Hyperspectral imaging detection architectures

for polyethylene (PE) and polypropylene (PP) identification

inside plastic waste streams

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Abstract

Since polymers are continuously replacing other materials in major consumer products, the consumption of plastic increases faster than the economy as a whole. One of the weakest points in the recycling system is the reuse of waste plastic. There are many kinds of plastics utilised in every day life: polyethylene (PE), polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC) and polyethylene terephthalate (PET). The most important polymers in the consumer goods and the least recycled plastics materials are the polyolefin's. The reason can be mainly attributed to the complexity of these wastes according to different polymers (rubber, foam, etc.) and polluting (not polymers) materials (wood, aluminium, copper, stones, glass, etc.) commonly present in plastic waste streams. In this paper an innovative sensing technology, based on an hyperspectral imaging (HSI) approach, is presented and discussed: i) to determine the quality of waste plastic feed and ii) to set up new sorting strategies for pure PP and PE recovery.

1   Introduction

Analyses by the European Community (EC) indicate that besides their ecologic importance, raw materials and energy are also the most important competitiveness factors for EU industries. Therefore the need to increase recycling, improving at the same time the quality and homogeneity of recycled materials to minimize environmental pollution and usage of resources is thus a topical subject for the EC. There is a strong drive to recycle polymers from end-of-life products and avoid their ending up in land fills and waste incinerators because plastics recycling reduces CO_2 emission and saves resources.

The worldwide production of plastics was 230 million ton in 2005 (JOHANSSON, 2007). In Europe, 53.5 million ton were produced in total. Out of 22 million ton of post-consumer

plastic waste in Europe in 2005, 53% was disposed, 29% was used for energy recovery and 18% was recycled (JOHANSSON, 2007). According to Directive 2004/12/EC on packaging and packaging waste, a recycling level of 22.5% should be achieved for plastics packaging by the end of 2008. New, more cost-effective separation technology can thus provide an important incentive to increase recycling rates.

Polyolefins constitute more than a third of the total plastics consumption in Europe, but they are the less recycled. There are many complex wastes rich in polyolefin, such as waste from electric and electronic equipment (WEEE), automotive shredder residue (ASR) or, simply, household waste (HW). Polyolefins are the largest group of thermoplastics, the term polyolefins means "oil-like" and refers to the oil feel that these materials have (GRAHAM SOLOMONS, 2001). They consist only of carbon and hydrogen atoms and they are non-aromatic. They are polymers of simple olefins (hydrocarbons containing one double bond per molecule) such as ethylene, propylene, butenes, isoprenes, pentenes and copolymers and modifications thereof. A characteristic common to all polyolefins is a non polar, non porous, low energy surface that is not receptive to inks and lacquers without special oxidative pre-treatment. The two most important and common polyolefins are polyethylene and polypropylene and they are very popular due to their low cost and wide range of applications.

Aim of this study is to evaluate the possibility to apply hyperspectral imaging based techniques to preliminary determine both the quality of feed and product streams in the recycling of plastic based post consumer waste and/or to develop innovative detection/sorting strategies specifically addressed to perform a preliminary recognition and a further separation of the different polyolefin's materials.

2 Polyolefins characteristics and recycling

Polyethylene, usually indicated as PE, is probably the most popular plastic in the world. It is a very versatile material that makes grocery bags, shampoo bottles, children toys, and even bullet proof vests. Although its wide application field, PE has a very simple structure, the simplest of all commercial polymers, consisting of long chains of the monomer ethylene. A molecule of PE is thus nothing more than a long chain of carbon atoms, with two hydrogen atoms attached to each carbon: $[CH_2-CH_2]_n$. This type of PE is called linear PE, or HDPE (High Density Polyethylene), because the carbon chain does not have any branches. Sometimes some of the carbons, instead of having hydrogen attached to them, have long chains of PE. This is called branched PE, or LDPE (Low Density Polyethylene). Because of these short and long chains branching, chains do not pack into the crystal structure. Therefore LDPE has a lower density and less strong intermolecular forces than HDPE. For common commercial HDPE the melting point is typically in the range 120°C to 130°C and the density is between 930 kg/m^3 and

1000 kg/m^3. The melting point for average commercial LDPE is typically 105°C to 115°C and the density is between 915 kg/m^3 and 930 kg/m^3.

Polypropylene, usually indicated as PP, is a rather versatile polymer. It serves double duty, both as plastic and as a fibre. It is used to make things like dishwasher-safe food containers. As a fibre, PP is used for its characteristics (easiness to make it colourful and water absorption resistance) to make indoor-outdoor carpeting. Structurally it is a vinyl polymer with a linear structure based on C_nH_{2n}. PP is similar to PE only that on every other carbon atom in the backbone chain has a methyl group attached to it. Most commercial PP has an intermediate level of crystallinity between that of LDPE and HDPE. Its Young's modulus is also intermediate. PP has a melting point of 160°C and a density lower than 915 kg/m^3 (usually greater than 850 kg/m^3).

Currently available separation techniques, based on the difference in flotation properties in water, can be used to separate lighter types of plastic such as PP, HDPE and LDPE from the heavier types such as polyethylene terephthalate (PET) and polyvinyl chloride (PVC). Even so, PP, HDPE and LDPE together are both difficult to separate and chemically incompatible, so that the recovered product is a mixture allowing to produce low-quality recycling based plastics. To produce high-purity granulates from these concentrates, the mixture must be sorted very accurately, and to be economically and ecologically sound, most of the polyolefins should end up in a useful product.

Different separation techniques have been thus investigated in the past and are currently under study in order to exploit and/or try to enhance the low differences, in terms of chemical-physical attributes, of PE and PP. Experimental studies carried out by DAIKU ET AL. (2001), adopting electrostatic separation, demonstrated as an high grade for both PE (99.9%) and PP (99.5%) can be achieved, but with very low recoveries, 61.5% for PE and 54.8% for PP, for a throughput of a 1000 kg/h as maximum. The presence of pollutants on the surfaces, as well as that of finer particles, negatively affects the charging process and the further separation, strongly reducing the efficiency of the separation. A preliminary wet handling and a further drying of the plastic should be thus adopted. Such an approach is practically unacceptable from an economic point of view. The possibility to investigate a separation method based on the fact that PP and PE present different melting points was also evaluated. The PE with the lowest melting point will stick to a drum, when the surface of the drum has a temperature between the melting point of PP and PE. Even not considering the complexity of the separation unit, through such an approach only low quantities of products should be obtained. Furthermore this separation should be intrinsically batch, introducing further technical problems in common "continuous" waste plastics processing layout. Commercially available technologies in principle exist. An example is represented by the separation device proposed by TiTech Visionsort GmbH (TITECH, 2005), where the particles are scanned with

near infrared and are separated into different types of material, like aluminium, PP, PE, poly(ethylene terephthalate) (PET) and polystyrene (PS). This type of separation equipment is widely applied in industry. The sorting architecture requires a relatively large minimum particle size, which is from 20 to 50 mm. Such dimensional limit represent a problem when finer particles have to be identified and sorted. For example the cap of a bottle is often made of PP or PE, being smaller than the required minimum particle size, PP and PE caps end up in the residue fraction and are only used for energy recovery. Furthermore this approach is not particularly suitable to separate black PP and PE, as in automotive polyolefins (BAKKER E.J. ET AL., 2008). A separation strategy based on the different density characteristics of the materials, i.e. sink-float process, could thus represent the easiest solutions to realise an effective separation with both high grade and recovery. Such a goal can be obviously reached if the difference in densities between the materials is large enough. This is how polyolefins are separated from PET in bottle recycling (BAKKER E.J. ET AL., 2008). About 80 mass% of the PP particles from shredder residue has a density lower than 910 kg/m^3, whereas virtually all of the LDPE has a density higher than 910 kg/m^3. For the HDPE more than 98 mass% has a higher density than 910 kg/m^3. A sink-float process with a density of 910 kg/m^3 would therefore give good results for the PP fraction. To get both a high grade PP fraction and a high grade PE fraction, it is necessary to remove the fraction between 910 and 930 kg/m^3. For a conventional sink-float process, this would require a separation in two steps. Another problem is the medium itself. Organic liquids (e.g., short chain alcohols) are used to produce a medium with a density lower than the density of water. This brings in economic and environmental problems (BAKKER E.J. ET AL., 2008). A valid alternative can be represented by a separation based on an emerging technology called Magnetic Density Separation (MDS) (BAKKER ET AL., 2007). MDS uses a strongly dilute mixture of water and ferrous oxide (nanometer sized ferrite particles) in a magnetic field. Such liquids derive their separation density from a combination of a magnetic field and gravity. The separation is realised achieving a lower apparent density than water by the combination of a gradient magnetic field and a magnetic liquid. An intriguing propriety of MDS liquids is that they have different separation densities in different layers of the fluid, according to different intensity of the magnetic field. In principle, this effect can be used to separate a complex mixture into many different materials in a single process step, using one of the same liquid. Other important advantages, linked to MDS liquids (composed by 99% water and 1% iron oxide), is that; i) they are environmentally harmless, in fact they can be used without the economic and environmental problems of organic liquids and ii) that they are very cheap to use, even if not fully recovered from the product materials.

Independently from the separation strategy adopted the need to operate a full control of the different plastic waste streams represent a key issue. Therefore a precise and on-

line assessment of composition of the process stream is of the great importance for both the plastic recycling and plastic compounder industry in the transition to the recycling of post-consumer plastic wastes. The former needs it to monitor the plastic waste feed streams. The latter demands it for the most accurate (and fast) composition assessment of the different products, polyolefin based, resulting from the different separation stages constituting the recycling plant. Hence fast on-line assessment is a key point to increase the value of secondary polyolefins.

Actually PE or PP concentrates in terms of the concentration of the other polyolefin as well as non-polyolefin contaminants is carried out by hand-sorting and DSC (Differential Scanning Calorimetry) analysis of samples in laboratory. Other methods are CRYSTAF (Crystallisation Analysis Fractionation), FTIR-ATR (Attenuated Transmission Infrared Spectroscopy) and TREF (Temperature Rising Elution Fractionation). Neither of these methods is suitable and accurate for the required on-line quality assessment and therefore new sensor technologies should be developed to quantify the concentration of contaminants and particles size distribution in each of the products.

3   Hyperspectral imaging

Hyperspectral cameras are able to deliver a wide spectrum of information. Wavelength intervals are usually those ranging between (400-700) nm and (400-1000) nm and (1000-1700 nm). Several applications based on such a technology have been developed, both at research and application level, in several sectors as astronomy (HEGE ET AL., 2003), agriculture (MONTEIRO ET AL., 2007) (SMAIL ET AL., 2006), pharmaceuticals (RODINOVA ET AL., 2005) (ROGGO ET AL., 2005), medicine (FERRIS ET AL.,2001) (KELLICUT ET AL., 2004) and waste recycling (SERRANTI AND BONIFAZI, 2007), with particular reference to cullets (SERRANTI ET AL., 2006), fluff (BONIFAZI AND SERRANTI, 2006A), compost (BONIFAZI AND SERRANTI, 2006B). The technology can be used on-line and is cheap and powerful.

Spectra, with reference to this study, can be correlated to particles composition. Other parameters are also collected, as particles morphological and morphometrical attributes distribution, spatial and temporal fluctuations of the particles streams, etc. The development beyond the state-of-the-art will be to interpret the possibilities of hyperspectral imaging in determining the quality of feed and product stream in the recycling of post consumer plastic waste and translate the images into the parameters that are requested by recycling operation, both in terms of control strategies set up and product quality assessment.
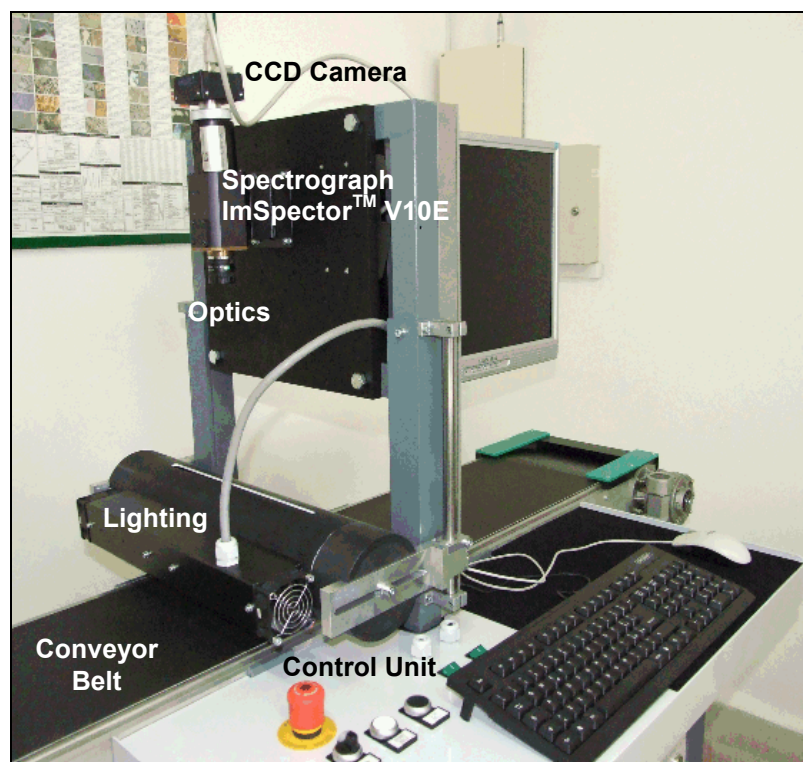
Figure 1   Spectral scanner architecture utilised to acquire plastic waste particle spectra.

4   Experimental

Tests have been carried out in order to verify the efficiency of the proposed approach in respect of: i) feed characterisation (particulate solids composition), ii) quality of the different flow streams resulting from specific processing actions (presence of contaminants and/or "pollutants") and iii) identification of PE and PP particles to set up new sorting strategies for their recovery. A specific hyperspectral detection based architecture was thus designed and realised at laboratory scale.

4.1   Laboratory set up, spectral acquisition and analysis

The spectral analyses have been carried out utilizing the detection architecture reported in Figure 1. The equipment assures a progressive and continuous horizontal translation of the sample and the "synchronized" acquisition (at a pre-established step) of the spectra. The sensing device being constituted by an ImSpector™ V10E working in the visible-near infrared spectral range (400-1000 nm), with a spectral resolution of 2.8 nm and a spatial resolution less than 9 μm (SSOM, 2008). Analysis have been carried out performing: i) a characterization of the "shape" of the entire detected spectra and/or identifying, at specific wavelengths, peaks or valley characterising the detected firm and ii) to verify, adopting a Principal Component Analysis (PCA) the possible correlation existing among detected spectra, sample textural attributes, presence, characteristics and local-

isation of the different materials and/or contaminants. A PCA is an orthogonal linear transformation of the data to a new coordinate system where the greatest variance by any projection of the data comes to lie on the first coordinate (first principal component, PC1), the second greatest variance on the second coordinate (PC2), and so on. PCA can be used for dimensionally reduction in a data set while retaining those characteristics of the data set that contribute most to its variance, by keeping lower-order principal components and ignoring higher-order ones.

4.2   Sample preparation

Waste product came from car dismantling after a shredding stage. Particle average diameter was less than 3÷4 mm. After sieving at 2 mm the retained product was hand sorted. Plastic was thus divided from other materials as: rubber, wood, stone and metal. In every mixture plastic constitutes the main material, contaminants are present only in small amounts. The plastic fraction was then subjected to a sink-float separation at a cut density of 1000 kg/m^3 in water. This approach was followed to separate polyolefins (float fraction: <1000 kg/m^3) from heavy plastics (sink fraction: >1000 kg/m^3). Sample was then subjected to several sink-float separation stages (using the static bath method at various cut densities in water and water-ethanol mixtures, at room temperature) to obtain classes of products characterized by different density distribution. The application of this separation strategy produced as result different products, that should be representative of: heavy plastic (density > 1000 kg/m^3), HDPE (density between 930 and 1000 kg/m^3), LDPE (density between 915 and 930 kg/m^3) and PP (density < 915 kg/m^3). The hyperspectral approach was thus applied: to investigate the sensitivity of the method in respect of both the waste plastic feed and the different flow streams resulting from processing stream to characterise, identify the different organic based materials (plastics, foams, rubber, tires, etc.) and contaminants (wood, finer fractions and metals).

5   Results

The acquired reflectance spectra for the particulate solids constituting the feed allow to identify the different materials constituting the plastic waste product resulting from car dismantling (Figure 2). Spectral plots clearly show as different materials present a different spectral signature (Figure 3). Unsorted plastics (PVC, PET, PE, PP, etc.), independently from their colours, are easily identifiable in respect of contaminants as wood, foam, aluminium, glass and tyre residues: wood shows an almost linear increase of reflectance in the wavelength range between 550 and 750 nm, foam shows a peak at 532 nm, aluminium shows a constant response in the NIR range (850÷1000 nm), finally glass and tyre residues are characterised by the highest and lowest reflectance between 650 and 750 nm, respectively.

1 cm

Figure 2   Example of different materials constituting the plastic waste product after the shredding phase of light fractions resulting from car dismantling.
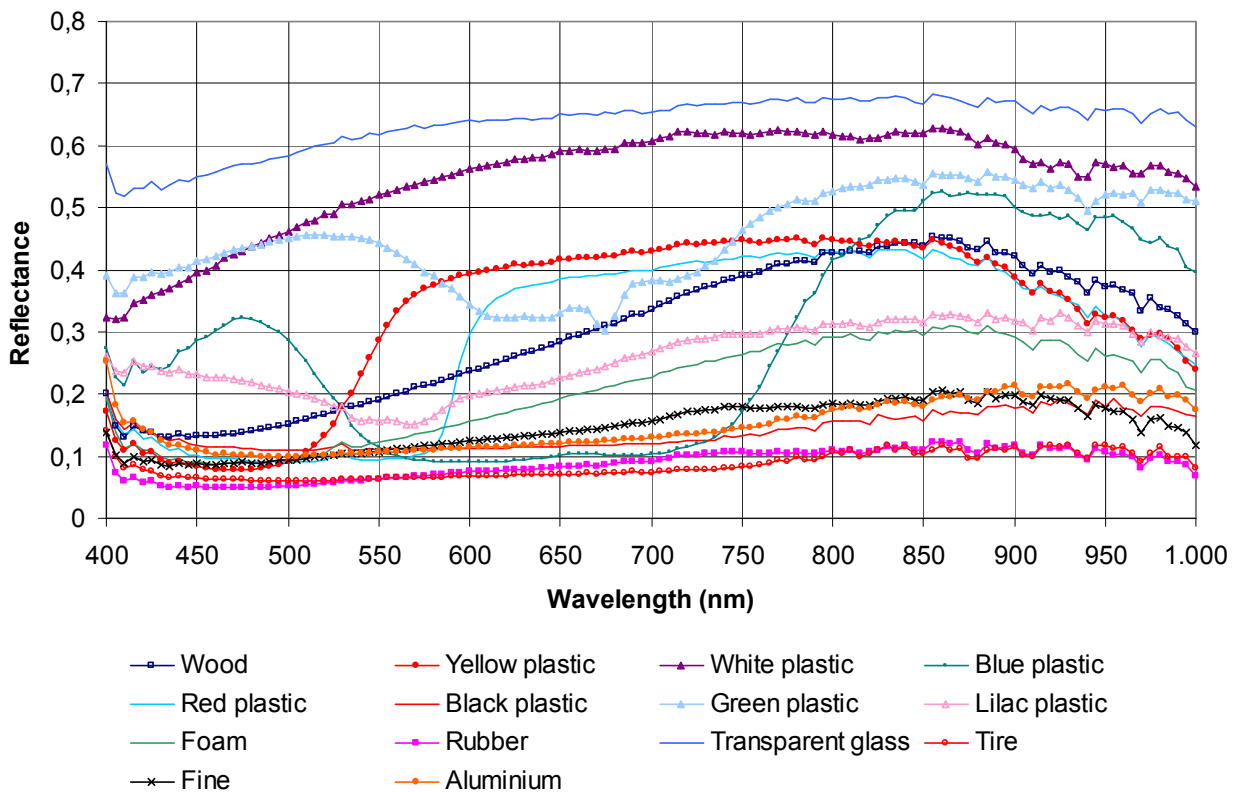

Figure 3   Average reflectance spectra in the VIS-NIR field (400-1000 nm) of the different particulate solids present in the waste plastic feed, as resulting after car dismantling (shredding), detected by the hyperspectral imaging based architecture.
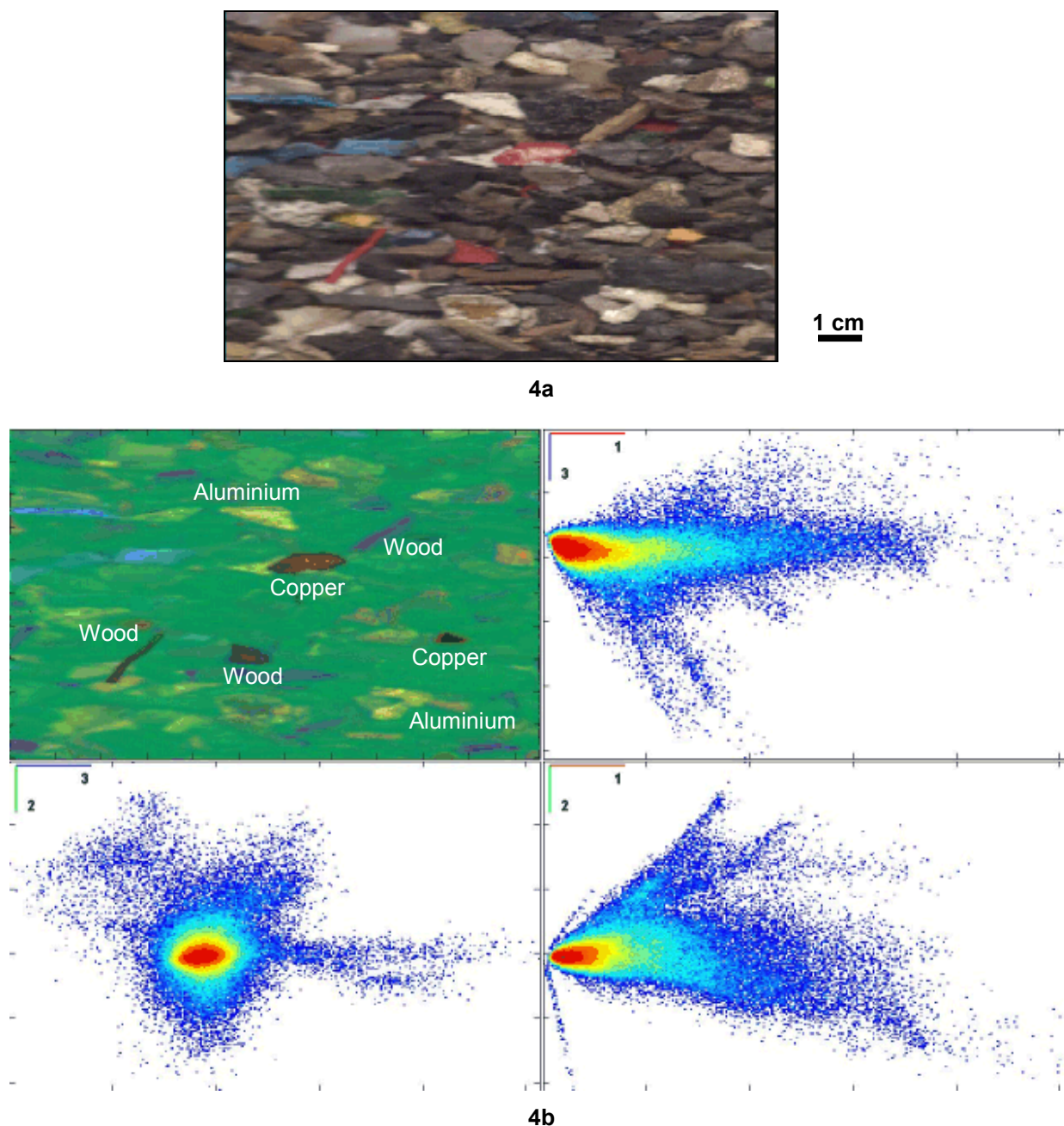
4a

4b

Figure 4   *Plastic waste product containing different contaminants. 4a: hyperspectral image as acquired, 4b: corresponding false colour image (upper left corner) embedding the results of all the three score plots [1-3] [3-2] [1-2] related to PC1, PC2 and PC3 components as resulting from the application of the HPCIA. Contaminants can be easily identified thanks to the different colours of the particles.*

PCA applied to the images of plastic waste product, adopting an **H**yperspectral **P**rincipal **C**omponent **I**maging **A**pproach (HPCIA), allows to identify pollutants (Figure 4). The analysis of the image related to PC1, PC2 and PC3 components permits, in fact, to detect presence, typology and position of different non plastic materials (contaminants). It is thus possible to quantitatively identify "undesidered particles" and, thanks to their topological assessment, to implement automatic sorting strategies for their removal.
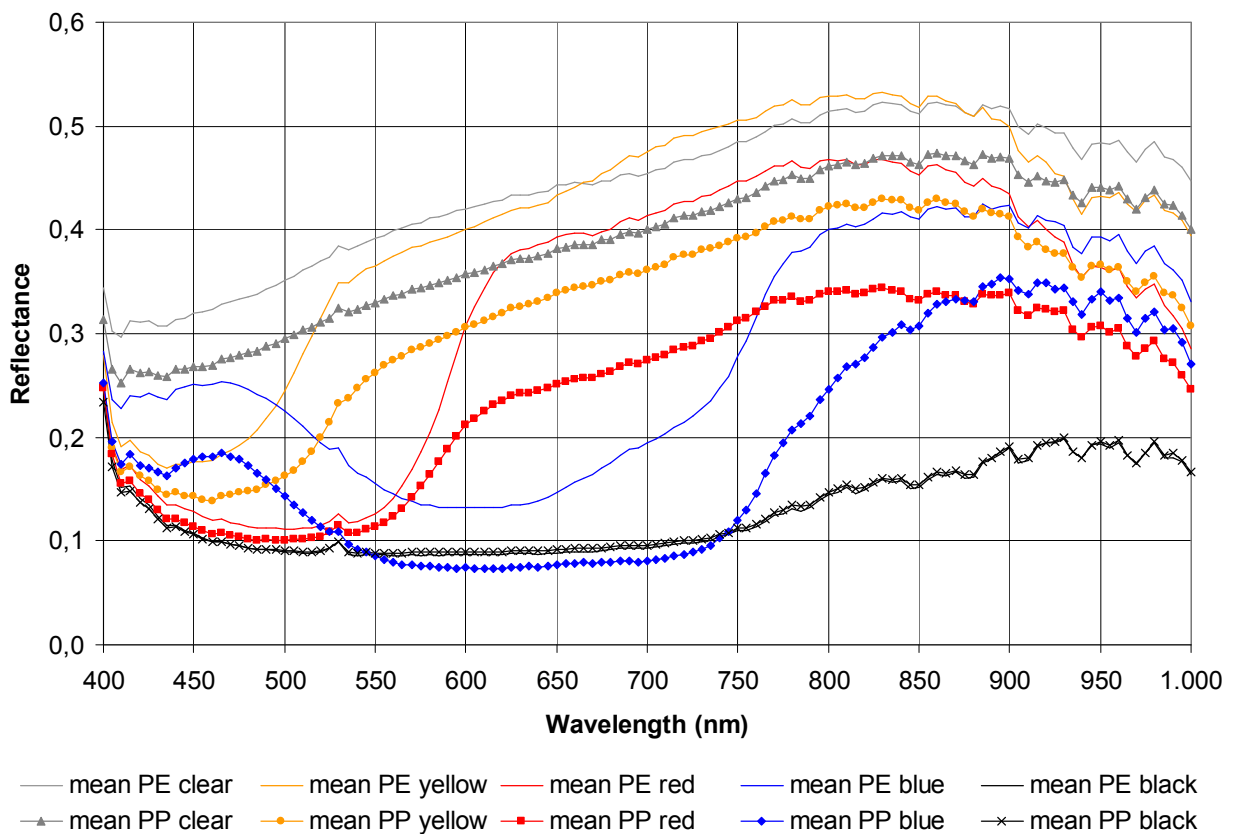
Figure 5   Average reflectance spectra of polyethylene (PE) and polypropylene (PP), collected in the VIS-NIR field by the hyperspectral imaging device.

The analyses carried out on different hyperspectral images of particulate products resulting from different processing actions and finalised to recover PE and PP also gave good results. Reflectance spectra for plastics belonging to the different classes of density have been compared in terms of average results, considering two groups of particles: those belonging to the density fractions (-1000 +960) kg/m^3, (-960 +930) kg/m^3, (-930 +915) kg/m^3 and those belonging to the classes (-915 +880) kg/m^{3}and less than 880 kg/m^3, that should be representative of PE and PP, respectively (Figure 5). Spectral plots showed as, for each class of colour, the reflectance level of PE particles is higher than that of PP particles. Such a result is valid for clear, yellow, red and blue particles, with the exception of black particles. A correlation can thus be established between particles reflectance and class of density. Reflectance level of particles increases with the increase of density. This result is quite important being utilised to set up and to apply innovative quality control strategies of PE and PP concentrated flow streams, according to PE and PP particles spectral signature (colour) and reflectance values (density).

6   Conclusions

The possibility to apply an hyperspectral imaging based approach to determine the quality of waste plastic feed and to evaluate the quality of recovered PE and PP particu-

late solids, resulting from recycling actions, was investigated.

Tests carried out on plastic waste feed results demonstrated as the proposed approach is quite efficient to detects contaminants on the base of the spectral response. The possibility to utilise an HPCIA approach to identify contaminants and their position in the flow stream opens interesting perspectives to develop and implement quality-control-sorting logics to remove contaminants.

The analyses carried out on PE and PP products, selected on the base of their colour, have been processed by a multi-stage-density-separation. Each product was thus analyzed, with reference to VIS-NIR (400-1000 nm) wavelength range, adopting the proposed HSI approach. Results showed as HSI allows to perform a recognition of the different classes of materials independently from their colour. The only exception is constituted by black particles, that cannot be recognized, at least on the base of the investigated spectral range. Further investigations will be carried out to evaluate, independently from the colour and surface status, how the different fillers, both in terms of typologies and quantities, can influence PE and PP particles spectral response. For black particles other regions of the spectrum should be investigated.

7   Literature

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