TESNIR

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EXTERNAL INSTITUTION
Circularity

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Executive summary

Nowadays, the textile industry has a massive environmental impact, involving depletion of resources in the production of garments and a very short life cycle of clothes. Indeed, there are usually produced, used and later thrown away without a proper recovery, pilling up in landfills. One of the main obstacles for an effective recycling of garments is the sorting phase, where workers selectively divide dismissed clothes by materials only considering the information on the labels, which are often missing. Thus, more efficient ways of sorting textiles must be explored to foster the transition of all the textile supply chain towards more sustainable models. The experience developed in recent years for the recognition of plastics can be translate to the textile sector. Specifically, the technology based on the use of Near Infrared (NIR) spectroscopy can recognize the material from its characteristic spectrum, which is a sort of fingerprint of its chemical structure, acquired in the near infrared region of light. Thus, the main objective of this work is to explore the capabilities and limitations of NIR optical systems in classifying textiles by materials.

An experimental study has been performed testing four NIR instruments in the department of Physics of Politecnico di Milano. Data analysis tools and recognition algorithms have been developed using samples of cotton and polyester, the most widely produced materials, but also on other pure and blended fibers. The main insights we could gain from the experimental work are that surface roughness does not alter the classification performance significantly and that NIR technology should operate in the wavelength range of 1100-1750 nm to prevent different colors of garments from masking the material information. However, some black pigments cannot allow a clear classification since they mask the NIR signal totally. Moreover, some types of fabric are not distinguishable: linen cannot be discriminated from cotton, whereas viscose can be confused with wool and nylon. Even if different compositions of polyester-cotton and polyester-elastane provide different spectra, polyester content below 20% and elastane content below 5% cannot be detected. The tested instruments have limited industrial applicability due to the long acquisition time (several minutes) and the manual introduction of samples inside the instruments.

To address possible improvements in the textile supply chain, industrial partners were interviewed thanks to the collaboration with the external partner Circularity. The interviews highlighted the difficulties in implementing a circular business model based on recycled fibers due to economic and technical issues, where quality, color and purity of the fibers are the most important parameters to take into consideration. Further on, a survey was proposed to more than 420 potential customers to understand the key factors influencing their choices when shopping clothes. According to their opinion, tactile feel of the garment, price and information on sustainability are high-impact characteristics to convince them to switch to more sustainable clothes. Thus, the final product should have recycled fibers pleasant to the touch and price comparable to virgin materials, as well as clear information regarding the decrease in environmental impact should be pointed out. Finally, 80% of respondents expressed the will to buy clothes made of recycled fibers, showing general interest in the circular model enabled by the sorting of textile waste using NIR technology.

Key Words

Textiles, sustainability, spectroscopy, classification.

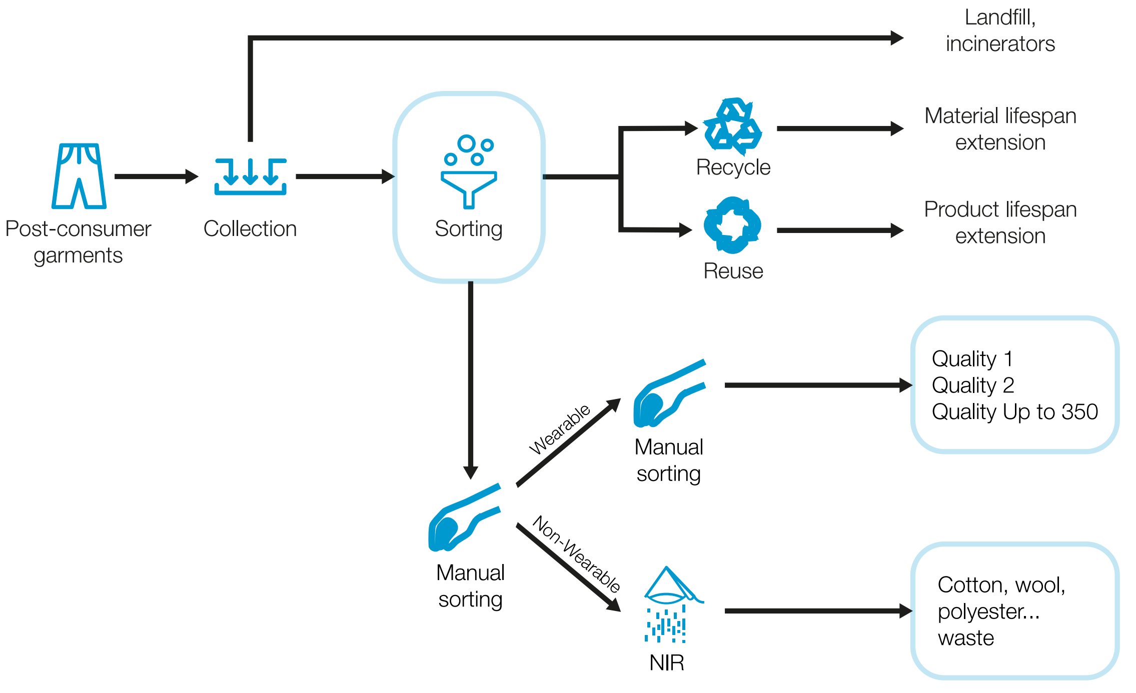

Figure 1. Infographic about textile supply chain including NIR technology

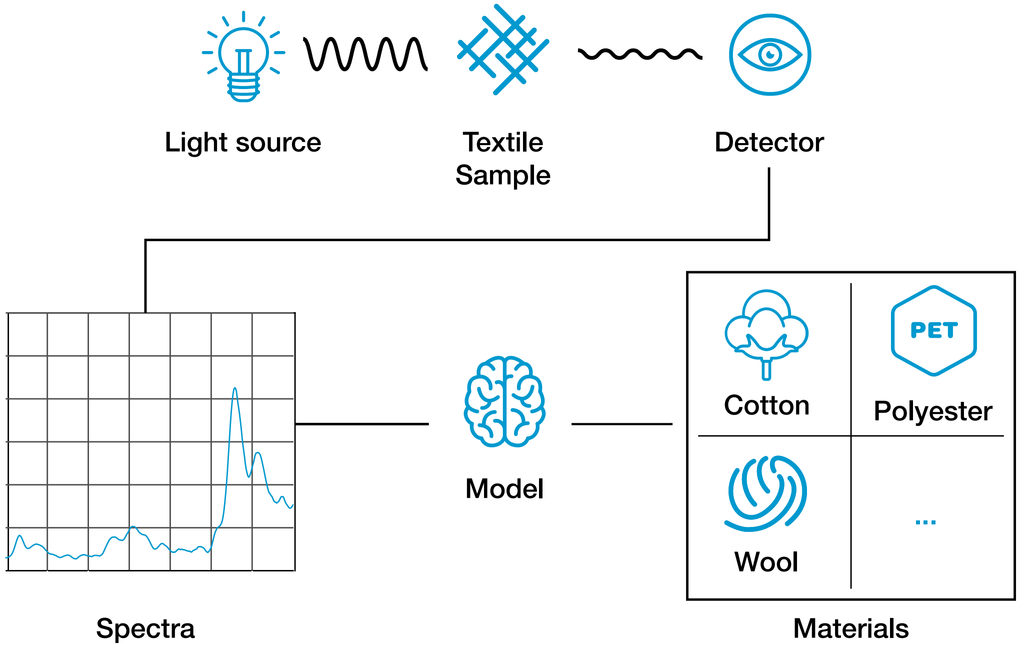

Figure 2. Infographic about the working principle of NIR technology

Project description written by the Principal Academic Tutor

Circularity, an Italian consultancy firm working in circular economy, sponsored the TESNIR project to promote a technological assessment on Near InfraRed (NIR) spectroscopy for the selection of end-of-life garments. The TESNIR team addressed the challenge from two complementary points of view.

First, a survey on the requirements of the textile industry to set up a circular business model was performed. To this purpose, the practices currently used to sort the different materials were analysed. It turned out that manual sorting based on the garment labels is still commonly used, although automatic sorting plants, based on technologies borrowed from plastic recycling, are starting to become available. The TESNIR Team could realize that a unique technological solution to setup a cost-effective circular economy for textiles is likely not realistic. In fact, a large variety of materials are involved, and end-of-life garments must be addressed toward different destinations according to their quality. However, despite the complexity of the problem, the TESNIR Team clearly understood that NIR spectroscopy is a valuable tool to overcoming the bottleneck of the textile sorting phase, even though only a few experimental facilities working with this technology have been established so far.

Then, in order to become aware of the critical aspects of this technology in sorting textile waste, the Team performed several experimental sessions of fabric analysis using laboratory based NIR instruments, under the supervision of the academic tutor. These measurements allowed the Team to acquire enough data to build a materials classification model based on multivariate analysis. The model proved effective to separate the most common families of materials and confirmed that NIR, in a specific spectral range, is appropriate for textile sorting.

In conclusion, the main outcome of the TESNIR project was a wealth of experience gained by the Team members on the critical issues and the direction to be taken to transform a pilot project into a possible industrial project.

Team description by skill

The TESNIR team comprises 6 members, one designer and five engineers from diverse disciplines.

Alessandro Della Porta is studying Materials Engineering and Nanotechnology. His background includes physical chemistry of matter, materials processing methods and characterization techniques. He is specializing in computational materials science.

Elisa Vasta is a MSc Biomedical Engineering student with a focus on Neuroengineering, Biomedical Signal Processing and Artificial Intelligence in Medicine.

Randeep Singh is studying Mathematical Engineering, with specialization in Statistical Learning, and he focuses on mathematical models for data science and scientific programming.

Giacomo Graziano is a Nanotechnology for ICTs student, and his studies are based on semiconductor devices, physical simulation and chip design.

Leonardo Gambarelli is a Mechatronics Engineering student with specialization in Industrial Technologies and with a focus on data-driven control systems and simulation modelling.

Davide Mammana is studying Design and Engineering with a focus on product development , from research to product engineering.

Goal

TESNIR project revolves around the application of Near-InfraRed (NIR) spectroscopy in the textile sector, enabling a proper recovery of end-of-life garments and promoting the development of circular economy based on recycled fibers.

The first objective of this work is to explore the capabilities and limitations of NIR optical systems in classifying garments by material based on their characteristic spectra, thus automatizing the sorting process of textile waste and making it more efficient. In this regard, it was essential to test first-hand different NIR technologies, identifying the specific optimal spectral bands and preprocessing methods, as well as the investigation of the effects introduced by color and surface roughness of garments. The experimental study had a wide breadth since it included both pure and blended materials, especially polyester and cotton for their industrial relevance. Moreover, different data exploration tools and classification algorithms were explored to discriminate the spectra by their chemical composition.

The second main goal of the project is to understand how to introduce the NIR technology in the current textile supply chain for an effective sorting and recycling of end-of-life garments. Thus, a market analysis was performed to identify requirements and possible interventions that are necessary to improve the identification of fabrics by NIR technology. Finally, the last objective of this part is to investigate if the circular economy model based on recycled fibers and promoted by the introduction of this technology could be embraced by consumers..

Understanding the problem

Nowadays, the textile industry is ruled by a linear model, meaning that clothes are generally produced, used and later thrown away without a proper recovery [1]. There is a growing concern for the sustainability in the sector, since garments can have massive environmental impacts throughout their lifecycle, from resource depletion (e.g. water, energy), to harmful emissions (e.g. greenhouse gases, microplastics) and vast untreated waste volumes [4]. Currently, the market is witnessing a strong opposition between a growing demand for clothes, driven by phenomena like fast-fashion, and a very limited fraction of waste that is properly recycled. Indeed, according to statistics (Figure 3), there is less than 1% of fiber-to-fiber recycling, which means that only a tiny part of the fabrics produced is later used to obtain recycled fibers with quality comparable to the virgin ones [3].

One of the main obstacles towards an effective recycling of textile waste and a transition to circular model is the sorting phase. Here, dismissed clothes are selectively divided to redirect them to different end-of-life operations. The main problems of this stage are related to the way waste textile are currently sorted: groups of workers inspect the composition of garments by manually reading labels or through their experience [7]. Hence, two major challenges arise. On the one hand, processable volumes are limited since the operation is time- and labor-intensive. On the other hand, accuracy is mined by the qualitative assessment of textiles and on the almost total reliance on labels, which may be inaccurate or lacking. Under this perspective, sorting can strongly influence the output of textile recycling processes since they often have strict requirements for the input material in terms of composition, color, and purity [3].

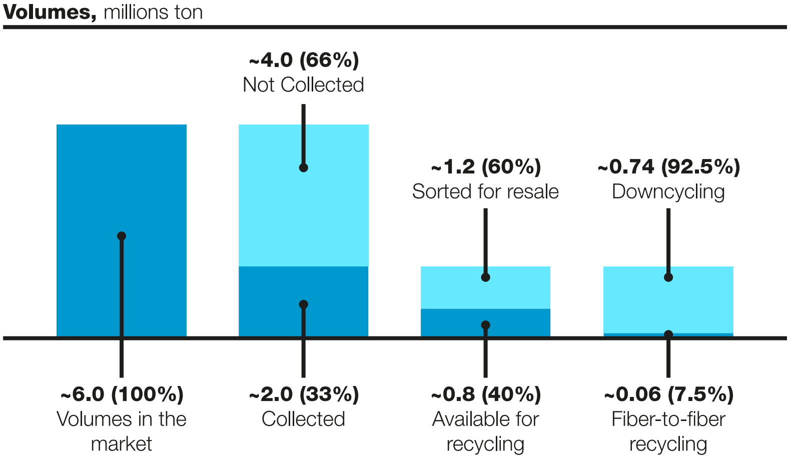

Figure 3. Infographic about the end-of-life of post-consumer textiles

Exploring the opportunities

TESNIR project is part of the strand of research that aims at automatizing the sorting process of textile waste, since one of the obstacles to creating a transition to circular economy resides in the way fabrics' refuse is separated. As explained before, the current paradigm based on manual sorting cannot match the sharp requirements of the recycling industry. Thus, introducing NIR technology in this phase can help guarantee the automatization and efficiency of the process, and it would generate the proper input material for the recycling industry. The in-depth analysis on the context of the textile supply chain identified the optimal position of NIR technology inside the sector, as summarized in Figure 1. First, post-consumer garments are thrown away and collected in specific containers by waste collection companies. Later, this huge amount of rejected textiles goes to incineration or landfill, or it is subjected to sorting towards recycling or second-hand market, allowing material and product lifespan extension. The first sorting step is performed manually in order to assess the wearability of the clothing. Later, NIR technology can be introduced for separating non-wearable textile products, and possibly supply them as input to recycling plants. Instead, still wearable clothing will be re-sold and re-used.

Moreover, translating NIR technology in this context can be seen as a demand-pull innovation. There is a global need for reducing waste of resources and minimizing the environmental impact of the textile sector. In addition, starting from 2025 in Europe and from 2023 in Italy, EU regulations will impose a separate waste collection also for fabrics [9]. In this scenario, the ASP project can help taking the most out of the large amount of textile waste expected due to the legislation, by enabling fibers' recycling and thus answering to society demands. Plus, to promote circular economy in this sector, the main strategy is to allow extending the lifespan of the fabric itself, discouraging the production of new raw materials. In this way, NIR technology would empower business models based on remaking, mostly using recycled fibers. Based on the results of a survey proposed to 423 potential consumers, the 80% expressed the will of buying new clothes made of recycled fibers, highlighting that the introduction of NIR technologies will promote a circular business that would be adopted by many people. Moreover, since new circular models in the fashion industry (resale, remake, repair and rental) represent a USD 73 billion market as of 2019 [2], betting on NIR technology could attract capital and match economical requirements for a future possible business plan.

Generating a solution

The original contribution of the project lies in defining the optimal role that NIR technology could play within the textile industry while testing the classification performance of infrared spectroscopy in identifying materials inside fabrics.

First, understanding the complexity of the textile supply chain and the relationship among the various stakeholders was crucial to define the main obstacles and opportunities for the adoption of NIR technology in this sector. Then, the effort was devoted to evaluating how this technology could provide a solution to the sorting problem of textile waste from a narrower perspective. The analysis mostly focused on the **acquisition of spectra** of the most relevant materials in visible, near-infrared, and medium-infrared light [5]. Four laboratory instruments in the departments of Physics and Chemistry of Politecnico di Milano were tested: the DISpersive Near-InfraRed (DIS-NIR) spectrometer, the Fourier Transform Near InfraRed (FT-NIR) spectrometer, the Hyperspectral Camera and the Attenuated Total Reflectance Fourier transform InfraRed (ATR-FTIR) photospectrometer. This experimental activity was essential given that no available datasets in the literature included spectra obtained from many types of pure fabrics and, above all, from mixtures of fibers of different materials (e.g., 30% cotton and 70% polyester). To tackle the need of experimental proof, 82 textiles samples were collected, both pure materials (cotton, polyester, nylon, viscose, wool, silk, acrylic, linen) and some blends, polyester-elastane, cotton-acrylic, and cotton-polyester.

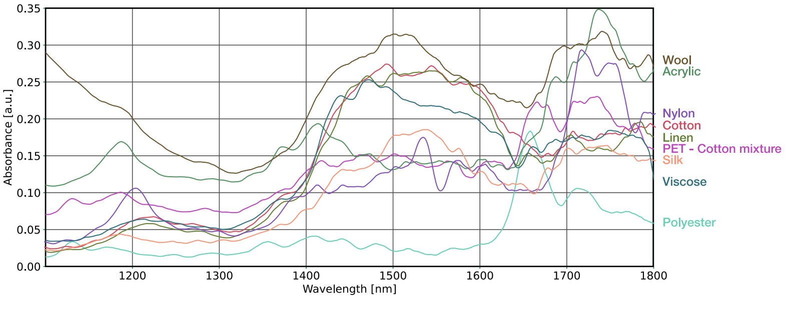

Figure 4. Absorption spectra acquired with the DIS-NIR spectrophotometer of the studied materials

Later, data analysis tools and classification algorithms were developed to discriminate the various spectra according to the material of the textile sample. In the first step, raw data from spectrometers were processed to obtain usable absorption spectra for the classification, and each instrument required a different approach. The best **spectra preprocessing** methods for spectra are: the Savitzky-Golay filter (SG), the Standard Normal Variate (SNV), Multiplicative Scatter Correction (MSC) and Derivative Spectram (DS) [8]. In general, the analysis revealed that SG was a necessary part, and that SNV was the best method since it can rescale the spectra without the need of a reference spectrum like MSC. Figure 4 represents the spectra of the DIS-NIR instrument after preprocessing.

Moreover, the analysis aimed at investigating the **influence of color and surface roughness** of garments. In the visible range (from 400 to 900 nm) and up to 1300 nm in some wool samples, solely color information was present in the spectra acquired from the DIS-NIR instrument. Plus, the analysis revealed that some black pigments mask the NIR signal completely, so they should be banned in clothes to promote optical sorting, Moreover, the light scattering for thick and rough samples was too high for a clear signal. In other cases, the reason for a low signal was ascribed to the low incident light intensity at specific frequency bands.

Further on, data exploration was conducted. **Principal Component Analysis** (PCA) could reduce the dimensionality of the spectra (more than 450 wavelengths) to a few components while preserving the variance explained [5]. Subsequently, **Cluster Analysis** (CA) was used to determine if spectra could be grouped by material and which materials had indistinguishable spectra, as shown in Figure 5. In particular, the DIS-NIR data had the clearest clustering, revealing that linen is indistinguishable from cotton, that 5% elastane is undetectable, and that viscose had some ambiguous spectra. Instead, spectra obtained from the FT-NIR spectrometer required heavy processing, and the resulting clusters were much fuzzier, revealing that net distinctions by material are more difficult with this instrument. The combination of PCA and CA helped identifying the optimal range of spectra acquisition for each instrument. For the DIS-NIR spectrometer, data was collected both in visible and NIR ranges of light (400-1850 nm), but the best interval was 1300-1750 nm, allowing to exclude both the signal from dyes and pigments and the noisy regions without information. For the FT-NIR spectrometer, the best interval was 1200-2300 nm, even though the data was collected in a larger range (900-2600 nm).

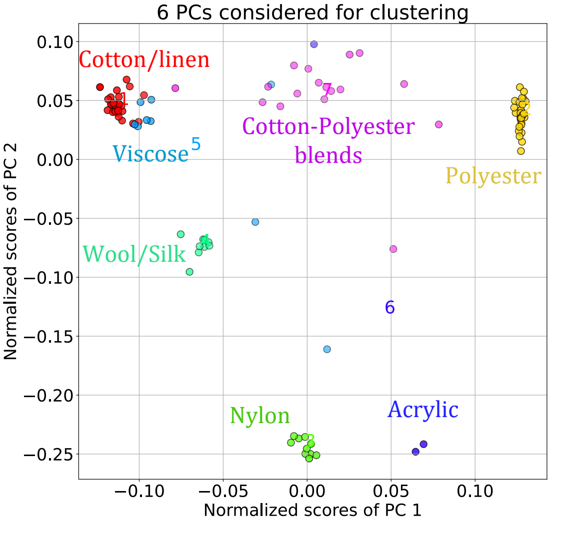

Figure 5. PCA+CA scatterplot of the first two principal components, where colors denote the formed clusters. Each cluster was associated to the shown material classes.

The classification tasks were applied to the DIS-NIR spectra processed by SNV in the interval 1300-1750 nm. The first algorithm was based on 1 Nearest Neighbor (1NN) classifier. Reference spectra were collected averaging SNV spectra of each material. An unknown spectrum can be classified by associating it to the reference one with the lowest cost function (e.g. Euclidian distance), after scaling it through SNV or MSC. The accuracy of this classifier was about 75%, limited by the inevitable similarities spotted with PCA and by confusion between blends of cotton-polyester with close percentages. The second classifier implemented was the Partial Least Squares Regression (PLS-R). Its performance is about 85% applied on all materials, more than 90% when applied on cotton-polyester blends, and 100% when applied solely on pure cotton and polyester. In general, especially for blends, the performance of the classifiers was limited by the few known spectra available.

The hyperspectral camera, a research instrument under development by Politecnico di Milano and CNR [6], was interesting for its ability to collect spectra of different garments at the same time (in an area of about 500 cm^2), without contact (about 1 m distance) and with a quite low acquisition time (some seconds). Even though this instrument represents a valid option in an industrial context, the acquired spectra were masked by interference and could not be used in further analysis. On the other hand, the ATR-FTIR allowed measurements at the level of the single fiber (about 1 μm^2) and in the medium infrared (MIR) range. The MIR range produces a much clearer signal from the material and spectra of cotton and polyester were largely distinguishable. However, this instrument has a low applicability in an industrial context because it is expensive, slow (several minutes for each spectrum) and it requires close contact with the textile samples.

The approach followed in this project did not include the other necessary parts to build an industrial plant based on automatic sorting, such as mechanical transport and the physical separation of garments and unwanted elements after the identification. Instead, one important outcome of the project is to have highlighted the necessary requirements to bring the sorting process based on NIR technology to the industrial scale, underlying the critical aspects of spectra acquisition and classification.

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