



Tracer technology in plastic identification— Past, present and future

S. Rafi Ahmad*

Senior R&D Consultant, NEXTEK (UK) Ltd

The evolution of concepts for the automation of post-consumer waste plastic sorting is chronicled, homing in on fluorescent tracer-based identification in binary combinations of dyes in different plastics. Aspects of the applied research needed for the development of a prototype identification and sorting system in the author's laboratory are also elaborated. This is followed by details of an industrial trial of the system in a commercial enterprise, replacing manual operation by the newly developed automated system, in conjunction with the use of fluorescent tracer-doped plastic bottles of different types. The procedures adopted for the selection of dyes with suitable characteristics for tagging different types of plastic with acceptable compatibility in binary combinations are also elaborated. The preliminary trial showed promise for commercialization. However, for cost-effective sorting of a wide variety of post-consumer plastic with acceptable end purity and commercial viability, there is an evident need for further developments in some areas, notably: better choice of dyes compatible with the constituents of all the polymer types selected for sorting; faster electronic data processing; and mechanical handling of individual items on a conveyer belt at much higher speeds (including enhancing the efficiency of the ejection mechanism).

1. The recycling issue

The perils of unregulated emission of greenhouse gases and the consequent environmental catastrophe have been discussed and plans adopted in twenty five past Conferences of Parties. One may ask what was special about COP26 (31 October–13 November 2021, Glasgow, Scotland)—and indeed, its successor, COP27 (6–18 November 2022, Sharm el Sheikh, Egypt)? Perhaps only now has it dawned on us that we are at a threshold and action is needed to avoid more and more catastrophic events. While greenhouse gas emissions remain the principal topic

* E-mail addresses: sheikhrafiahmad@hotmail.com; website: <https://sheikhrafiahmad.co.uk>

on the agenda of these conferences, the perils imposed on our ecosystem due to ever-increasing plastic waste has not been addressed in these or any other international conferences with any seriousness. However, while organic waste can be effectively recycled by composting (or converted into hydrocarbon fuel by anaerobic digestion), this is not applicable for waste plastics. Plastic—synthetic organic polymers—being largely nondegradable (indeed for many uses this is a desirable attribute) poses one of the major pollution problem on land and in water bodies, particularly the oceans. This is of the utmost concern for the maintenance of critical balance in our ecosystem. Although the problems of what to do with waste plastics have been addressed over the last two and a half decades,^{1,2} finding an effective solution has, so far, eluded us. The technology for addressing the problem is available, but its cost-effective implementation is found to depend on general adoption of a circular economy.^{3,4,5} For that, a complex looped-chain of players and processes, each needing to play important roles, is needed. These include different stakeholders, namely polymer producers, recyclers, brand owners, packaging producers, packaging material producers, waste collectors and, last but not the least, sorters. However, the driver of the overall process remains the economic viability for all individual players in the circular loop and that viability needs to be managed and coordinated by an effective government or other public body. It transpires that *efficient sorting* of waste plastics into its generic types or constituents is an essential prerequisite for cost-effective recycling in a circular loop.

2. Sorting technologies

2.1 Review of sorting technologies

Plastic commodities come in a variety of shapes, forms and colours. However, the vast majority of such items come in the form of bottles. Therefore, technologies are mainly geared up to sort plastic bottles and the present article will be concerned with bottle sorting. Table 1 gives the advantages and disadvantages of some technologies for automatic sorting of plastic bottles that have already been tried and tested.

A system based on infrared reflexion/absorption spectroscopy (#5 in Table 1), developed by Bühler Ltd (Switzerland), underwent commercial application, but with limited success.^{6,7} It was able to sort only PE, PP, PVC, PS and PET, by comparing absorption spectra (165–1830 nm

¹ N. Singh, D. Hui, R. Singh, I.P.S. Ahuja, L. Feo and F. Fraternali. Recycling of plastic solid waste: A state of art review and future applications. *Composites B: Engng* **115** (2017) 409–422.

² J.R. Jambeck, R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady and R. Narayan. Marine pollution: Plastic waste inputs from land into ocean. *Science* **347** (2015) 768–771.

³ A.E. Schwarz, T.N. Lighthart, D.G. Bizarro, P. de Wild, B. Vreugdenhil and T. van Harmelen. Plastic recycling in a circular economy: Determining environmental performance through an LCA matrix model approach. *Waste Management* **121** (2021) 331–342.

⁴ J. Payene, P. McKeown and M.D. Jones. A circular economy approach to plastic waste. *Polymer Degradation and Stability* **165** (2019) 170–181.

⁵ E. Kosior and J. Mitchell. Decoupling plastic waste from growth: The role of design in removing blockages to the circular economy. *Nanotechnol. Perceptions* **17** (2021) 116–125.

⁶ M.K. Alam, S.L. Stanton and G.A. Hebner. Near infra-red spectroscopy and neural network for resin identification. *Spectroscopy* **9** (1994) 31–39.

⁷ D.M. Scott. A two-coloured near-infrared sensor for sorting recycled plastic waste. *Measurement Sci. Tech.* **6** (1994) 156–159.

Table 1. Comparison of potential plastic sorting technologies.

N ^o	TECHNOLOGY	ADVANTAGES	DISADVANTAGES
1	Density difference	Cheap, reliable	Applicable only to polyolefins
2	Electrostatics	Cheap	Susceptible to surface conditions; applicable only to PC, PP ABS & Nylon
3	X-ray spectroscopy	Reliable, selective	Applicable only to PVC & PVDC; expensive & poses radiation hazard
4	Raman scattering	Reliable, versatile	Susceptible to surface contamination; require expensive & sophisticated excitation & monitoring systems
5	Infrared spectroscopy	Selective, fast	Susceptible to surface conditions & expensive
6	Fluorescent tracer technology	Reliable, fast, versatile & could be cheap	Requires introduction of tracers in the product before manufacturing and the removal of coverings
7	Digital watermarking	Currently on trial, a holy grail of sorting	May have problems with sample presentation and other unknowns

range). However, it lost popularity because of its lack of versatility. For example, it cannot sort different grades of PE, nor polymers with unknown additives or with surface contamination.

Already, 85 stakeholders have participated in the ongoing development and trials of digital watermarking technology for sorting plastic (under the European Union's HolyGrail 2.0 project). Its success, if realized, would pave the way for this to become the sorting technology of the future. However, at present the most cost-effective and versatile technology is considered to be tracer-based and the present article is concerned with the past, present and future of this technology.

2.2 History of tracer-based sorting technology

The concept of using tracers in plastics for their characterization and identification was conceived by the author^{8,9} while researching on the interaction of UV light from a N₂ laser (337 nm) with polymeric materials back in the early 1980s. In the early 1990s, when plastic recycling started to become a pressing issue worldwide, manual sorting of plastic by visual means was abandoned as the need for automatable technologies became a priority for sorting and recycling, not only a large number of different types of plastic, but also different grades of the same type. This inspired the author to conceive the idea of using tracer pigments for automatic identification of post-consumer plastic. A consortium of European companies and stakeholders was formed, spearheaded by the author,¹⁰ to evaluate the feasibility and commercial viability of optical tracer-based automatic sorting.

⁸ S.R. Ahmad. UV laser-induced fluorescence in high-density polyethylene. *J. Phys. D Appl. Phys.* **16** (1983) 137–144.

⁹ S.R. Ahmad. Photodecomposition and characterization of polymers by UV laser interaction. *J. Phys. D Appl. Phys.* **20** (1987) 1315–1317

¹⁰ S.R. Ahmad. Partners wanted for polymer research project. *Materials Research Weekly* (8 August 1992) 14.

The consortium consisted of the following members: Pira International, UK (migration tests and sample preparations); Association of Plastics Manufacturers in Europe, Belgium (tracer-doped sample preparation); Cranfield University, UK (sensor research & development; project coordination); Integrated Recycling Systems Ltd, UK (industrial sorting trial); Laboratoire National d'Essai, France (weathering and heat stability tests). The project entitled "Identification and separation of plastics in mixed waste" ran from December 1993 to October 1997 and was partially funded by the EU under the Brite/Euram programme (BRE2-CT93-0541 / BE-7148). Extensive R&D was conducted in the author's laboratories, culminating in a field trial of a tracer-based plastic sorting system. The findings of the R&D, including the results of a successful field trial of a prototype system in an industrial sorting machine, were included in a patent application.¹¹ Research findings on the use of fluorescent tracers for plastic identification were patented by two other research groups as early as 1993.^{12,13} It is noted that the concept of using tracers was first conceived by the author in 1992.⁸ Besides, their use in a binary combination (*vide infra*) was included only in the author's patent application.

3. Tracer technology

3.1 Rationale

From Table 1 it is noted that tracer-based optical identification and sorting offers the best option for implementing plastic identification and sorting. Therefore, the waste plastic commodities to be sorted need to have traceability conferred on them; i.e., doped with dyes. In the present scenario the tracers are organic or inorganic compounds, exhibiting strong fluorescence within one or more narrow wavelength bands in the visible to near-infrared domains, when excited by suitable light. For cost-effective sorting both the tracer dyes and the exciting and monitoring systems need to be optimized. The criteria for optimization are given below.

3.2 Characteristics of tracer dyes

In addition to cost considerations and their minimum required concentrations in the plastic material, the tracer dyes (both organic and inorganic) need to meet the following criteria:

- i. Be compatible with polar and nonpolar plastics;
- ii. Be chemically and photophysically noninteractive with host matrices or other dyes;
- iii. Be stable under UV light (weathering) and at high temperatures (during melting in shape processing);
- iv. Be nontoxic and have low migration in plastics;
- v. Have low optical absorbance at visible wavelengths;
- vi. Have high fluorescence quantum yield;
- vii. Exhibit identifiable spectral signatures in combination.

¹¹ S.R. Ahmad et al., Identifying plastics for recycling. UK Patent Application GB 2,330,409A (filing date 17 October 1997).

¹² A. Becker et al. Method for identification of plastics. US Patent Application 5,329,127A (filing date 4 December 1993).

¹³ K. Luthermann et al. Research for identifying plastics by adding fluorescence dye. US Patent Application 5,201,921A (filing date 6 September 1991).

Polymers come with different degrees of polarities (i.e., dipole moments and/or electrostatic charges); they range from nonpolar like PE, PTFE, PP, PS etc. to polar like PA, PC, PVC, PMMA, ABS etc. To incorporate organic dyes into polymer matrices the dye solvent needs to be suitable for both the dye and the polymers. Solvation of polymers is largely dependent on the polarity of the solvent.¹⁴ For polymerization, the solvents for monomers are usually nonpolar aliphatic chemicals (alkanes). Polar polymers easily make chemical bonds with dye molecules, thereby providing high stability. For food and medicine packaging, low toxicity of the dyes and their negligible migration inside the matrix material are factors to be taken into consideration. While stability of the dye is highly desirable, it is necessary to ensure that any changes in chemical and physical properties of the host matrices are also negligible and the dye molecules do not chemically interact with the host matrix while undergoing photophysical excitation (i.e., providing fluorescence emission). This criterion also applies when the doped plastic is exposed to the weather during storage and transportation. Low absorbance of visible light will ensure low photochemical degradation of the plastic and the dye. In the trade-offs between all the above-mentioned criteria for an ideal tracer dye for a particular polymer type, optimization of the quantum yield of fluorescence¹⁵ in the narrowest possible wavelength band at a desirable peak wavelength position remains an important consideration. This has been achieved to some extent by slightly manipulating (“tweaking”) the molecular structure of the fluorescent dyes and by a judicious choice of excitation wavelength.

The last criterion (vii) in the list above requires the use of combinations of dyes with emission bands in separate, discrete wavelength positions, so that with a number n of potential tracers the number of dopants (polymer types/grades/uses) achievable is

$$n_d = (2^n - 1) \quad (1)$$

(see Fig. 1).

4. System for binary detection and identification

Within the Brite/Euram project “Identification and separation of plastics in mixed waste”, the system shown in Fig. 2 was constructed, the parts of which are described in detail in the following sections.

4.1 Excitation source unit

Excitation with UV light provides the highest yields of fluorescence from most dyes.¹⁵ A high-output source emitting in a nearly parallel beam in a narrow bandwidth in the UV (or near-UV) region is needed for efficient excitation. The fluorescence emitted from the selected tracer dyes needs to be discrete, i.e. in narrow bands, and in the visible wavelength region. From cost, size and, most importantly, high output power considerations a thermal source was designed and constructed to fulfil the above criteria. Currently, commercially available UV-emitting laser diodes with adequate output power may be preferred contenders, albeit expensive, for this purpose.

¹⁴ L. Malavolta, E. Oliveira, E.M. Cilli and C.R. Nakaie. Solvation of polymers as model for solvent effect investigation: Proposition of a novel polarity scale. *Tetrahedron* **58** (2002) 4344–4566.

¹⁵ S.R. Ahmad, Spectroscopy—a technology looking for applications. *Nanotechnol. Perceptions* **17** (2021) 141–154.

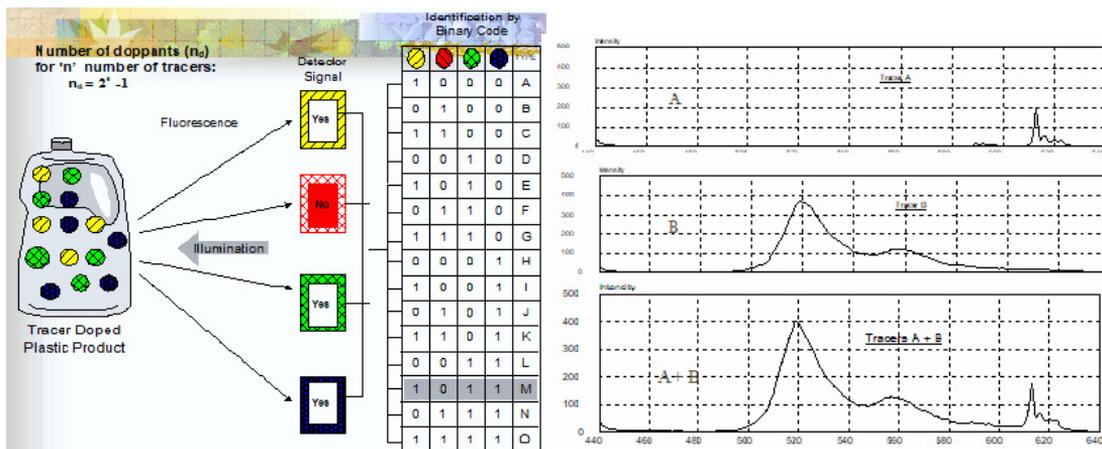


Figure 1. (Left) schematic representation of doping a plastic with four different dyes. The dyes are chosen to dope fifteen different types, grades and uses of plastics (A–O) in binary combinations as per equation (1). The illustrated sample (M) is doped with a combination of dyes exhibiting fluorescence in three different spectral positions (yellow, green and blue). Sample A, on the other hand, is doped with only one dye, exhibiting fluorescence in the yellow region of the spectrum. (Right) examples of the fluorescence spectra from two dyes separately and in binary combination, enabling only three different plastics to be distinguished.

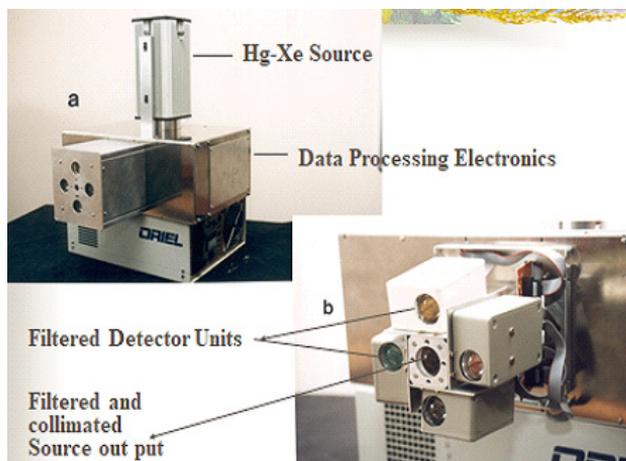


Figure 2. Fluorosensor assembly, including excitation source and identification units for binary identification. See text for details.

The source unit consists of a commercial modular arc discharge enclosure with a built-in power supply (Photomax, LOT-Oriel; it allows use of different types of light sources). To avoid water and air cooling and to make the system easily portable a 50 watt mercury–xenon arc lamp, emitting strongly in the UV–vis regions, is used. The enclosure also has a built-in high collection angle ellipsoidal reflector with a small opening for inserting the source at one of its foci. Position control knobs fitted to the enclosure allow accurate positioning of the source. The

emission from the arc lamp at some discrete lines within the 310–450 nm range is concentrated at the other focus of the ellipsoidal mirror. The beam is made parallel using a source filter system coupled to a reverse telescope arrangement. This produces a near-parallel beam when it emerges after undergoing reflexions successively from four dichroic reflecting filters (Fig. 3). The beam is partially optically filtered at each reflexion to provide a fairly narrow band $\sim 368 \pm 6$ nm for fluorescence excitation.

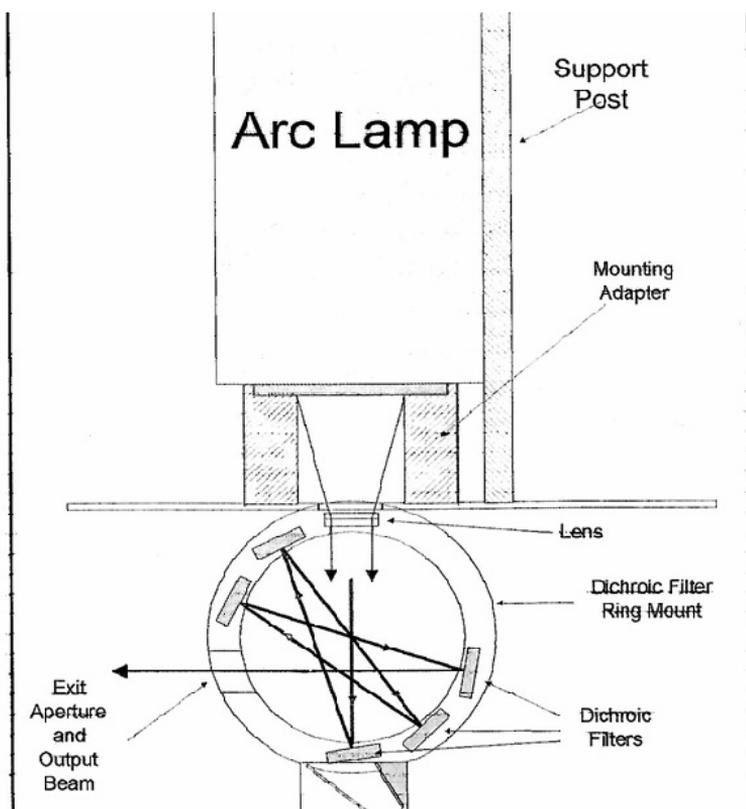


Figure 3. Schematic diagram of the excitation unit, including the Hg–Xe lamp and optical filter assemblies (see text for more details).

4.2 The photodetection units

Four photodetector units are incorporated in a binary detection and identification assembly. The units are spaced at equal distances from each other and also from the centrally located excitation output channel (see Fig. 2). This allows a maximum of four differently coloured fluorescence signals from four different dyes in fifteen differently doped samples in various binary combinations (Fig. 1). Each photodetector unit (Fig. 4) consist of a telescope system to focus the near-parallel fluorescence emission beam onto the photomultiplier. Commercially available interference filters each for transmitting fluorescence from one dye only are inserted before the

beam reaches the photomultiplier. The latter is connected to an electronic package consisting of a power source and signal processing electronics for amplification and analogue-to-digital conversion. Four such photodetectors with four different filters are used in the overall detection assembly, consisting of the excitation source at the centre and four photodetectors equally spaced around it.

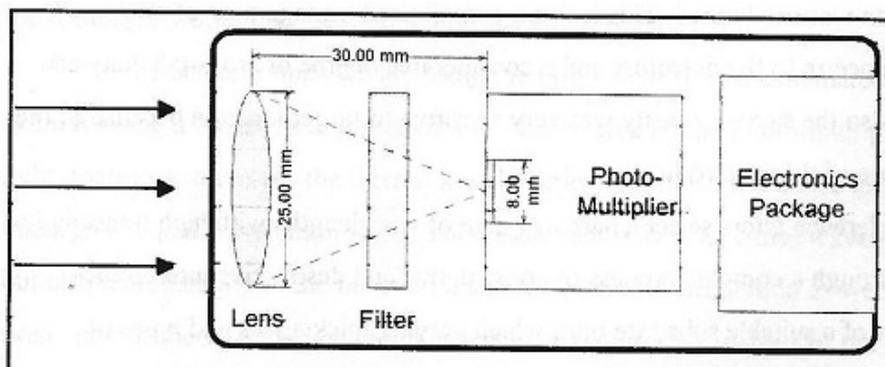


Figure 4. Photoelectric detection unit, comprising photomultiplier, focusing lens, optical filter, power source and data processing electronics (see text for more details).

5. Sourcing and testing of doped polymers

5.1 Sourcing of dyes

Although high fluorescence quantum yield at the selected wavelength band is the most desirable criterion, some judiciously considered trade-offs needed to be made in the selection of the dyes. For this reason a large number of dyestuffs, both organic and inorganic, was sourced from various companies within the EU and the UK. Despite their relatively low fluorescence yields the inorganic dyes have good light and thermal stabilities and exhibit narrow-band emission lines. A total of 37 different dyes were considered, initially on the basis of fluorescence and other relevant data available from their suppliers. These were then incorporated into 5 selected polymers (high-density polyethylene (HDPE), low-density polyethylene (LDPE), ethyl vinyl acetate (EVA), polypropylene (PP) and polyvinyl chloride (PVC). Samples of polymer materials, each doped in binary combination with four selected dyes, were assessed for the suitability of their tracers for automatic identification. The salient characteristics that were considered are described in the following sections.

5.2. Testing dyes for suitability

i. Compatibility: Ability of the selected dyes in both polar and nonpolar polymer matrices to create a stable bond to the matrix was initially evaluated from data available in the literature on chemical structures and other properties of the polymer matrices and the dyes.

ii. Quenching: Stability of fluorescence quantum yield¹⁵ of the dyes during interaction and/or actual reaction with host matrices and with each other (when used in combination) was

carried out using fluorescence spectroscopy. Any diminution of fluorescence quantum yield (quenching effect) was taken as an indicative factor of reaction or interaction and required due investigation.

iii. Thermal stability: For these tests all doped polymer materials were formed into plaques, sandwiched between two metal plates and placed between the platens of an electrically heated hydraulic press. They were then subjected to a pressure of 18 tons. Under this pressure the samples were heated for 30 minutes at 170 °C (or as appropriate depending on the moulding temperature of the selected polymer). The polymer plaques were then cooled and shaped and subjected to spectroscopic analysis for assessing thermal stability of the dyes.

iv. Weathering: It is defined by the UV light stability of the dyes inside polymer matrices. Tests were carried out using an Accelerated Weather-O-Meter-CI 400 from ATLAS. It was equipped with a 6,500 watt xenon arc lamp and solid borosilicate 7740 filters to expose the samples to radiation similar to solar. The doped samples were tested in accordance with the ISO 4892.2 standard without watering, at 50 °C and relative humidity of ~55%. The fluorescence spectra of the dye-doped samples before and after accelerated weathering equivalent to 6 months of exposure to solar radiation in summer conditions were compared in order to select suitable samples.

v. Migration tests:

a) Inorganic dyes: Tests were carried out using doped polymers (shaped into plaques) and three food simulants recommended by EU directive 82/711/EEC: 3% (w/v) acetic acid, 15 % (v/v) ethanol and 95% (v/v) ethanol. Plaques were immersed in these three solutions for 10 days at 40 °C. The solutions were then evaporated to dryness and the residues redissolved in 10 mL of an aqueous solution of 1% nitric acid and 0.5% (w/v) potassium chloride. For the evaluation of migration of vanadium, yttrium and europium atoms in the selected inorganic dyes the solutions thus prepared were subjected to atomic absorption spectroscopy. The measured absorbance was compared with a standard prepared under similar conditions. The acceptable level of migration for the inorganic dyes was deemed to be within the limit of detection (LoD), viz. ~0.05 mg/kg.

b) Organic dyes: Similar tests were carried out using a solution of 20% water, 35% methanol and 45% ethyl acetate. Dye-doped polymer samples were immersed in this solution for 10 days at 40 °C, and the solutions then analysed with high-performance liquid chromatography (HPLC), with fluorescence (of the respective dyes) detection. The acceptable level of migration for the organic dyes was deemed to be within the LoD of 0.02 mg/kg.

5.3. Final selection of dyes

This is carried out using a chart constructed with salient data according to the criteria outlined in Section 5.2, and using the selected polymers as host matrices and incorporating tracer dyes at 10 ppm (w/w) and exciting the fluorescence at 365 ± 5 nm). Making judicious use of the chart, and making acceptable trade-offs, 3 organic and 4 inorganic dyes were selected out of the original 37. From further considerations of quenching, good separation of emission bands (λ_{em}) for use in binary combinations and cost-effectiveness a further selection of only 3 organic dyes from Riedel-de Haën (Germany) was made: CDE9453 ($\lambda_{em} = 480$ nm), CDE9362 ($\lambda_{em} = 520$ nm) and CD 340 ($\lambda_{em} = 613$ nm).

5.4 Doping procedure

Doping was carried out by dry-mixing the dyes with the polymers in granular form and the mixture was then extruded by a compounder, followed by pelleting the material. For uniform mixing the pellets were run through the compounder twice. Initially master batches were prepared with 200 ppm dye. In order to produce 10 ppm concentrations of the dye molecules, 1 part of the sample was mixed and dry-blended with 19 parts of the virgin material. The doped samples were tested for compliance with the criteria set out in Section 3.2. Both miniature-size and commercial-size bottles were formed out of these polymer materials for, respectively, laboratory and industrial trials.

6. Laboratory trials

For this a prototype laboratory model of an identification and sorting unit, a miniaturized replica of the industrial system to be used later, was designed and constructed (Fig. 5).

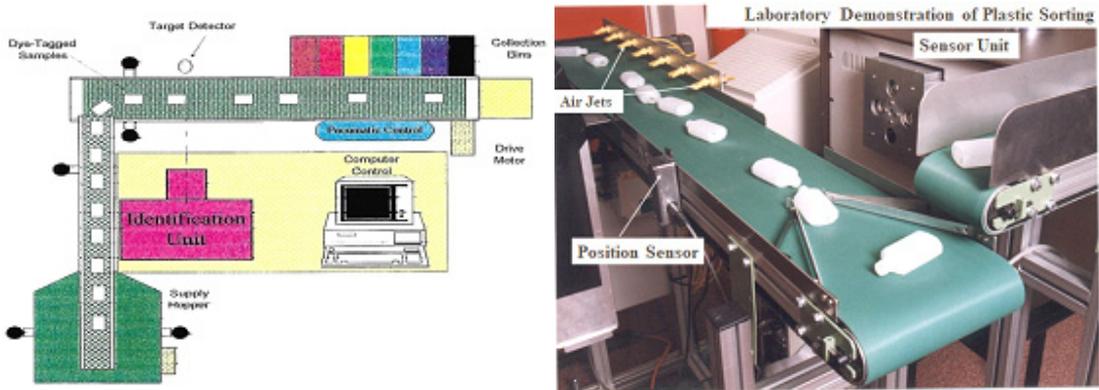


Figure 5. Laboratory fluorosensor system. (Left) schematic diagram; (right) in operation.

For the sake of convenience, only miniature HDPE bottles (0.25 litres, 60 mm diameter and 140 mm high) were doped with the three selected dyes in binary combinations at a concentration of 10 ppm. The bottles were also coded (in terms of binary combination sequences) manually (ink marking) for the verification of trial success. Bottles were put into a hopper that delivered the samples onto a conveyor belt allowing “singulation” (separation) of items. The separated and correctly positioned items then passed across a position sensor and then the detection/identification sensor unit. The bottle identification data from the fluorescence signatures, along with the position data, were sent to a computer, which converted the analogue signals to digital form before calculating the appropriate response (see Fig. 6) and sending a signal to the correct pneumatic actuator of the air jet valve to blow away the item into the appropriate bin. The system also provided variable speed control for testing the limits of the rate of sorting, and a bin for nonidentified items. Following successful laboratory demonstrations, the sensor system was incorporated into an existing industrial identification and sorting system at Sompting near the south coast of England.

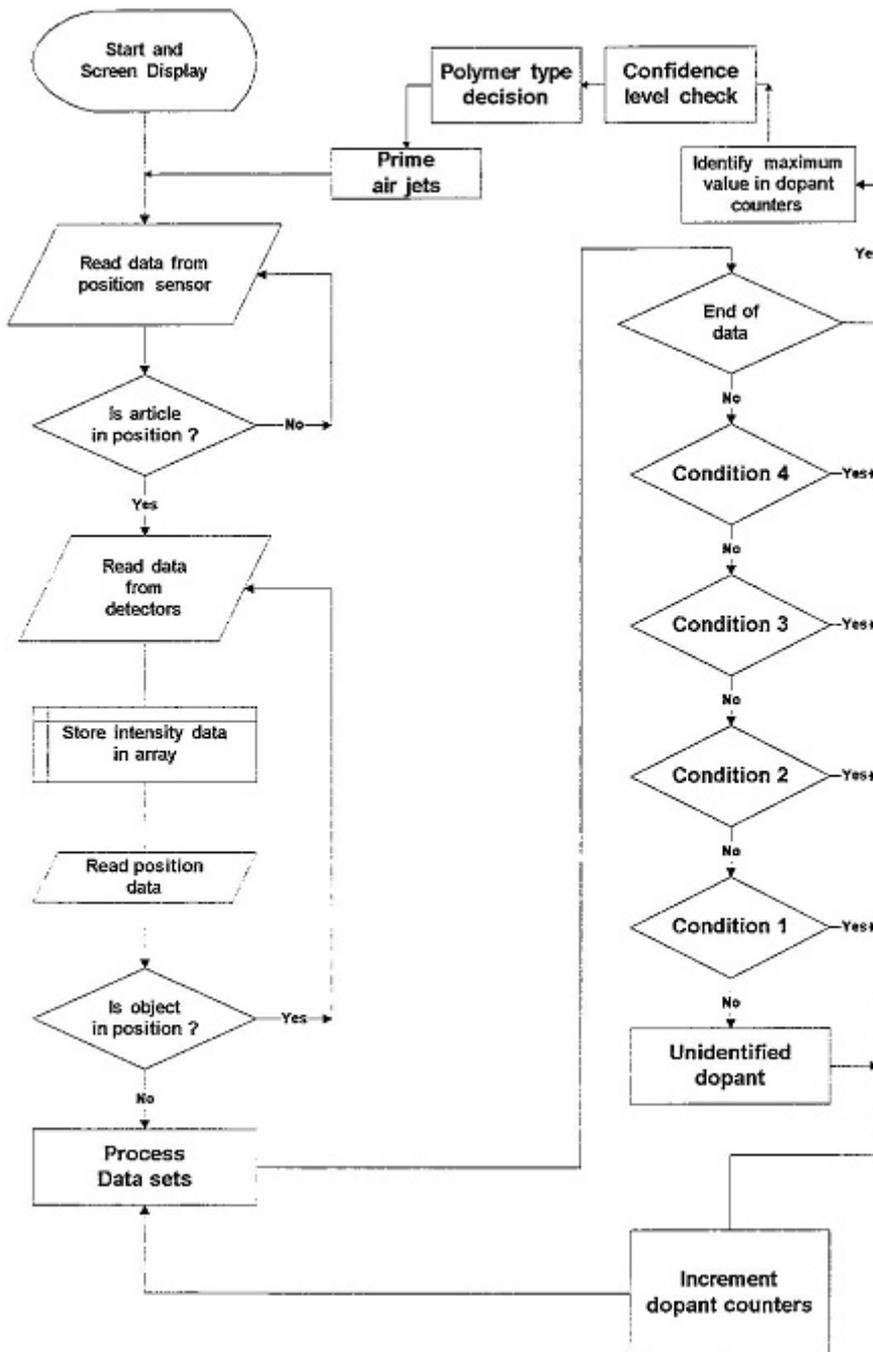


Figure 6. Flow chart of algorithm used in signal processing for identification and sorting of doped plastics.

7. Industrial trial and evaluation

7.1 System and protocol

Doped polymer samples were moulded into bottles of common commercial size, viz. 5 litre capacity (130 mm diameter, 360 mm high). Five different types of plastic samples, PET, HDPE, PVC, PS and PP were used for this proving trial. In principle (equation 1, Fig. 1), 3 dyes allow doping and detection–identification of 7 different polymer types. In this the manual operatives of the existing system were replaced by the system constructed in our laboratory for automatic identification and sorting as shown in photographs (Fig. 7) at different stages of the process.

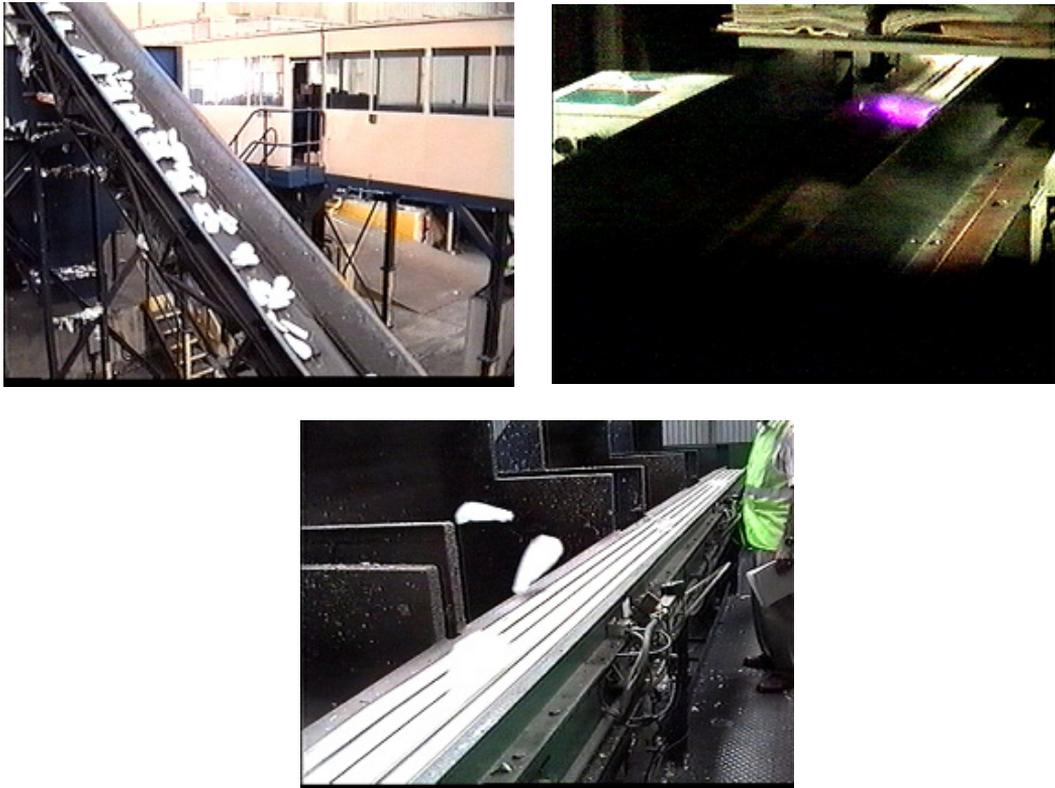


Figure 7. Scenarios of the salient stages of the industrial trial of the plastic separation system. (Upper left) bottles being conveyed to the singulation system; (upper right) separated bottles are presented to the sensor assembly; (lower centre) bottles are ejected to the designated buckets.

7.2 Evaluation of the industrial trial

At a data sampling rate of 4 kHz for the electronic processor used and a line speed of 3.5 m/s, approximately 360 data samples (“votes”) per bottle (0.3 m effective size) are obtained. It is to be noted that the sampling speed could easily be enhanced with a faster electronic processor, providing greater purity of the sorted materials, or faster sorting speed.

Sorting purity depends on both the line speed and the effective size of the article. For 0.3 m bottles and at a line speed of 3.5 m/s, the purity of the sorted materials was found to be ~95%. Performance irregularities connected with the mechanical or pneumatic impulse for ejecting the bottles from the line into the designated bin, and singulation at the hopper, were the main causes for the limited purity of the sorted objects.

With the present setup, object dimensions down to 15 mm have been positively identified and sorted at a belt speed of 3.5 m/s.

Normal surface coverings and typical contamination (e.g., grease, dirt, water) do not adversely affect identification. This is primarily thanks to the high number of votes per object.

Pigments in plastics decrease the fluorescence quantum yield of the dyes, hence requiring higher concentrations and cost.

For black pigmented plastics, such as those used for automobile parts and bags commonly commercially supplied for mailing merchandise and for domestic and commercial garbage, quenching of the fluorescence is too high to allow the system to operate. To overcome this, inordinately high concentrations and fluorescence yields of the dyes would be required, rendering the technology too costly to be effective.

With an optimized system, operating at a commercially viable line speed (3.5 m/s) approximately 1.5 m tonnes of waste plastic per hour per stream can be sorted.

8. Conclusions

Although the present research was focused on sorting domestic waste plastics, the technology has also been successfully applied to sorting industrial waste plastics. With minor modifications the technology has the potential for cost-effective sorting of other industrial wastes such as textiles, tannery residues, pharmaceuticals etc. for recovery and reuse. It is envisaged that if the dyes are chosen to withstand the moulding temperature, tagged waste plastics can be sorted without the further introduction of dyes. The downside of this technology is the requirement of rather complicated processes for selecting and introducing the dye into the plastic.

There are a few emerging technologies for sorting plastics. As mentioned, the HolyGrail project has tested and reported a technology based on “digital watermarking” based on patterns (codes) embossed onto the body of the plastic article or imprinted on its wrapping, which can be read by a camera (cf. the code readers at supermarket payment counters). A Dutch company has demonstrated sorting with 98% purity. The versatility and cost-effective practicability have as yet to be validated before the technology can be deemed commercially viable. Tomra (UK) has launched a project to validate mechanical sorting by identification using deep level AI technology.¹⁶

Considering the complexity and diversity of waste plastic, it is envisaged that a truly high-purity output sorting system needs to employ a succession of multiple technologies. In the meantime, considerations are also given to altogether get away from sorting and resort to chemical recycling.¹⁷ Such technology has its problems, such as dealing with the chlorine from

¹⁶ Raj Kishore, Plastic detection and classification using deep learning (available at: <https://www.researchgate.net/publication/360725969>)

¹⁷ B. Jameson. Chemical recycling. *Nanotechnol. Perceptions* **16** (2020) 331–335.

PVC (although PVC could be pre-separated), and general contamination (e.g., residues from whatever the plastic object contained, although often these are materials atomically germane to the polymer). Besides cost-effectiveness, the effect of a technology on the environment also needs to be assessed.¹⁸ Furthermore, full cooperation with brand owners needs to be encouraged to simplify the waste sorting process as much as possible.⁵ In the meantime, many improvements may be made in all aspects of the tracer-based technology to achieve a much higher yield of high-purity sorted materials.

Acknowledgments

The project was partly funded by the EU under the BRE2-CT93-0541 project. The contributions of the following partners are gratefully acknowledged: Pira International (UK), Association of Plastic Manufacturers in Europe (Belgium), the Centre National de la Recherche Scientifique (France), Integrated Recycling Systems Ltd (UK) and the Laboratoire National d'Essai (France).

¹⁸ Environmental disbenefits should, of course, be properly accounted for and included in the cost analysis, as advocated by Mishan.¹⁹

¹⁹ E.J. Mishan. *The Costs of Economic Growth*. London: Staples Press (1967).