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C. A. Bernardo, Carla L. Simões, and Lígia M. Costa Pinto

Environmental and Economic Life Cycle Analysis of Plastic Waste Management Options. A Review

C. A. Bernardo[1,2, a)], Carla L. Simões[1,2, b)] and Lígia M. Costa Pinto[3, c)]

[1]IPC, Institute for Polymers and Composites/I3N, Minho University, Campus de Azurém, 4800-058 Guimarães, Portugal
[2]PIEP, Innovation in Polymer Engineering, Minho University, Campus de Azurém, 4800-058 Guimarães, Portugal
[3] NIMA, Department of Economics, Minho University, Campus de Gualtar, 4710-057 Braga, Portugal.

[a)]Corresponding author: cbernardo@dep.uminho.pt
[b)]carla.simoes@piep.pt
[c)]ligiacpinto.eeg@gmail.com

Abstract. In recent years, rising worldwide plastic consumption led to the generation of increasing amounts of plastic waste and to the awareness of the importance of its management. In that framework, the present work describes how Life Cycle Assessment (LCA) and economic assessment methodologies can be used for evaluating environmental and economic impacts of alternative plastic waste management systems. The literature on LCA of plastic waste management systems is vast and the results reported are generally consistent, showing that recycling has the lowest environmental impact on Global Warming Potential (GWP) and Total Energy Use (TEU) impacts. On the other hand, the literature addressing the economic assessment of plastic waste, namely the various End-of-Life (EoL) treatments, is rather limited. Other methodologies, such as integration of LCA and Life Cycle Costing (LCC) of plastic products, are almost never addressed. In any case, the overarching conclusion is that plastic materials usually have environmental and economic advantages over conventional materials throughout their Life Cycle, with or without consideration of the EoL stage.

INTRODUCTION

In the past six decades plastics production and consumption worldwide has increased at an average yearly rate of about 8%, attaining an all times maximum in 2013, at 299 million tonnes (1). By simple extrapolation of historical data it can be predicted that by 2020 production will exceed 420 million tonnes. This exponential growth has led to increasing amounts of plastic waste. As a consequence, in the last years several Life Cycle Assessment (LCA) (2) and economic analysis studies (3, 4, 5, 6) were performed to assess the environmental and economic impacts of the various plastic waste management options. Life Cycle Thinking is a powerful approach to address those options, as emphasised by the WFD, the revised Waste Framework Directive 2008/98/EC (7). Taking a life cycle perspective requires a policy developer, environmental manager or product designer to look up and down the supply chain (8). The WFD also establishes a hierarchy that should be applied in waste prevention and management policies, in order to attain the best environmental outcome: [1] prevention; [2] preparing for reuse; [3] recycling (either mechanical or feedstock recycling); [4] other recovery, e.g. energy recovery; [5] disposal. Regarding the existing End-of-Life treatments, mechanical recycling, corresponds to the reprocessing of plastic waste to produce new products. Feedstock recycling is the transformation of used plastics into smaller molecules which are suitable for use as a feedstock for the production of new petrochemicals and polymers. Energy recovery, also known as thermal recycling, is the combustion of plastic waste to produce energy in the form of heat, steam and electricity. Plastics have a high calorific value when compared with other materials (mostly due to being essentially made from crude oil), making them a convenient energy source. The WFD ranks landfilling last in the EoL treatments hierarchy. However, in 2012, landfills were still the destiny of the highest portion of plastic waste in the European Union and

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worldwide (1). When considering diversion from landfills, both recycling and energy recovery should be considered, as they are complementary treatments, necessary to achieve this objective.

The present work focuses on how Life Cycle Thinking, LCA, and economic assessment methodologies can be used to evaluate environmental and economic impacts of alternative plastic waste management systems. This is done by reviewing current publications and discussing differences in methodology and results. It was concluded that there is a vast literature on LCA of those systems, addressing various environmental impact categories, such as *Ozone layer depletion potential*, *Photochemical oxidation*, *Eutrophication potential*, etc. However, *Global Warming Potential* (GWP) and *Total Energy Use* (TEU) (5, 9, 10) predominate, due to global awareness of the greenhouse gases effect. On the other hand, the economic literature addressing the plastic waste fraction alone, namely its End-of-Life (EoL) treatments, is scarce, and different methodologies are used to perform the economic analyses (3, 6). Some of the studies reviewed are limited to financial costs, others incorporate also externalities (external costs), but all focus solely on thermoplastic polymers. Therefore efforts should be made to implement a proper economic assessment methodology, with the corresponding standard methods, and apply it to all types of plastic waste.

METHODOLOGY

Recent published LCA and economic assessment studies for plastic waste management systems were reviewed. Not all of these were full LCA studies, some were essentially energy and CO_2 emissions analyses. GWP and TEU were selected as environmental impact categories, since almost all studies analysed reported results on them.

LCA and Economic Assessment of Alternative EoL Treatments for Plastic Waste

Over the past 15-20 years, a number of studies have analysed plastic waste management from a life cycle perspective. Table 1 summarizes the plastic materials and waste methods described in those studies.

TABLE 1. LCA studies comparing recycling (R), incineration (I) and landfill (L) of plastic waste

Reference	Material/application	GWP	TEU
Arena et al. 2003 (11)	PE and PET liquid containers[a]	R<L<I	R<I<L
Beigl and Salhofer 2004 (12)	Plastic packaging[a]	R<I	-
Chilton et al. 2010 (13)	PET[a]	R<I	-
Craighill and Powell 1996 (14)	PET, HDPE and PVC[a]	R<L	-
Dodbiba et al. 2008 (15)	Plastics (PE, PS and PVC)[a]	R<I	-
Eriksson and Finnveden 2009 (4)	Non-recyclable plastic	I<L	-
Eriksson et al. 2005 (9)	PE[a]	R<I<L	R<I<L
	PE, PP, PS and PET[a]	R<I<L	R<I<L
Finnveden et al. 2005 (5)	PVC[a]	R≈I<L	R<I<L
	PE, PP, PS, PET and PVC[b]	I<L<R	I<R<L
Foolmaun and Ramjeeawon 2013 (10)	PET	R<L<I	R<I<L
Grant et al. 2001 (16)	PET, HDPE and PVC[a]	R<L	R<L
Moberg et al. 2005 (17)	PET[a]	R<I<L	R<I<L
Mølgaard 1995 (18)	Plastics[a]	-	R<I<L
	Plastics[b]		I<L<R
Perigini et al. 2004 (19)	PE and PET liquid containers[a]	R<L<I	R<I<L
Perigini et al. 2005 (20)	PE and PET liquid containers[a]	R<L<I	R<I<L
Rajendran et al. 2013 (21)	Plastics[a]	R<I	-
US EPA 2006 (22)	HDPE, LDPE and PET[a]	R<L<I	R<I<L
Wenisch et al. 2004 (23)	Plastics[a]	R≈I	-
Wollny et al. 2001 (2)	Plastic packaging[b]	R<L<I	R<I<L
M. Al-Maaded et al 2012 (25)	Plastics, non specified	R<L	-
Shonfield 2008 (26)	Plastics[a]	R<L<I	R<I<L
	Plastics[b]	I<L<R	-

(a) avoided virgin material; (b) avoided material other than virgin polymer, e.g. wood derivates or fuels

The results reported in Table 1 are consistent, showing that recycling has the lowest environmental impact on both GWP and TEU in most, but not all, of the cases. The few conflicting results may be explained by key factors such as: type of recycled materials, type of materials avoided by recycling, energy sources avoided through energy recovery by incineration, and the timeframe of a specific landfill. Incineration is preferable to using recycled plastic instead of virgin plastics to substitute wood derivate materials in plastic lumber (5, 18, 26). Methodological assumptions, such as selection efficiencies, the adopted technologies and avoided products, might drastically change the overall results of a waste management system LCA (27). Both GWP and TEU are in general lower for recycling than incineration or landfill of plastic waste. Hence, the avoided burdens of recycled plastic are significant enough to motivate recycling. The different energy sources used and different efficiencies for electricity production may also influence the choice between incineration and other plastic waste treatment (4, 28, 29). Another factor that must be accounted for is the timeframe used in the landfill model. Some studies assess other environmental impact categories and how they rank in terms of EoL hierarchy. *Acidification Potential*, *Eutrophication Potential* and *Depletion of Abiotic Resources* are the impact categories calculated more often. Overall, the results are consistent, showing again that recycling has the lowest environmental impact on most environmental impact categories. For lack of space those studies will not be referred to herein.

The literature concerning the decision support to the choice of waste management solutions is overwhelming vast, and the economic dimension has obviously been a substantial element of that choice. Initially limited to the analysis of financial costs, an important innovation of the last two decades was the incorporation of environmental costs (externalities) in the evaluation (30, 31). Both costs and revenues that accrue in plastic waste management should be considered when performing an economic assessment (32). Generally a gate fee is charged by the operators of waste management facilities for disposal of received waste. Gate fees are set at a level that allows recovering all capital and operating costs, but often include also a profit element. In the case of recycling, sometimes a price is paid for the reception of recycled materials, which can be viewed as a negative gate fee. Indeed, in recycling and incineration with energy recovery, significant revenues can also be obtained from material and energy sales (33). Although there are many publications dedicated to MSW in the economic literature, publications addressing only the plastic waste fraction are quite scarce. As a matter of fact, to the best of the authors' knowledge, only three studies were published on that subject, whose waste and economic assessment methods are summarized in Table 2.

TABLE 2. Economic assessment of alternative EoL treatments for plastic waste

Reference	Waste method	Material	Economic analysis method
Axion Consulting 2009 (3)	Material Recovery Facility Plastic sorting facility Reprocessing facility	Mixed plastics	LCC(excludes externalities)
Eriksson et al. 2005 (9)	Recycling Incineration	Plastic containers	LCC(includes externalities)
Lea 1996 (6)	Recycling Landfill Waste-to-energy	Plastic waste fraction	Economic analysis (excludes externalities)

Of these studies, two (3, 9) can be considered as Life Cycle Costing (LCC) studies in the framework defined by Ciroth et al. and Swarr et al. (34, 35), but only one incorporates externalities (9). The first study addresses the financial models (private costs) of a Material Recovery Facility (MRF) and a plastic sorting and reprocessing facility for mixed plastics waste recycling (3). The financial models indicate that satisfactory returns can be earned from investment in the MRF and in an integrated plastic sorting and reprocessing plant due to the mixed plastics that it provides. The second study deals with the integration of LCA and economic results in the context of the end of life of plastic containers (9). This study shows that material recycling of plastic containers is comparable to incineration from an economic welfare point of view (financial costs plus aggregated environmental costs). On the other hand, when plastic recyclates replace virgin plastic in the same application, less energy is used and the environmental impact is smaller. The third publication investigates the energy cost savings that could be obtained from the plastic waste fraction using recycling and waste-to-energy (WTE) processes (6). It concludes that energy savings from plastic waste recycling is negligible, especially when sorting costs are taken into account. While it may be considered that plastic recycling saves energy compared to landfilling of a single-use plastic product, this is due only to the inherent energy content, not to any process energy savings. Therefore, energy cost savings from plastic waste can only be accomplished through WTE conversion, which, however, may have other undesirable results.

CONCLUSIONS

Plastics are ubiquitous materials in all advanced societies. Because of their advantageous characteristics they have contributed decisively to improving the standard of living of those societies. However, all good things have a dark side. In the case of plastics this dark side is their EoL. Deciding which is the best management method for plastic waste is thus of critical importance. Tools such as LCA and economic analysis can be effectively used to assist in that decision. The existing literature on LCA of plastic waste management is vast and the results reported are generally consistent, showing that recycling generates the lowest GWP and TEU environmental impacts. The few conflicting results may be explained by specific factors such as: type of recycled materials, type of materials avoided by recycling, energy consumption avoided by energy recovery from incineration, and specific landfill timeframes. Some studies also report results on other environmental impact categories, such as the *Acidification Potential*, *Eutrophication Potential* and *Depletion of Abiotic Resources*, attaining similar conclusions. On the other hand, the economic literature addressing only the MSW plastic fraction is scarce. Furthermore, several methodologies were used to perform the economic analyses, some limited only to financial costs, a few studies including also externalities (external costs). Hence, while the LCA methodology seems to be well established in plastic waste management systems, efforts have still to be made to implement an economic assessment methodology, as well as the corresponding standard methods. In spite of that, the present work allows the conclusion that existing assessment tools may effectively assist in establishing a plastic waste prevention and management hierarchy, as mandated by the Waste Framework Directive.

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