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Classification of polyolefins from building and construction waste using NIR hyperspectral imaging system

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ABSTRACT

This work was carried out to develop a hyperspectral imaging system in the near infrared (NIR) range (1000–1700 nm) to classify polyolefin particles from complex waste streams in order to improve their recovery, producing high purity polypropylene (PP) and polyethylene (PE) granulates, according to market requirements. In particular, hyperspectral images were acquired for polyolefins coming from building & construction waste (B&CW), divided into 9 different density fractions, ranging from <0.88 g/cm^3 up to 0.96 g/cm^3 and in different color classes. Spectral data were analyzed using principal component analysis (PCA) to reduce the high dimensionality of data and for selecting some effective wavelengths. Results showed that it was possible to recognize PP and PE waste particles and to define the "real cut density" between PP and PE from B&CW, to be utilized in the recycling process based on magnetic density separation (MDS). The results revealed the potentiality of NIR hyperspectral imaging as an objective and non-destructive method for classification and quality control purposes in the recycling chain of polyolefins.

1. Introduction

Polyolefins (PO) recovery from plastic solid waste is considered a great opportunity but also a big challenge because, despite their large consumption, they are the least recycled plastic materials due to the difficulties faced in their separation (Bonifazi et al., 2009). In fact, there are many PO-rich complex wastes, such as waste from building and construction (B&CW), electric and electronic equipment (WEEE), automotive shredder residue (ASR) or household waste (HW) that, at present, are not well exploited as a source of secondary pure PO.

In recycling technologies of plastics from post-consumer waste, the capability to separate different polymers is one of the key points in order to obtain pure secondary raw materials for the production of new high quality products. In this paper the use of NIR hyperspectral imaging (HSI) has been applied to the classification of PO coming from B&CW for quality control of the products resulting from an innovative recycling process, based on magnetic density separation (MDS) (Bakker et al., 2009). In particular, such an approach is under development in the framework of a European FP7 Project: "*Magnetic Sorting and Ultrasound Sensor Technologies for Production of High Purity Secondary Polyolefins from Waste (W2Plastics)*" in which on-line quality control logics for the feed of the process, i.e. complex plastic waste streams, and for the final products resulting from the sorting process, should be developed and implemented (Di Maio et al., 2010).

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. The two most important and common PO are polyethylene (PE) and polypropylene (PP), very popular due to their low cost and wide range of applications.

PE is probably the most diffused 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 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.

PP is a rather versatile polymer, serving both as plastic and as a fiber. It is used to make things like dishwasher-safe food containers. As a fiber, PP is used for its characteristics (easiness to make it colorful and water absorption resistance) to make indoor–outdoor carpeting. Structurally it is a vinyl polymer with a linear structure

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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.

Separation of PO is not a goal easy to reach with conventional technologies based on sink and float strategies, due to their very close density (Di Maio et al., 2011): $\delta_{HDPE} = 0.940–0.960\,g/cm^3$, $\delta_{LDPE} = 0.910–0.935\,g/cm^3$, $\delta_{PP} = 0.880–0.915\,g/cm^3$. Currently available techniques, based on the difference in flotation properties in water, can be used to separate lighter types of plastic, such as PO, from the heavier types, such as polyethylene terephthalate (PET) and polyvinyl chloride (PVC). The resulting PO mixture can be utilized to produce only low-quality recycled objects as they loose their physical and mechanical properties characterizing the virgin polymers. To produce high-purity granulates from these concentrates, the mixture must be sorted very accurately, to obtain two pure separate products: PP and PE.

Among the different techniques under study or available in the market, MDS appears to be a valid solution for PO recycling (Bakker et al., 2009). 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 realized 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) they are very cheap to use, even if not fully recovered from the product materials.

Independently from the adopted separation strategy, the need to operate a full quality control of the plastic waste streams represents a key issue of great importance for both plastic recycling and compounder industries. Therefore, a fast on-line assessment to monitor the plastic waste feed streams and to characterize the composition of the different PO products, is fundamental to increase the value of secondary PO. In this perspective an HSI based architecture allows to fulfill both the “required” control goals, that is: a continuous monitoring (on-line control) of the fed and processed waste flow streams and an important decrease of the analytical costs and a contemporary increase of the speed of the analytical processing of the samples. Furthermore the proposed approach could contribute to perform a big step forward, in terms of new possible logics-separation technologies implementation, in the field of plastic recycling and more specifically for PO recovery.

HSI is based on the utilization of an integrated hardware and software architecture able to digitally capture and handle spectra, as an image sequence, as they result along a pre-defined alignment on a surface sample properly energized (Hyvarinen et al., 1998; Geladi et al., 2007). Spatial and spectral information can be obtained at the same time from sample object of investigation. The information are thus contained in a 3D dataset (i.e. *the hypercube*), characterized by two dimensions related to spatial information (i.e. x and y) and one related to spectral information (i.e. z). Different physical–chemical attributes of the samples (i.e. PO particles) can be thus collected and analyzed according to different energizing sources characteristics (i.e. wavelengths) and spectral resolution and sensitivity of the device/s.

In these last years HSI has rapidly emerged and fast-grown especially in food inspection (e.g. Gowen et al., 2007; Sun, 2010; Del Fiore et al., 2010), in pharmaceutical sector (Gowen et al., 2008; Fortunato de Carvalho Rocha et al., 2011), in medicine (Jolivot et al., 2011; Liu et al., 2007), in artworks (Kubik, 2007) and in polymer science (Gosselin et al., 2011). Studies have been also carried out in solid waste sectors: waste paper recovery (Tatzer et al., 2005), glass recycling (Bonifazi and Serranti, 2006a), fluff characterization from ASR (Bonifazi and Serranti, 2006b), bottom ash from municipal solid waste incinerators (Bonifazi and Serranti, 2007), compost products quality control (Serranti et al., 2009), polymers (Leitner et al., 2003) and polyolefins (Serranti et al., 2010, 2011) identification.

The studies based on the application of HSI techniques to material and/or products classification and inspection are increasing every day, demonstrating as such a technique represents a very smart and promising analytical tool for the development of fast, reliable and low cost quality control strategies.

2. Materials and methods

2.1. Samples

A mixed PO sample from B&CW (Fig. 1) has been collected in a recycling facility located in France. The sample is constituted by shredded particles ranging in size from 5 to 20 mm, representing the float fraction (density < 1 g/cm^3) of a sink-float preprocessing step, i.e. mainly PO, as the other polymers are characterized by density greater than that of water (1 g/cm^3). The sample has been then classified in 9 different density fractions in laboratory, by several sink-float separation stages (using the static bath method at various cut densities in water and water–ethanol mixtures, at room temperature). The selected density intervals are typical of PP and PE, ranging from <0.88 g/cm^3 up to 0.96 g/cm^3 (Table 1). Plastic particles of different colors have been selected from the 9 density classes, identifying 9 main colors (Fig. 2): transparent, white, pink, red, orange, grey, blue, green and yellow. Black particles have not been taken into account at this stage of the research due to their weak reflectance characteristics. 18 particles have been selected for each density class, 2 for each of the 9 dominant colors, for a total of 162 particles.

Virgin PP and PE samples (Fig. 3) have been utilized as reference standards for the recognition of the unknown waste PO particles based on their spectral signatures (Serranti et al., 2011).

Fig. 1. Source sample of polyolefins from building and construction waste.