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Exemplarily view on selected fluorescence textile products

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ABSTRACT

Fluorescent materials emit light of higher wavelength, in case of illumination with light exhibiting lower wavelength. In many commercial applications, fluorescent materials transfer non-visible ultraviolet (UV) light into visible light. By this an additional color effect and higher visibility is reached. One typical field for application of fluorescence dyes is the textile area. Here, fluorescent textile products are manifold used and offered, e.g. for brightening effects, light effects and UV protection. With this background, the aim of the current study is the investigation of typical commercially available textile products with fluorescent properties. For this, four different polyester fiber-based materials of different coloration and purpose are selected for investigation. Investigations are performed by illumination under different illumination arrangements with UV light and visible light. CIE-Lab measurements are done. Further, scanning electronic microscopy (SEM) and Fourier Transform infrared (FT-IR) spectroscopy are used. Light emission and excitation of the samples is recorded by fluorescence spectroscopy. 2D fluorescence spectroscopy is performed. The chemical composition of the investigated textile samples is determined by using electron dispersive spectroscopy (EDS). For all investigated commercial textile products, the light emission during illumination with UV light is extraordinary strong. The color appearance can be enhanced strongly by this fluorescence effect. Beside the absorption of UV light by the present fluorescence dyes, also the presence of titanium dioxide supports an UV protective property of the textile samples. Finally, it can be concluded that fluorescent fiber materials are well established products for advanced and functional textiles. These materials can be even found in cost effective and everyday consumer products.

Keywords
fluorescence,
luminescence,
polyester,
spectroscopy,
light effects

1 Introduction

Among a variety of different textile materials, luminescent textiles also have a place in the textile industry [1-4]. The product category of luminescent textiles includes fluorescence and phosphorescence textiles. Fluorescence is from the chemical point of view a kind of luminescence resulting from the absorption of photons [5,6]. Fluorescent materials absorb light with lower wavelength (higher photon energy) and emit light with longer wavelength (lower photon energy). In case of fluorescent materials, the emission stops after the absorption of light is stopped [6,7]. Phosphorescent materials are as well photoluminescent, but in contrast to fluorescent materials their emission proceeds after the absorption of light is finished [8]. Fluorescent compounds are mainly used in the field of optical brighteners for textiles, paper and plastics [9-11]. Here, the non-visible ultraviolet (UV) light is transferred to visible light with longer wavelength, so finally the amount of visible light is increased. By this, the white color of the material is supported and a natural yellowing of raw materials is covered. In textile products, fluorescent materials are mainly used in the area of occupational safety. High-visibility polyester textile products, for example, are also made by application of fluorescent dyes [12]. The application of several fluorescent naphthalimide and phthalimidylhydrazone dyes on polyester fibers is described earlier supporting an excellent correlation between chemical structure to color and fluorescent properties [13,14]. The application of fluorescent dyes onto textile fabrics is also possible under assistance of microwave technology or with supercritical carbon dioxide as solvent [15,16]. Beside polyester fabrics, also fabrics based on cellulosic fibers can be dyed by use of fluorescent dyes [17,18]. Here a simple dyeing process using direct dyes is possible, e.g. with the well-known fluorescent dye Rhodamin B [17]. Further interesting approaches discussed in literature are e.g. wearable textile sensors or double functional treatment combining fluorescent effect with antimicrobial properties realized by fluorescent active disperse dyes [19,20]. Luminescent textiles can also be found in everyday life. Phosphorescence is often used in the field of home textiles and clothes for children [8]. The aim of the recent study is the investigation of fluorescence on textiles available as low-cost consumer products. These products are compared with each other in terms of colors and material composition. Finally, four different textiles are examined with respect to their fluorescence properties. The investigated items are an orange high-visible vest with two reflective strips and three microfiber towels in the colors magenta, orange and green. The three compared microfiber products are quite similar from the material point of view and only differing in their coloration. One intention for selection of this sample collection is to support a view on quite similar consumer materials which are mainly different in coloration and type of fluorescence dye, because the main topic of the current paper is the fluorescence effect. These towels are compared to another typical product in the field of fluorescence textiles – a high-visible vest. According to the supplier information on the textile label attached to the textile products, the four test specimens are each made of 100% polyester. The optical appearance is evaluated by illumination using different illumination arrangements with UV-light and visible light. CIE-Lab measurements are done to determine the coloration. Further, scanning electronic microscopy (SEM) is performed. The chemical composition of the investigated textile samples is determined by using electron dispersive spectroscopy (EDS). Fluorescent light emission and excitation of the samples is recorded by fluorescence spectroscopy.

2 Textile materials and analytical methods

2.1 Textile materials

The investigation on fluorescence properties of commercially available textile materials is done on four different samples for typical applications. These samples are listed in Table 1 and summarized together with some information given be the suppliers of the products. All samples exhibit a strong coloration which is obviously enhanced by the fluorescence effect. Samples 1 to 3 are polyester microfiber towels of different coloration sold in spring 2022 in Germany by the same supplier. The price per piece is with 3.99 Euro for each sample quite low. The sample 4 is a high-visible vest, where the supplier is not specified. Such high-visible vests are usually classified and distributed in Germany according to the standard ISO 20471:2013. The price per vest is usually in the range of 2 to 3 Euro depending on the supplier. An example for such a supplier in Germany is the Arbeitsschutz-Express GmbH (Leipheim, Germany) [21].

Table 1. Overview on the discussed fluorescent textile samples.

Sample no.	Coloration impression	Fiber material	Supplier	Application purpose	Price per piece (Euro)
1	Orange	Polyester, microfiber	Ernsting's Family	Towel	3.99
2	Magenta	Polyester, microfiber	Ernsting's Family	Towel	3.99
3	Green	Polyester, microfiber	Ernsting's Family	Towel	3.99
4	Orange	Polyester, fabric	Not specified	High-visible vest	Around 2.- to 3.-

2.2 Analytical methods

Fluorescence emission spectra of investigated samples are recorded by using a RF-6000 spectrofluorometer supplied by Shimadzu (Japan). For sample excitation light of 360 nm or 380 nm is used. This fluorescence spectrometer is also used to record 2D fluorescence spectra as overview for each textile sample. Microscopic investigations are done by using a scanning electron microscope Tabletop TM3000 supplied by Hitachi (Japan). This electron microscope is also equipped with an EDS (electron dispersive spectroscopy) unit Quantax70 from Bruker, which allows the detection of chemical elements on the sample surface. Photographic documentation of the samples is done under different illumination. For illumination with visible light, an illumination chamber Verivide is used with standard light D65. The same illumination chamber is also used for illumination with UV-black light. Further a second type of illumination with UV light is performed. For this a UV black light lamp UV Omnilux 230V_25W is used in a dark room. Both types of used UV lamp are emitting so-called black light and exhibit an emission maximum in the range of 360 to 380 nm. For determination of color properties, the CIE L*a*b* indices are determined using a photospectrometer device DATA Color 400 (Rotkreuz, Switzerland). As fastness property, the rubbing fastness is tested as dry and wet rubbing by using a crockmeter. This testing is done according to standard DIN EN ISO 105-X12. The fastness properties are evaluated and graded with a grey standard with the grades 1 to 5 according to the standard DIN EN 20105-A02. The infrared spectra of investigated textile samples are recorded with a FT-IR spectrometer IRTracer-100 from Shimadzu (Japan).

3 Results and Discussion

3.1 Microscopic topography and elemental composition

The microscopic topographies are recorded by SEM and presented in Figure 1. For the samples 1 to 3, the structure of a non-woven microfiber is clearly visible. In contrast, sample 4 exhibits a fabric structure.

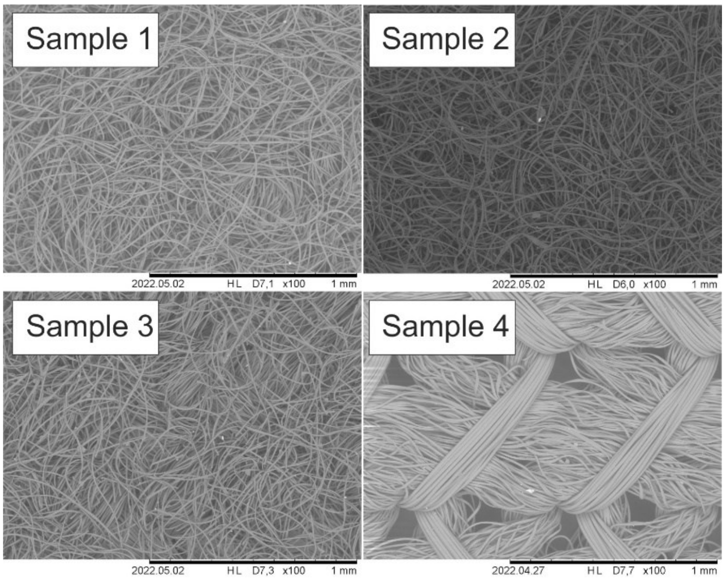

Fig. 1 Microscopic images of the different evaluated samples. These images are recorded by SEM in the same magnification.

The elemental surface compositions of the investigated samples are determined by EDS and listed in Table 2. The main component is carbon (with around 63 wt-%), followed by oxygen (with around 36 wt-%). This relation of carbon to oxygen is clearly related to the chemical composition of the polyester PET and a typical result of EDS investigations on PET materials [22]. The chemical element hydrogen cannot be detected by EDS method. For the samples 2 to 4, also a small content of around 0.3 wt-% titanium is determined. This small content of titanium is probable dedicated to the presence of titanium dioxide TiO_2 added during the spinning process to the fiber. TiO_2 is often used and added as white pigment to synthetic fibers [23]. Sample 3 exhibits also a small content of around 0.1 wt-% chlorine. This chlorine can occur as residue from washing procedures or as part of an applied dye stuff. Chlorine atoms bonded to the chromophore of dye molecules are often acting as auxochromic groups to enhance and modify the coloration of a dye stuff [24]. An example for a fluorescent dye (Disperse Yellow 232) containing chlorine as auxochromic group is given by Szuster et al. [12].

Table 2. Elemental surface composition of textile samples as weight content. Chemical elements with a concentration of less than 0.1 wt-% are not recorded. Further, the chemical element hydrogen cannot be recorded by the EDS method.

Sample no.	Carbon content (wt-%)	Oxygen content (wt-%)	Titanium content (wt-%)	Chlorine content (wt-%)
1	62.88	37.12	---	---
2	63.44	36.15	0.32	---
3	63.31	36.32	0.26	0.11
4	62.53	37.21	0.26	---

3.2 Color appearance of textile products

Visual color impressions under different types of illumination are presented in Figure 2. Especially interesting is the comparison of color impression between illumination with daylight or UV-light. If a sample exhibits a coloration while illumination only with UV light, the fluorescence effect of this sample is demonstrated impressively. In case of illumination with UV light, a coloration is only visible if the sample contains fluorescence properties. Without fluorescence effect, the emitted UV light will be simply absorbed or reflected, but is still not visible for the human eye. In current comparison, all four samples show nearly the same coloration independent of different UV light type 1 or type 2 used for illumination. Probably, all these samples exhibit the same excitation profile for the fluorescence effect. Remarkable is sample 2, because this sample shows a different coloration if the illumination is done by UV light or daylight. The spectral range of fluorescence light emission with UV light illumination is probably not similar to the color impression as a result from interaction with daylight. A similar case is reported earlier by Youm et al., who investigated yellow disperse dyes emitting green light while illuminated with UV light [14].

In addition to the visual impressions given with Figure 2, the color properties of the samples are described by the CIE-L*a*b* values presented in Table 3. Samples 1 and 4 exhibit CIE-L*a*b* values in the same range and contain thus a similar coloration. Significant differences in coloration are detected for samples 2 and 3. The value L* describes the brightness of the samples and exhibits values from 0 to 100 [25]. For this value L*, the green sample 3 exhibits the highest number and is thus the brightest of all presented materials. The value a* describes the red and green content of coloration, with a scale from -170 to +100 (negative numbers for green and positive for red). The value b* describes blue and yellow contents of coloration, with a scale from -100 to +150 (negative numbers for blue and positive for yellow) [25]. Both orange samples exhibit high positive numbers for a* and b*, standing for the combination of red and yellow leading to the orange coloration. Sample 2 described as magenta appearance contains a b* value near zero. The green sample 3 exhibits a significantly negative value a* and a positive value b*, standing for the combination of green and yellow. In a certain way the CIE-L*a*b* values of this green sample 3 can be compared to the values reported by Szuster et al. for various yellow fluorescent dyes applied on polyester fabrics [12].

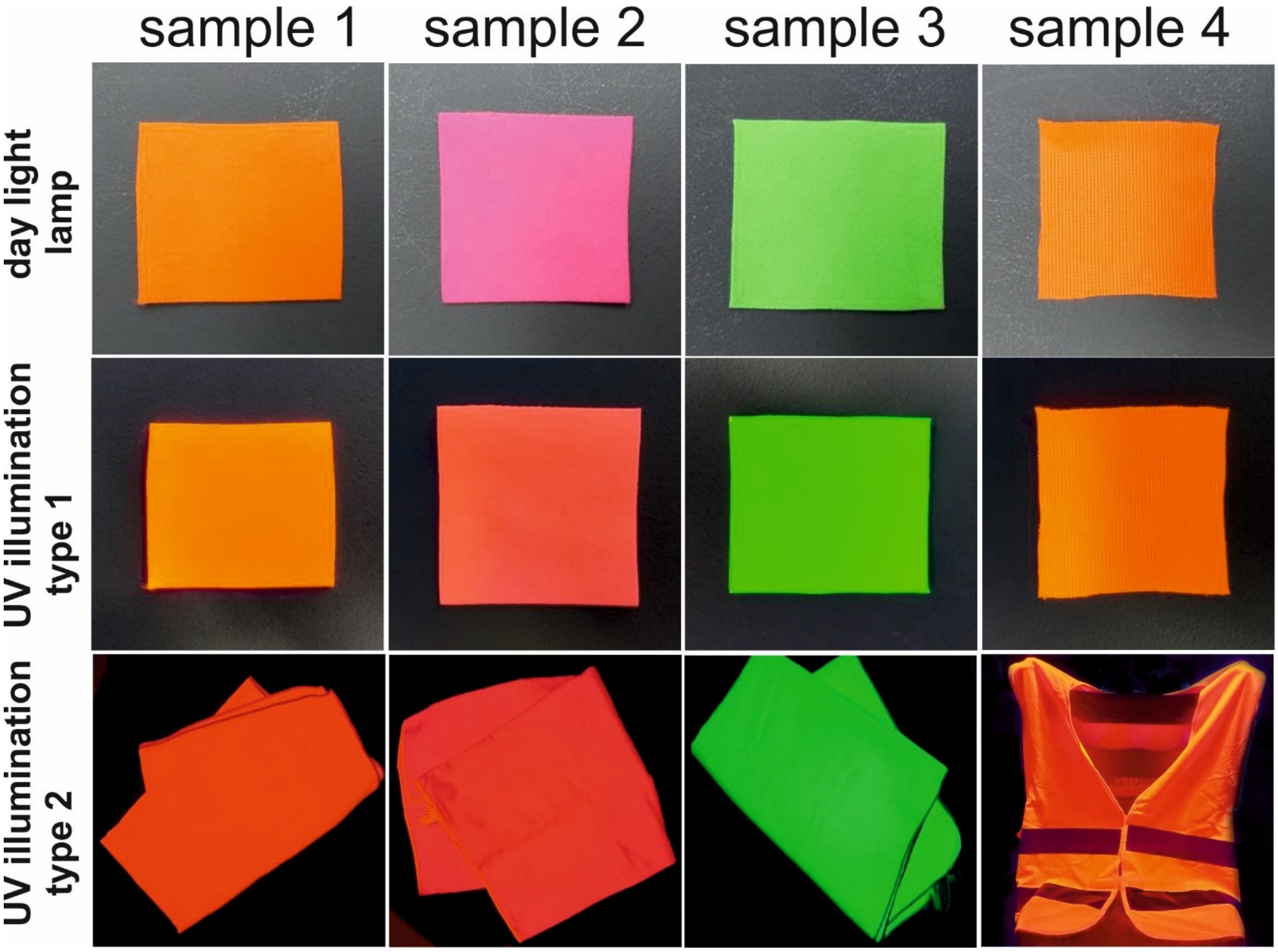

Fig. 2 Overview on different evaluated samples under different kinds of illumination.

*Table 3. CIE-L*a*b* values for the investigated samples.*

Sample no.	**L***	**a***	**b***
1	73.5	77.3	76.6
2	67.4	76.1	0.1
3	92.3	-57.4	64.5
4	74.1	79.7	74.1

3.3 Fluorescence properties

For determination of fluorescence properties, at first 2D fluorescence spectra are recorded for each sample as overview (Figure 3). In each 2D spectrum, diagonal lines of high intensity appear. These diagonal lines are not related to the measured textile samples. They occur for all samples at the same position and are caused by measurement arrangement and sample holder. In these overviews, the samples 1, 2 and 4 exhibits nearly the same fluorescence emission properties with a maximum emission at around 625 nm (orange light). This fluorescence emission is coursed by excitation with UV light. However, also the excitation with visible light is possible and can lead to even stronger fluorescence emission. This fluorescence behavior is in a certain way similar to polyester fabrics dyed with hydrazone disperse dyes showing fluorescent emission maxima between 550 to 565 nm [26]. The fluorescence emission of sample 3 is different, because here the maximum emission is around 510 nm (green light). The fluorescence excitation of sample 3 is mainly done by UV light in the range between 350 to 400 nm and by violet and blue visible light. Remarkable is especially that the fluorescence effect is not only driven by excitation with UV light. Also, visible light of shorter wavelengths is transferred to fluorescence emission of visible light with higher wavelength.

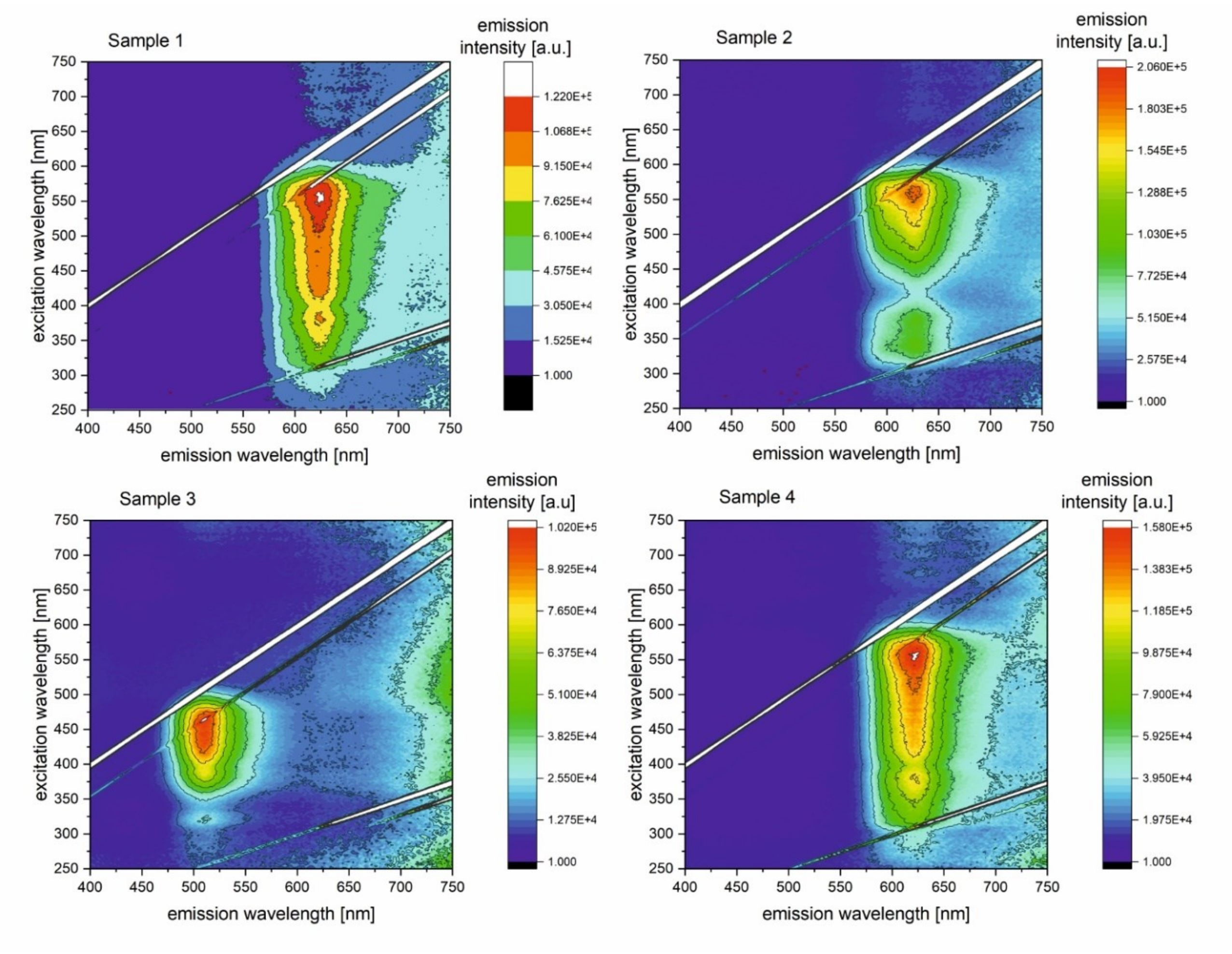

Fig. 3 2D fluorescence spectra of different evaluated samples.

For more detailed evaluation of the fluorescence properties conventional fluorescence spectra are recorded for excitation with UV light of 360 nm or 380 nm (Figure 4). The excitation with this type of light is chosen, because it is for several applications the most typical UV light – with significant content in sunlight and in commonly used artificial UV light (black light). UV light in the spectra range around 360 to 380 nm is emitted by UV black light lamps but also by conventional lamps emitting white visible light [27]. These fluorescence spectra presented in Figure 4 verify the statements made by discussion of the 2D fluorescence spectra. Additionally, it can be stated that sample 1 shows significantly the strongest fluorescence emission.

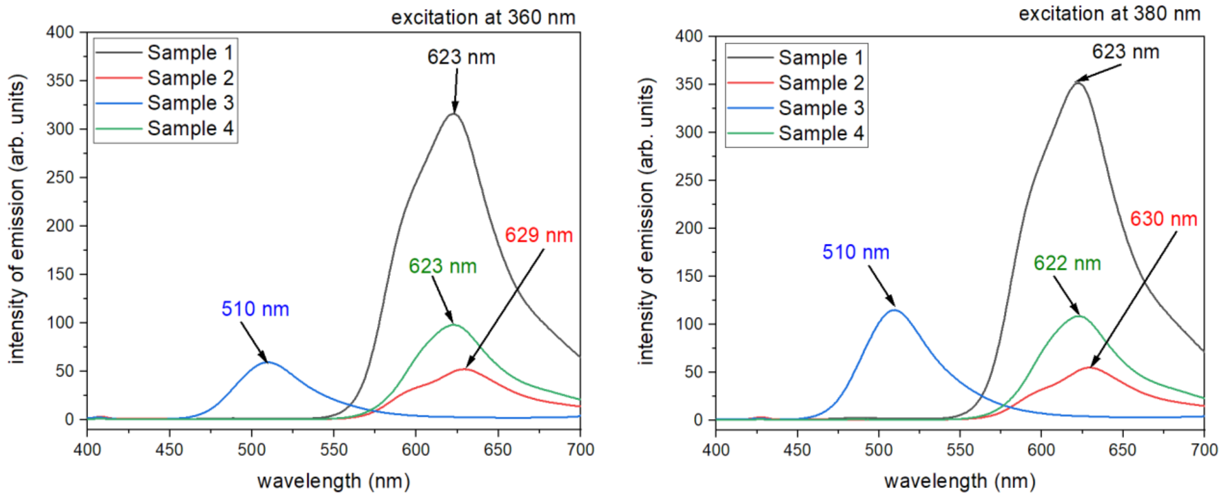

Fig. 4 Fluorescence emission spectra of different evaluated samples – left: excitation performed with light of 360 nm / right: excitation performed with light of 380 nm.

3.4 Fastness properties

According to supplier information, the textile samples 1 to 3 should be washed before use and a color transfer to other fabrics could be possible. Nevertheless, all samples exhibit in dry and even in the wet rubbing test the best grade of 5 for the crock fastness. Almost no color transfer to the wet cotton fabric is determined after the rubbing test. This result is significantly better compared to rubbing fastness reported for polyester/cotton blended fabrics treated with coumarin based fluorescent disperse dyes [28]. This weaker result on the blended fabric can be explained by the low adhesion of disperse dyes on cotton fibers. In comparison for the actually discussed commercial textile products, the applied fluorescence dyes are perfectly fixed on fabrics made from 100% PET fibers. Although no information according to the dyeing process is given by the material suppliers, it can be expected that for the application on PET fibers disperse dyes are used [24,29]. The physical embedding of disperse dyes in the PET fibers is an excellent method to realize strong fastness properties [24,29].

3.5 Infrared spectroscopy

Infrared spectroscopy (IR spectroscopy) is performed mainly for two reasons. First, the supplier information is checked that the fabrics are made from 100 % polyester PET fiber material. Second, it is investigated if the different sample materials exhibit different features in the IR spectra, because of different treatments with different fluorescent dyes and other chemicals. The IR spectra of all four investigated samples are similar and their nearly identical finger print area of IR spectra are presented in Figure 5.

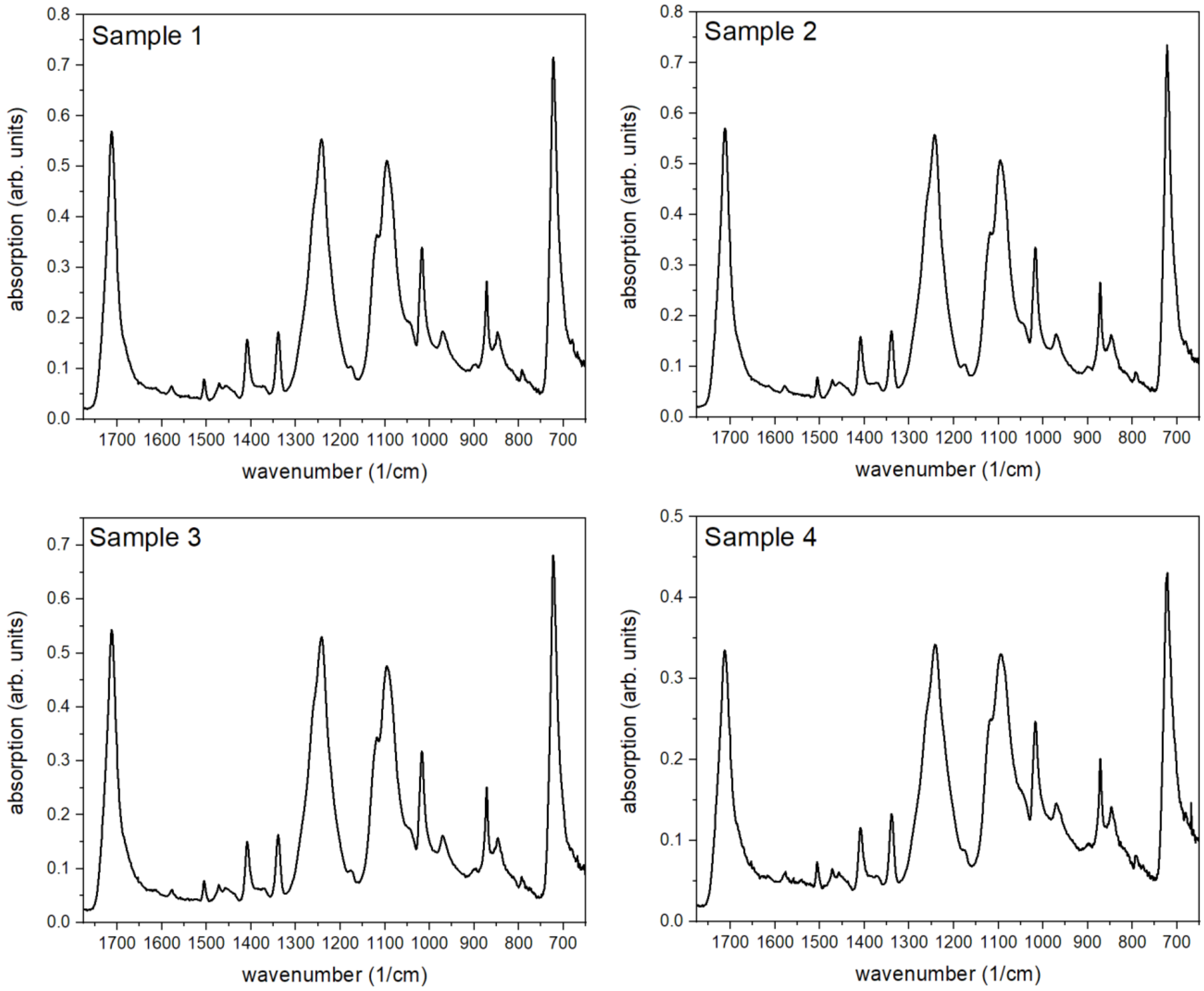

Fig. 5 Infrared spectra of the different evaluated samples – shown are the fingerprint regions of the IR spectra.

The detected IR spectra are in good accordance to IR spectra of polyester PET fabrics and PET bottles reported in the literature [30,31]. No additional signal related to the chemical modification of the fibers can be identified. It can be stated that all samples are made from 100% PET fiber material and it is not possible to identify by IR spectroscopy the type of chemical treatment used to implement the fluorescent effect. Probably the amount of applied fluorescent dye is small compared to the amount of PET substrate, so identification is not possible. The main signals detected in the IR spectra of the PET fiber materials can be assigned to several vibrations. Three weak signals at 2851 cm^{-1}, 2922 cm^{-1} and 2966 cm^{-1} are related to C-H stretching vibrations at aliphatic and aromatic groups. The strong peaks at 1713 cm^{-1} and 1243 cm^{-1} are assigned to C=O and C-O-C stretching vibrations of the ester groups. The strong signal at 1097 cm^{-1} is related to C-C stretching vibration of the aliphatic unit next to the ester group. The strongest peak at 722 cm^{-1} can be assigned to a deformation vibration of the $-CH_2-$ unit (rocking vibration) [30,32,33].

4 Conclusions

Four commercially available fluorescent textile materials are evaluated. All four samples exhibit strong fluorescence emission and strong coloration when they are illuminated by UV light. Their wet and dry rubbing fastness is excellent. For this it can be stated that even products from the low-cost segment contain strong fluorescence and excellent fastness properties. The coloration effects can be significantly enhanced by fluorescence effects. It can be stated that fluorescent textile materials are part of everyday consumer products.

Author Contributions

V. Ernst and L. Schröder: illumination experiments, spectroscopic measurements and rubbing tests; B. Mahltig: supervision, writing, review, editing, spectroscopic and microscopic measurements.

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Conflicts of Interest

The authors declare no conflict of interest.

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