



The valorization of plastic solid waste (PSW) by primary to quaternary routes: From re-use to energy and chemicals

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ABSTRACT

Polymers are the most versatile material in our modern day and age. With certain chemicals and additives (pigments, concentrates, anti-blockers, light transformers (LTs), UV-stabilizers, etc.), they become what we know as plastics. The aim of this review is to provide the reader with an in depth analysis regarding the recovery, treatment and recycling routes of plastic solid waste (PSW), as well as the main advantages and disadvantages associated with every route. Recovery and recycling of PSW can be categorized by four main routes, i.e. re-extrusion, mechanical, chemical and energy recovery. Re-extrusion (primary recycling) utilizes scrap plastics by re-introducing the remainder of certain extruded thermoplastics (mainly poly- α -olefins) into heat cycles within a processing line. When plastic articles are discarded after a number of life cycles, mechanical recycling techniques present themselves as a candidate for utilizing a percentage of the waste as recycle and/or fillers. Collectively, all technologies that convert polymers to either monomers (monomer recycling) or petrochemicals (feedstock recycling) are referred to as chemical recycling. The technology behind its success is the depolymerization processes (e.g. thermolysis) that can result in a very profitable and sustainable industrial scheme, providing a high product yield and a minimal waste. Nevertheless, due to their high calorific value and embodied energy, plastics are being incinerated solely or in combination with municipal solid waste (MSW) in many developed countries. This review also presents a number of application and technologies currently being used to incinerate plastics. Cement kilns and fluidized beds are the two most common units used to recover energy from PSW or MSW with high PSW content. It is concluded that, tertiary (chemical methods) and quaternary (energy recovery) are robust enough to be investigated and researched in the near future, for they provide a very sustainable solution to the PSW cycle.

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Contents

1. Introduction	104
1.1. Plastic solid waste (PSW) issue: generation and quantities	104
1.2. Re-use and major sorting techniques	106
1.3. Source reduction and primary recycling	106
1.4. Mechanical (secondary) recycling	106

Abbreviations: ABS, acrylonitrile butadiene styrene; API, Alliance for the Polyurethane Industry; ASR, automotive shredder residues; BFBs, bubbling fluidized beds; BTX, benzene, toluene and xylene (aromatics); CAPE, carboxylated polyethylene; CCGT, combined cycle gas turbine; DEFRA, Department of Environment and Rural Affairs (UK); DMSO, dimethylsulfoxide; FRs, flame retardants; GCC, Gulf Council Countries; GHGs, greenhouse gases; HCV, high calorific value; HDPE, high density polyethylene; IWM, integrated waste management; LCA, life cycle assessment; LDPE, low-density polyethylene; LHV, lower heating value; LLDPE, linear low-density polyethylene; MAPE, maleated polyethylene; MBCs, mass burn combustors; MDPE, medium density polyethylene; ME, mean error (%); MSW, municipal solid waste; MSWI, municipal solid waste incinerator; MSWIP, municipal solid waste incineration plants; PA 6, nylon 6 or polyamide 6; PAH, polyaromatic hydrocarbons; PAHs, polycyclic aromatic hydrocarbons; PBT, polybutylene terephthalate; PC, polycarbonate; PE, polyethylene; PET, polyethylene terephthalate; PMMA, poly (methyl methacrylate); POM, polyoxomethylene; PP, polypropylene; PS, polystyrene; PSW, plastic solid waste; PU, polyurethane; PVC, polyvinyl chloride; PVDF, polyvinylidene fluoride; R&D, Research and Development; RDFCs, refuse-derived fuel combustors; RHDPE, recycled high density polyethylene; SE, sum of error; TBE, tetrabromoethane; TDM, titanium-derived mixture; TGA, thermogravimetric analysis/analyser; UPR, unsaturated polyester; VCC, viable cascade controller; XRF, X-ray fluorescent; PCDFs, polychlorinated dibenzofurans.

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2.	From PSW to petrochemicals via chemical means	107
2.1.	Principles, parameters and R&D activities	107
2.2.	Pyrolysis (thermal cracking in inert atmospheres)	107
2.2.1.	Case study #1: thermal cracking kinetics modelling in an isothermal mode of high density polyethylene (HDPE)	108
2.2.2.	Case study #2: dynamic micro-pyrolysis of high density polyethylene (HDPE)	111
2.3.	Gasification	114
2.4.	Concluding remarks on pyrolysis and gasification	115
2.5.	Hydrogenation (hydrocracking)	115
2.6.	Treatments of chemical nature	116
3.	Energy recovery: quaternary treatments of PSW via combustion processes	116
3.1.	Background information	116
3.2.	Co-incineration (direct one stage, two stage and fluidized bed combustion process of waste)	118
3.3.	Rotary and cement kiln combustion	119
3.4.	Blast furnace application	120
3.4.1.	Simplified design approach for pulverized particle injection	120
3.4.2.	Blast furnace combustion characteristics	121
3.5.	Environmental concerns and management issues of PSW incineration	121
4.	Towards a more sustainable practice through recognizing PSW as a feedstock	125
4.1.	Life cycle assessment (LCA) implementation	125
4.2.	Integrated solid waste management (ISWM) in PSW management systems	126
5.	Conclusions and recommendations	126
	References	126

1. Introduction

1.1. Plastic solid waste (PSW) issue: generation and quantities

Plastic materials production has reached global maximum capacities levelling at 260 million tonnes in 2007, where in 1990 the global production capacity was estimated at an 80 million tonnes [1]. It is estimated that production of plastics worldwide is growing at a rate of about 5% per year [2]. Over the past seventy years, the plastic industry has witnessed a drastic growth, namely in the production of synthetic polymers represented by polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl alcohol (PVA) and polyvinyl chloride (PVC). Plastics also contribute to our daily life functions in many aspects. Household goods nowadays are mainly composed of plastic or plastic reinforced materials, from packaging, clothing, appliances and electrical and vehicle equipments, to insulations, industrial applications, greenhouses, automotive parts, aerospace and mulches. In 1996 the total plastics consumption in Western Europe was estimated at 33.4 million tonnes, whilst in 2007 it was estimated at 48.3 million tonnes, increasing by an average of 4% per year. This results in the high estimate of almost 60% of plastic solid waste (PSW) being discarded in open space or landfilled worldwide [2,3]. In the EU member states, directive 2008/98/EC of the European parliament states that no less than 30% of PSW should be utilized for re-use or recycling use. The directive clearly states that by 2020, all solid waste streams (including plastics) should be diverted towards thermal and/or mechanical treatment and energy recovery, reducing the percentage of solid waste being landfilled to a minimal.

Polymerization and plastic conversion has its toll on every economy. The UK used approximately 4.5 million tonnes of locally produced plastic during the year 2000 and 4.68 million tonnes during 2001 [4]. It is estimated that the plastic sector accounted for 7.5% of the UK demand for chemicals in 1998. Figs. 1 and 2 show the UK market consumption by sector and polymer type in 2007, respectively.

Most plastic items sold become waste either within a year or a single life cycle (one use or trip). Yet still, waste polymeric articles present themselves as an advantageous feedstock. That is mainly due to their versatility and light weight. In addition, low weight is

translated into resource savings throughout the polymers life cycle (Fig. 3). Examples of such are the energy savings achieved in food and goods transportation, saving in the process an average of 30% of fuel consumption. Value from PSW should be recovered through either recycling or energy and fuel recovery. Residual waste from different recycling processes (i.e. refuse-derived fuel, RDF) should be treated separately, either by thermo-chemical means or by incineration. Energy is then recovered as heat, which can be used for power generation. PSW recycling processes could be allocated to four major categories [5], re-extrusion (primary), mechanical (secondary), chemical (tertiary) and energy recovery (quaternary). Each method provides a unique set of advantages that make it particularly beneficial for specific locations, applications or requirements. Mechanical recycling (i.e. secondary or material recycling) involves physical treatment, whilst chemical recycling (i.e. tertiary encompassing feedstock recycling) produces feedstock chemicals for the chemical industry, and energy recovery involves complete or partial oxidation of the material, producing heat, power and/or gaseous fuels, oils and chars besides by-products that must be disposed of, such as ash.

Due to the high resistance of plastics, the rapid market changes and introduction of open loop recycling concept (i.e. manufacturing products from a number of articles of less quality) [36], chemical recycling is gaining more importance. Like all recycling processes, technical, economic feasibility and overall commercial viability of advanced recycling methods must be considered in each step of the recycling chain. Collection, processing, and marketing are each critical to the success of chemical recycling and energy recovery. In polyolefins thermolysis (thermo-chemical treatment aimed at degrading the polymer under controlled temperatures), products obtained mainly depend on cracking reactions in the gas phase. Thermolysis produces three different phases: a solid phase (char, 5–25 wt%), a liquid phase (tars, 10–45 wt%) and a gas phase [6]. Gasification and pyrolysis technology worldwide are predicted to grow by 30% until 2015 [7–9]. First products yielded are usually in the range of C₂₀ to C₅₀. These products are cracked in the gas phase to obtain lighter hydrocarbons, as ethene and propene, which are unstable at high temperatures and react to form aromatic compounds as benzene or toluene. If the residence time is long, coke, methane and hydrogen form [10]. Long residence times of volatiles in reactors and high temperatures decrease tar production

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