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Environmentally degradable plastics and waste management

Summary — The paper gives a general introduction about international effort, exemplified by activities at ICS-UNIDO, in the field of environmentally degradable plastics (EDPs). These activities and projects reveal some major problems that concern both industry and the society. Standardization, availability of renewable and non-renewable resources for production of EDPs, integration of policies and regulations relevant to waste management and EDPs, life cycle approach and Eco-design of product are identified as key issues for EDPs promotion and large scale application. A discussion on strategy toward these issues is presented.
Key words: bio-degradable polymer/plastic, waste management, composting, environmental regulations and standards.

The production and consumption of polymeric materials in the last decades have generated plastic wastes, which are increasingly putting stress on the environment all over the world. In the 21st century, the demand for polymeric materials is of a 2 to 3 times increase in production as a consequence of the increased consumption in developing countries and countries in transition. The overall production of polymeric materials and plastics is expected to reach a value as high as 350—400 million tons per year in the future.

Both industry and society have to face all the constraints and regulations already operative or to be issued in the near future, dealing with the management of primary and post-consumer plastic-waste. In this respect, the production of environmentally friendly polymeric materials should be a strategic option among those available for the management of plastic waste. With the introduction of these new plastics, the need for organic recycling such as composting and bio-gasification will increase. This may lead to competition with other waste management technologies such as landfill, incineration with energy recovery and mechanical or chemical recycling. More integrated and comprehensive approaches are thus required. These aspects are of particular importance for developing countries and emerging economies, where the concept of waste management and rational production of plastic items need to be harmonized.

ENVIRONMENTALLY DEGRADABLE PLASTICS (EDPs) RELATED ACTIVITIES AT ICS-UNIDO — GENERAL CHARACTERISTIC

The International Center for Science and High Technology (ICS), an institution within the legal framework of UNIDO located in Trieste, Italy, focuses on the transfer of know-how and technology from industrialized to developing countries.

At present, ICS activities focus on specific sectors within the areas of:

— pure and applied chemistry,

— earth, environmental and marine sciences and technologies,

— high technology and new materials,

— technology management and transfer.

The area of pure and applied chemistry currently includes the following subprograms:

Catalysis and sustainable chemistry

This is an important area for the development of environmentally friendly chemical processes, which are the basis for cleaner industrial production and also the key elements for an industrial pollution prevention approach. New, less polluting processes together with the optimization of existing processes depend to a great extent upon the improvement of catalyst performance in bulk and fine chemical production lines, with direct impact on the by-products or wastes generated.

Remediation technologies

One of the most urgent problems at global level is the decontamination of soil and waters polluted through domestic and industrial activities. Large polluted areas, in

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addition to having lost their eco-functionality, often represent a serious threat to human health. Policy for the restoration of natural resources is thus a priority in developing as well as in industrialized countries. Recently, several remediation technologies have been developed for the decontamination of polluted sites, and many have proved very promising for the clean-up of contaminated water and soils.

Combinatorial chemistry and technologies

These technologies have a strong impact on the development of new chemicals (pharmaceutical industry, agro-chemicals, new materials). Developing countries need to become familiar with and gain expertise in combinatorial technologies in order to help local enterprises remain competitive and economically viable the coming decades. Combinatorial chemistry and technologies have a potential influence not only on industrial growth, but also on environment protection. In fact, by optimizing industrial processes and production, with the lowering of relevant costs, less wastes and fewer by-products are created.

Environmentally degradable plastics

The expanding production and consumption of polymeric materials coupled with increasing public awareness of environmental issues have led to serious concern about problems related to the disposal of plastic wastes generated by various areas of human activity. Besides recycling, re-use, incineration and composting, new technological developments of environmentally degradable plastics contribute dramatically to the tackling of the environmental issue in specific sectors of plastics use.

The EDPs subprogram as one major branch of ICS activity aims at bringing the updated knowledge directly to developing countries, and stimulating a diffusion of harmonic decisions on the global issue of plastic waste to the benefit of these countries. During 2000—2001, the actions undertaken in the subprogram of EDPs included project outcomes and workshops, which have met a strong interest and resulted in many proposals of co-operative projects, feasibility studies and networking coordinated by ICS-UNIDO.

The main projects in the field of EDPs, recently completed or being developed are:

— **Management of Innovation in Environmentally Degradable Plastics**, a project funded by the European Commission within the framework of the Leonardo da Vinci Program. Major outcomes are: an information package, a training package and database of EDPs technologies, companies, relevant regulations, standards and waste management issues.

— **Plastic Waste Management and EDPs in Egypt and Turkey**, aims to produce and update an infopack and database on the situation of plastic waste and its management in countries of the Mediterranean region (Egypt and Turkey) and at disseminating of the best practices in the relevant institutions. An accurate analysis of the infrastructure necessary for the production and use of EDPs and management of post-consumer plastic items will be carried out.

— **Eco-compatible Bioplastic Packaging in China Based on Polyesters from Renewable Resources**, aims at accelerating in China the production of polyhydroxyalkanoates (PHAs) obtained from renewable resources (sugar — sugar molasses and whey permeate) to form ecocompatible biodegradable packaging (films, containers and disposable utensils) as a safe and environmentally sound material. This will help China to tackle the problem of plastic waste, so called "white pollution", and will open new export markets for Chinese sugar cane farmers.

— **Development of a Project Proposal on Industrial Promotion of EDPs Concept in Korea**, will involve both academic institutions and companies. The demonstration project is expected to result in the transfer of technology for the production of EDPs from renewable resources and manufacturing of packaging items.

EDPs are expected to serve as a promising solution to: (a) pollution problems caused by difficult-to-recycle plastic items and litters of disposable plastic products; (b) over-filled landfills by diverting part of bulky volume plastic packaging to other means of waste management; (c) conservation of the valuable resources, non-renewable in particular, as the principle of sustainable development requires a society based more on renewable resources. Besides environmental concerns, research and application of EDPs in medical and pharmaceutical fields are greatly beneficial to human being.

Among these three objectives of EDPs, the first two are among the top concerns throughout the world. Both are closely related and directly beneficial to waste management. In the following sections, we will analyse major problems facing the development and large scale application of EDPs. Based on that, a further discussion is made on the implication of wide application of EDPs in environmentally sound waste management and strategy to tackle the challenges.

STANDARDIZATION

One of the key issue that hotly debated in the field of EDPs is standardization.

Consensus has been reached that standards and criteria regarding biodegradability and compostability of EDPs are crucial for the success of EDPs. Regulation and standards defining the quality of compost will pave the way for the large-scale application of EDPs by enhancing and ensuring the adsorption of its recycled product, the compost.

The majority of the standards concern the composting disposal environment, treating the composting as an important, ecologically sound disposal method that generates useful soil amendment product. So far all available standards relevant to EDPs are based on compostability. They are generally composed of several aspects: material characteristics, biodegradability in certain environment and compost quality.

— **Biodegradability:** most standardization organizations in Europe (*e.g.* CEN of EU, DIN of Germany) agree on the necessity of complete biodegradation of compostable materials. Some consensus must still be reached on the minor components, namely the need for testing components between 1 and 10% separately.

— **Quality of compost:** may not be negatively influenced by the addition of compostable products to the compost feedstock. Yet, more research is still needed in order to establish precise testing procedures and criteria of contaminants level (*e.g.* organic chemicals and heavy metals).

— **Anaerobic biogasification,** which so far has been more or less neglected in standards. In 1997, such plants made more than 1/3 of all public bidding for biological solid waste treatment systems in Europe. The total capacity has increased dramatically the last years and is expected to grow further. Therefore, if compostable products are envisaged to be applied in a large scale they will need to be treated in biogasification systems too. The standards and guidelines specifying precise requirements for bio-polymers in anaerobic systems will need to be established.

— **Bio-degradability standards in environments other than composting** must be developed, such as soil or marine conditions. In these environments lower temperatures and eventually less aggressive microbial life prevail which can reduce degradation significantly. For these reasons it is necessary to develop specific standards and acceptance criteria for environments other than compost where biopolymers are used and are advertised biodegradable.

— **Eco-toxicity tests** have been suggested but are not required for the moment because of insufficient knowledge and experience regarding the test procedures and acceptance criteria.

Another future challenge in standardization is how to regulate house composting, a more varied composting method than industrial one. Since house composting is regarded as a way of waste reduction, it is being encouraged and the need for standardization will emerge soon [1].

AVAILABILITY OF RENEWABLE AND NON-RENEWABLE RESOURCES FOR EDPs

Growing concerns about the "Green-house Effect" is one key driver for consequent actions toward technologies that are more friendly to our environment. One of the most promising approaches is the use of renewable resources and closing the cycles by collection and reutilization of waste materials instead of starting from non-renewable resources. In the field of plastics, this ideology could be followed by taking biopolymers, either occurring naturally (see Table 1) or being chemically or enzymatically modified.

Table 1. Naturally occurring polymers according to type of repeating units

Polysaccharides	Alginates, cellulose, chitin / chitosan, curdlan, dextran, elsinan, konjac, levan, pullulan, scleroglucan, starch, xanthan
Proteins	Albumin, casein, collagen, elastin, fibrinogen, gelatins, silk
Polyesters	Polyhydroxyalkanoates (PHA)
Others	Lignin, melanins, natural rubber, poly(γ-glutamic acid), shellac

Table 2. EDPs from renewable resources [2]

Advantages	Drawbacks	Remedies
— Ample structural variety combined with high versatility	— Higher production costs	— Provide more encouragements for R&D and application of EDPs
— Limited dependence on raw material supply from crude oil and coal price fluctuations	— Constraints in processability imposed by inherent structural susceptibility to side reactions	— Political decisions tending to diffuse and appreciate the impact of EDPs in different commercial and industrial exploitation segments
— Reduced contribution to greenhouse effect	— Limits of adaptation of existing process technology and machinery	
— Easy and convenient disposal by composting	— Unsatisfactory mechanical properties	

Synthetic EDPs are produced mainly from crude oil and thus so-called petrochemical origin. Also they can be synthesized from agricultural feedstock by microbial method. Biodegradable synthetic polymers include mainly aliphatic polyesters [such as poly(lactic acid) (PLA) and poly(ε-caprolactone) (PCL)], PHAs, polyamides, poly(vinyl alcohol) (PVAL), poly(vinyl esters), polyanhydrides, polyphosphazenes and poly(aspartic acid).

Starting from the two different sources of raw material, chemical and/or biochemical methods are required to obtain the monomeric components that are converted by chemical or biochemical routes to macromolecular compounds at a first stage. The route of renewable resources may offer the opportunity to directly obtain the macromolecular compounds, which after processing can produce the final products. The chemical routes are the most commonly used due to their versatility and minimum number of constraints.

It is much debated whether the connection between environmentally degradable plastics and renewable resources as raw materials has to be taken for granted. Indeed, EDPs from renewable resources have some drawbacks in addition to their higher cost (see Table 2). Life-cycle assessment of the plastic article of different origin is thus necessary to justify decision-making.

IMPLICATION OF EDPs ON WASTE MANAGEMENT TECHNOLOGIES

Environmentally sound solid waste management (generally shortened as SWM), as defined by UNEP, means taking all practical steps to ensure that wastes are managed in a manner which will protect human health and the environment against the adverse effects which may result from such wastes.

Experience indicates that the most efficient and sustainable way for SWM is to eliminate the generation and to reduce the amount of waste at source. For the wastes that nevertheless are generated, a strong control should be involved over the life cycle of the product from design, production and use to after-use stages to minimize the impacts. Waste management should follow the logical hierarchy of Reduce, Reuse, Recycle (or recovery of materials) if can not be reused, and Recovery the energy content (through incineration for example) if not recyclable before final disposal, usually landfill.

Recycling

Introduction of EDPs is mainly driven by the need of handling the non-recyclable in an economically viable way. Inherently, EDPs are not created for material recycling. In general, a typical plastic recycling process involves re-heating, during which EDPs will usually decompose and make further processing impossible. Mixing of EDPs in the feedstock of recycling will damage the process and the quality of recycled products. Therefore, an effective sorting becomes more important after EDPs are widely adopted. Policy makers as well as industry will need to prepare in advance.

Recovery energy from wastes or incineration

Incineration is not the desired destination of EDPs, not much research available yet regarding the possible effects of EDPs if combusted in wastes incinerators. The major environmental and health concern over the incineration of waste plastics are heavy metals and hazardous by-products such as dioxins.

Composting (organic recycling)

Composting is the most relevant waste treatment technology for EDPs, particularly for the applications other than medical and pharmaceutical. So far, the international accepted definitions and standards for EDPs are all based on their compostability. The success of EDPs will depend on the availability of composting facilities. On the other hand, demand for EDPs will stimulate development of organic recycling (composting and biogasification *etc.*).

The success and failures of industrial scale composting in many countries demonstrate that to ensure the quality of finished product, the compost, with acceptable low contaminants level is essential if municipal waste composting is to be successful as a recycling of organic wastes. Mixed wastes composting should be replaced by composting of well-sorted organic waste with minimum contaminants. A further discussion along this line is carried out in the next section.

Landfill

The accidental entry of EDPs should not cause any problem in a standard landfill inside which degradation of wastes are supposed to be kept at very low level. However, in many less developed countries, the landfills are usually substandard. Entry of EDPs will contribute further to the biodegradation already existing and will worsen the contamination of ground and surface water, ambient environment by generating more leachate and gases. It is clear that application of EDPs puts higher requirement on sorting at source, separate collection and recycling. In a word, it demands more integrated approach toward the whole waste management system and beyond, the production and consumption systems.

INTEGRATED WASTE MANAGEMENT WITH EDPs

To achieve the possible benefit of EDPs to waste management in comparison with conventional plastics, it is necessary to adopt EDPs to a significant scale necessary for the change. Obstacles imposed by improper or fragmented policies and regulations should be identified and removed. The last section briefly analyses the possible challenges that might be brought by commercialization of EDPs in commonly practiced waste management technologies. It highlights the importance of integrated waste management from source separation to sound operation.

Take the example of composting as it is the most relevant for EDPs. It has been identified that the reduction of contaminants level is crucial for the success of composting, which in return provide guarantee for the acceptance of EDPs. There are various options to get cleaner compost:

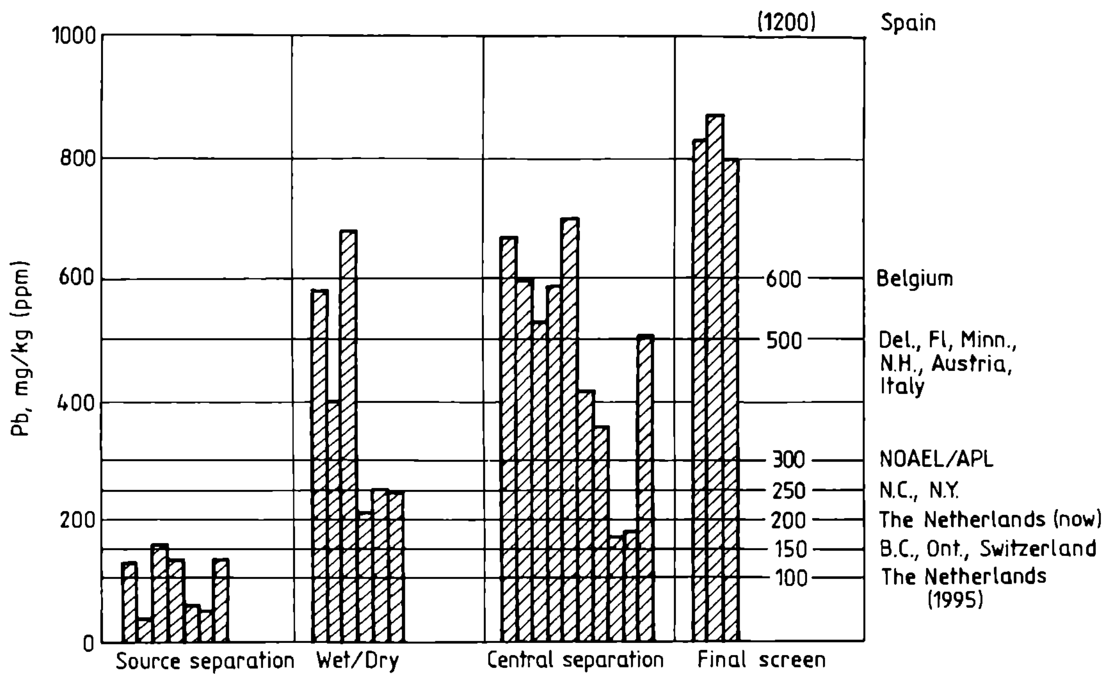

*Fig. 1. Pb levels in municipal waste composts from experimental studies comparing several separation approaches. Standards from several U.S. states, Canadian provinces, and European countries are listed on the right axis [3]; *) NOAEL: No Observed Adverse Effect Level, APL: Alternate Pollutant Limit*

— Reduce or eliminate contaminants in product design so as to facilitate the after-use disposal and improve the quality of recycled products, such as compost. It calls for life cycle consideration beyond waste management system to design, production and consumption (see the next section).

— Source separation of waste by households and commercial consumers into recyclable, compostable wastes (organic wastes and non-recyclable papers *etc.*) and wastes for final disposal.

— Sorting at a centralized facility after collection and prior to composting, is included in most of the modern municipal waste composting facilities.

— To separate contaminants after composting, the practice of the first generation of municipal waste composting facilities, normally results in highest level of heavy metal contamination.

Evidence from the experimental trials and operating facilities show that options at the top of the above list have higher potential to reduce contaminant level than those lower ones thus should be prioritized and encouraged. It is very expensive to remove contaminants from mixed waste compost in order to meet the increasingly stringent requirements set by many countries on quality of compost. This is actually the major reason why large scale composting didn't succeed in the past. Centralized sorting before composting becomes increasingly difficult and less effective too with the increase of separation cost. Moreover, some liquid contaminants, fine dust or paint chips containing heavy metals and/or toxic chemicals can attach to the otherwise clean organic wastes during collection and storage.

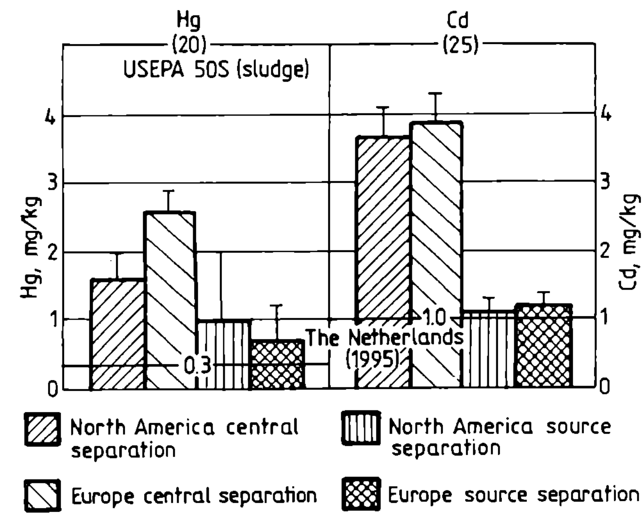

*Fig. 2. Average mercury and cadmium levels in municipal waste composts from centralized separation versus source separation of organic compostable wastes in North America and Europe. USEPA (NOAEL/APL for sewage sludge, not for compost yet) standards and that from The Netherlands are included; *) NOAEL: No Observed Adverse Effect Level, APL: Alternate Pollutant Limit*

Source separation, on the other hand, provides higher quality of compost with significantly lower contaminant levels than centralized sorting and after-composting screening, as revealed by research in some European countries and study in USA (see Figure 1 and 2). Source separation of organic wastes can achieve a high level of diversion potential of wastes from landfill, estimated in the range of 25—50% [3], which is comparable to that of centralized sorting. Effective source separation needs cooperation of a public, well motivated by educational programs, environmental awareness raising campaigns and mass media. More important is the integration of policies, regulations, economic instruments to create a concerted pressure as well as economic encouragement to promote source reduction and separation of wastes.

LIFE CYCLE APPROACH

So far only limited life cycle assessments (LCA) have been carried out for biodegradable polymer products, resulting in conclusions favorable to EDPs [4], though in some other cases, the opposite. The authors complained that during the process of data collection and investigation, companies are reluctant to provide information for proprietary reasons or for fear of the time-consuming recording and documenting processes required by an standard LCA. These difficulties highlight the need of external pressure from government regulations or the public and internal incentives such as financial and competitiveness considerations.

Introducing life cycle consideration into design of novel polymers and polymeric products is a new challenge facing polymer scientists and producers. One of the main ideas of the so called Design-for-the-Environment (DfE) or Eco-design is to go beyond the traditional logic and procedure of product design to take the after-use stage of the product into account. A truly environmentally benign product should have minimum adverse impacts on human health and the environment not only during its production and applications phases, but also in final disposal after discarded. As discussed previously, Eco-design of EDPs will facilitate waste management through decreasing the use of toxic chemicals and heavy metals undesirable at all disposal methods, organic recycling in particular. This should be born in mind while developing EDPs and planning new applications.

CONCLUSION

EDPs provide new chances yet new challenges to plastics industry, waste management and sustainable development as a whole. To what extent these new products will benefit both the environment and the society will depend much on how effectively we can tackle the key issues and challenges facing us. A holistic view, a life cycle strategy and an integrated approach proved to be necessary for the success of large scale application of EDPs.

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