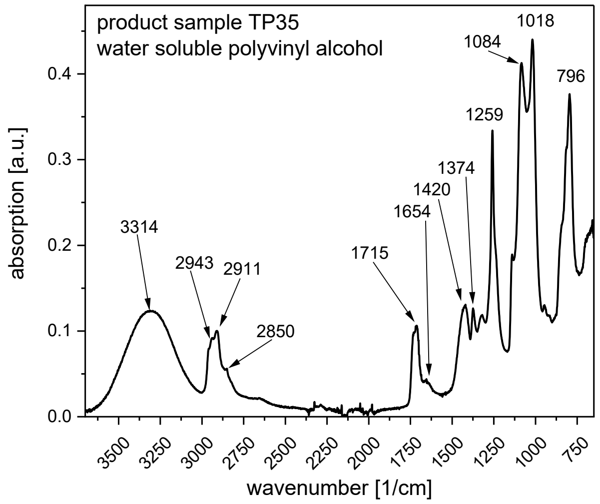

Fig. 35 IR spectrum of a water-soluble sewing yarn made from polyvinyl alcohol.

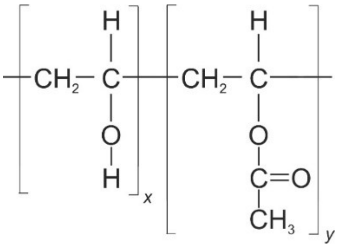

Fig. 36 Chemical structure of a polyvinyl alcohol co-polymer with a polyvinyl acetate co-unit.

3.10 Special fiber materials

In this section several special fiber materials are presented. These fiber materials are mainly based on chlorine containing polymers, which are exhibiting inherent flame-retardant properties. The products samples SP1 and SP2 are from different polyvinylchloride fibers (PVC fibers). A significant overview on the IR spectra of different polyvinylchloride fibers was given by Kirret et al. [121]. The product sample SP2 is from Rhovyl fibers, which are made from polyvinylchloride PVC [122-124]. The IR spectra of both fiber products SP1 and SP2 are quite similar (Figure 37). These IR-spectra are as well quite comparable with IR spectra reported for PVC bulk materials [125, 126]. The assignments of the spectroscopic signals are according to PVC as followed. The four signals in the range of 2815 cm^{-1} to 2971 cm^{-1} are related to C-H stretching vibrations of different aliphatic units. The sharp peak around 1425 cm^{-1} is assigned to deformation vibration (wagging) of the CH_2 unit. The two signals around 1250 cm^{-1} and around 1330 cm^{-1} are related to C-H deformation vibration of the CHCl unit. The average peak at around 1095 cm^{-1} is related to C-C stretching vibration. The signal at around 960 cm^{-1} is related to rocking vibration of the CH_2 unit. The strongest peak at 608 cm^{-1} and the medium peak at around 682 cm^{-1} are assigned to different C-Cl stretching vibrations. Further both PVC fiber samples exhibit weak signals in the range from 1615 cm^{-1} to 1733 cm^{-1} (Figure 37). These weak signals can be related to C=O stretching vibrations from carbonyl units which are formed by photo-oxidation processes with PVC [127, 128].

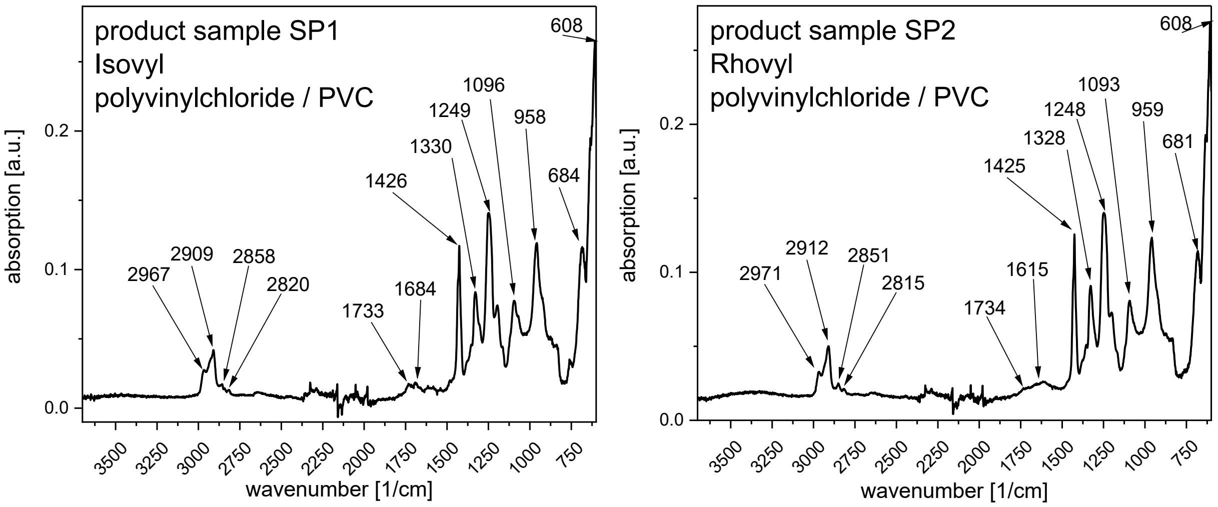

Fig. 37 IR spectra recorded from two different types of polyvinylchloride fibers (PVC-fibers).

The product sample SP3 is made from Thermovyl fibers. Thermovyl fibers are described to be modified PVC based fiber with improved mechanical properties [122]. There are also Thermovyl fibers available which are made from chlorinated PVC [122]. The IR spectrum recorded from fiber sample SP3 is presented in Figure 38. The IR spectrum of sample SP3 is nearly identical to the both IR spectra of the other two PVC based fibers (compare Figure 37). All three fiber types SP1, SP2 and SP3 are mainly based on the polymer PVC which is partly undergoing a photooxidative process.

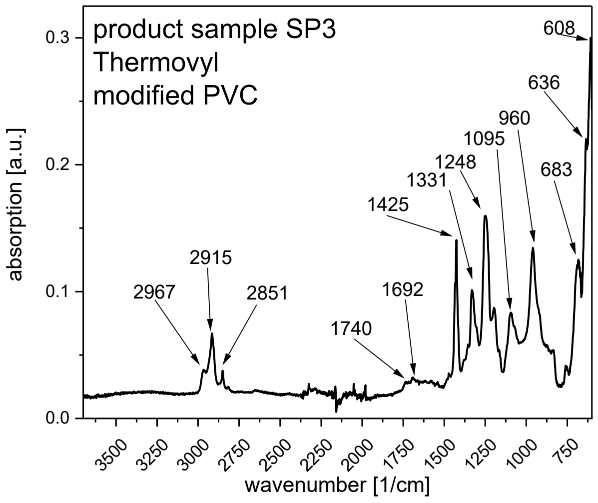

Fig. 38 IR spectrum recorded from fibers of modified PVC.

The products sample SP4 is from Saran fibers. Saran fibers are made from polyvinylidene PVDC [122]. Also, Saran fiber types are offered which are made from co-polymers of PVC and PVDC [122, 129]. The IR spectrum recorded from product SP4 is presented in Figure 39. This determined IR spectrum form the fiber sample is nearly similar to a reported IR spectrum recently recorded from a PVDC bulk material [130]. The assignments of the spectroscopic signals are according to PVDC as followed. The four medium signals in the range of 2853 cm^{-1} to 2987 cm^{-1} are related to C-H stretching vibrations of different aliphatic units. The signals between 1043 cm^{-1} to 1466 cm^{-1} are assigned to different deformation vibration of CH_2 units. The weak signal at 749 cm^{-1} is related to a rocking vibration of the CH_2 unit. The peak at 655 cm^{-1} is assigned to the C-Cl stretching vibration [130]. The clear signal at 1723 cm^{-1} is probable caused by a C=O stretching vibration of an ester group, which is formally not part of the PVDC polymer structure. It is considered that in commercial PVDC materials also ester group containing acrylate comonomer units are present [130].

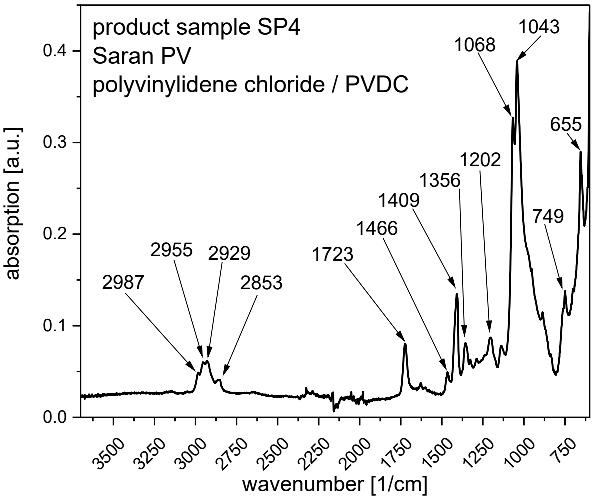

Fig. 39 IR spectrum recorded from PVDC fibers.

The product samples SP5 and SP6 are fibers made from copolymers of acrylonitrile and vinylchloride and distributed under the names of VinyonN and Dynel fibers. Vinyon N fibers are made from co-polymers of acrylonitrile and vinyl chloride [131]. Dynel fibers are made from co-polymer of the same type [122, 132]. For Dynel fibers a ratio of 40%:60% acrylonitrile and vinyl chloride are mentioned [122]. Even if both fiber samples are built up by the same type of copolymer, their IR spectra exhibit significant differences. For both IR spectra similar signals are following described. The two signals around 2851 cm^{-1} to 2924 cm^{-1} are related to C-H stretching vibrations from aliphatic units. The peak at 2242 cm^{-1} is assigned to the stretching vibration of the CN triple bond of the nitrile group which is typical for acrylonitrile polymers. The signal around 1438 cm^{-1} is related to a deformation vibration of the CH_2 unit. Finally, the strongest signal around 620 cm^{-1} is assigned to a C-Cl stretching vibration.

Additional to these quite similar signals, the IR spectrum recorded from Dynel fibers exhibits a broad signal at around 3370 cm^{-1} which is typical for an O-H stretching vibration of hydroxy groups. Further a broad signal is determined at 1590 cm^{-1} which is probable related to a C=O stretching vibration of a carbonyl unit. Both groups – hydroxy and carbonyl – can be part components used for modification of the fiber samples or the results of photooxidative processes damaging the fiber surface. In comparison for the fiber sample SP5, two weak signals at 1624 cm^{-1} and 1719 cm^{-1} are determined. Here the signal at 1624 cm^{-1} might be related to DMF used as solvent in fiber production. The signal at 1719 cm^{-1} might be caused by C=O stretching vibrations from an ester group which is part of a comonomer unit. However, both signals could be also caused by C=O stretching vibrations of oxygen containing units which are formed as result of photooxidative processes.

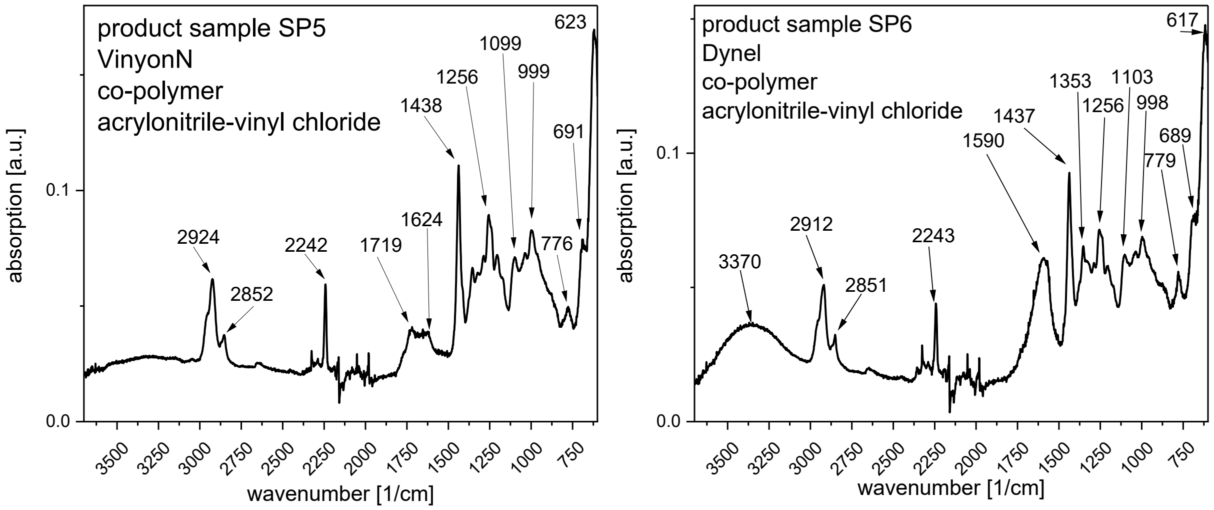

Fig. 40 IR spectra recorded from two different types of fibers made from co-polymer acrylonitrile-vinyl chloride.

Product sample SP7 contains Vinylon fibers. Vinylon fibers are based on polyvinylalcohol and are not water soluble [133, 134]. Vinylon fibers are also reported to be polyvinylalcohol fibers with flame retardant properties. Vinylon fibers can be used in fiber blends to realize flame retardant materials built up from different types of fibers [135]. For Vinylon fibers a further hydrophobic modification by acetal forming reactions of polyvinylalcohol with formaldehyde is mentioned [133]. The IR spectrum recorded form not water soluble polyvinylalcohol fibers (Vinylon) is presented in Figure 41 and show be compared with the IR spectrum of the water soluble polyvinylalcohol fiber (Figure 35). Both fibers are originally produced from polyvinylacetate which is saponified to remove the acetate unit gaining finally the alcohol groups of the polyvinylalcohol fibers. For the water soluble polyvinylalcohol, the saponification is not done completely, Here, a significant amount of acetate groups is still present in this fiber causing the typical signals in the IR spectrum, which are related to vibrations of ester units. In comparison for Vinylon fibers this saponification is nearly completed and only a very weak signal at 1714 cm^{-1} can be related to the C=O stretching vibration of the ester unit from remaining acetate groups.

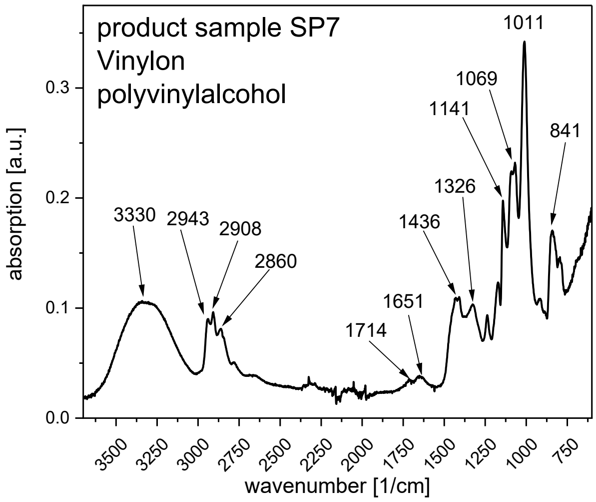

Fig. 41 IR spectrum recorded from polyvinyl alcohol fibers.

4 Summary on IR spectroscopic signals

Each type of fiber exhibits typical signals in its IR spectrum. Some fiber types show a quite similar IR spectrum, because of a certain chemical identity, as e.g. polyamide and wool which contain both amide groups as main functional groups or cotton and viscose which are both mainly built up by cellulose molecules. To support a fast orientation, in Table 4 a selection of typical IR signals for fiber materials are listed together with related fibers, assigned vibration and functional groups.

Table 4. Overview on a selection of IR signals typical for certain fiber components and their assignments to related vibrations and functional groups.

Spectral range of signal (cm^{-1})	**Intensity and shape**	**Assigned vibration and molecular structure**	**Typical fibers**
3200-3350	Broad intensive signal	Stretching vibration from O-H and N-H bonds, related to hydroxy and amide groups, absorbed water	Cotton, polyamide, wool, regenerated cellulose
~3070	medium	Overton of Amide II signal	Polyamide, wool
2850- 2970	Several peaks, weak to strong	C-H stretching vibration of aliphatic units	All organic fibers, but for polyester weak signal
~2240	Sharp peak, weak to medium	stretching vibration of CN triple bond (nitrile unit)	Polyacrylic fibers, difficult to detect in fiber blends
1710-1735	Strong peak	C=O stretching vibration from ester groups	Polyester, acetate cellulose, co-unit of polyacrylate fibers
~1630	Strong peak	C=O stretching vibration of amide groups, Amide I signal	Polyamide, wool
~1520	Strong peak	Combined vibration of C-N stretching with deformation vibration of C-N-H, Amide II	Polyamide, wool
~1270	Medium peak	Combined vibration of NH and OCN units, Amide III	Polyamide
~1240	Strong peak	C-O stretching vibration	Polyester
~1100	Strong peak	C-O stretching vibration	Polyester
~1030	Strong peak	C-O stretching vibration	Cotton, viscose, cellulose acetate
~720	Strong peak	C-H wagging vibration at aromatic ring system	Polyester
600-650	Medium to strong	C-Cl stretching vibration	Polyvinylchloride or other chloride containing polymers

5 Conclusions

The current paper gives a broad overview on different textile consumer products and their IR spectra. These IR spectra are discussed according to fiber composition in the textile products and the chemical structure of the fibers. In case of textile mono-materials only made from one type of fiber, the identification of the fibers by IR spectroscopy is easily possible. In some cases of strongly dyed textile fabrics (as e.g. blue jeans), the applied dye stuff can support with additional signals to the IR spectrum of the textile material. More challenging is the identification of certain fibers in blended yarns and blended fabrics. In blended textile materials, polyester fibers (polyethylene terephthalate, PET) is easily identified even in smaller amounts by appearance of two signals at around 1715 cm^{-1} and 720 cm^{-1}, which are assigned to two typical vibrations. The signal at 1715 cm^{-1} is caused by vibration of C=O double bond of the ester group. The signal at around 720 cm^{-1} is related to C-H wagging vibrations at aromatic ring system. The appearance of this second signal at 720 cm^{-1} is especially important, because it help to distinguish PET from other also ester containing materials, as e.g. cellulose acetate. As well polyamide fibers (nylon) can be easily determined in fiber blends mainly by the appearance of three signals at around 3070 cm^{-1}, 1630 cm^{-1} and 1533 cm^{-1}, which are related to different vibrations of the amide group as prominent functional group in polyamide. However, it is challenging to distinguish polyamide from wool fibers in blended materials, because of the high content of amide groups present in the protein structure of wool. The presence of cotton in a blend with hydrophobic polyester fibers, can be mainly determined by appearance of the broad signal at around 3300 cm^{-1} related to stretching vibrations of O-H bonds from hydroxy groups. However, it is difficult to distinguish cotton fibers from fibers which are as well built up by cellulosic molecules. Mono-materials from polyacrylic fibers (PAN) can be identified by the sharp peak at around 2240 cm^{-1}, which is related to the stretching vibration of the nitrile group CN. However, in fiber blends this signal appears only weak, so the detection of polyacrylic fibers in blended materials is challenging. Usually, the IR spectra of polyacrylic fibers exhibit additionally to the peak at 2240 cm^{-1} a second typical signal at around 1730 cm^{-1}, which is related to an ester group containing co-unit of the polyacrylic co-polymer. This second signal can be used for identification of polyacrylic fibers blended with cotton fibers. However, flame-retardant polyacrylic fibers with chlorinated co-units might not contain an ester group bearing co-unit as well and are for this not identified by a second signal at around 1730 cm^{-1}. The IR spectra of polypropylene (PP) and polyethylene (PE) fiber materials are mainly determined by different types of different C-H stretching and deformation vibrations. However, in these materials also additives and coatings can contribute with additional signals in the IR spectra, especially if these compounds contain ester or amide functional groups. Overall the current overview supports many IR spectra recorded from various commercial textile products and guides through a discussion based on material composition. This broad range of different materials offers a helpful tool for fiber material identification by IR spectroscopic method and is for this helpful for material analytics in quality control and in recycling processes. The IR spectroscopy is an excellent, fast and non-destructive method for analyzing fiber-based materials. Nevertheless, it is clear that actually and in future the IR spectroscopy can be improved by chemometric methods and machine learning techniques for automatic fiber identification.

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Conflicts of Interest

The author declares no conflict of interest.

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