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Environmental and economic life cycle assessment of polymers and polymer matrix composites: a review

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Abstract

The present work reviews studies on the use of the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies for evaluating environmental and economic impacts of polymers and polymer composites. Current publications were reviewed and differences in methods and results discussed. It was concluded that literature results on LCA of polymers and polymer composites are generally consistent, showing that indicators, such as Global Warming Potential (GWP) and Total Energy Use (TEU) are generally lower than those of alternative materials. On the other hand, the economic literature is not so extensive and standard methods still need to be adopted, since different economic analysis methodologies were used in the studies reviewed.

Keywords: polymers; composites; environment; life cycle assessment; life cycle costing.

1. Introduction

In the last few years, rising plastic consumption worldwide has led to increasing amounts of plastic waste. Approximately 50% of plastics are used for single-use disposable applications, such as packaging and agricultural films. Only 20-25% of plastics are used in long-term infrastructure items, such as pipes, cable coatings and structural materials. The remainder is used for intermediate lifespan consumer applications, such as electronic goods, furniture and vehicles components [1]. Disposal of plastic waste poses significant difficulties, in part due to the fact that plastic products have small service lifespans. In some applications, such as plastic packaging, it can be less than one month [2]. The problem is enhanced by the fact that plastics have low density, and are often used in hollow products (thus, with very little apparent density) and consequently are highly visible in the waste streams. In fact, although the volume weight fraction of plastics in municipal solid waste (MSW) can represent 20-30%, its mass is only 7-9% of the total MSW mass [3]. In some streams, however, like those from the manufacturing and service industries, plastic waste can appear in much higher proportions. Another aggravating factor is that plastics usually are non-biodegradable, and thus tend to remain in nature for a long time. Considering all types of waste, plastic mass fraction has increased from less than 1% in 1960 to 12% in 2006 [4], of which thermoplastic represent 78% [2]. This ubiquitous presence has caused increased public concern about the potential environmental impact of plastics usage. Public concern, on its turn, has induced multiple studies, namely Life Cycle Assessments (LCA), aimed at evaluating the impact of plastic products throughout their Life Cycle. More recently, economic assessments have complemented those studies.

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The aim of the present work is to review recent LCA and Life Cycle Costing (LCC) studies evaluating the environmental and economic impacts of polymers and polymer composites.

2. LCA of polymers and polymer composites

In the pursuit to eliminate all that is not "green", plastics seem to be a natural target. The focus is usually placed on their high energy content and on the ubiquity of their presence as litter in the environment. This bias, however, is seldom supported by quantitative studies found in recent literature. In fact, when studies assessing the environmental and economic impact of alternative materials are made, plastics often present quite positive life cycle (LC) profiles. Table 1 summarizes published LCA studies comparing the environmental performance of polymers and polymer composites, essentially thermoplastic, with other materials with respect to Global Warming Potential (GWP) and Total Energy Use (TEU). These environmental impact categories were selected since almost all studies consider them, due to the current importance of greenhouse gases enhancement. Some studies also report data on other environmental impact categories, such as Ozone layer depletion potential, Photochemical oxidation, Acidification and Eutrophication, but, as this is not a general feature, they were not included in Table 1.

The results show that, in most cases, and contrarily to public perceptions, the use of conventional polymers generates lower (or, at most, similar) GWP and TEU environmental impacts than other materials. It is also evident that reuse, avoiding the consumption of non-renewable resources, minimises the environmental impact in both indicators. The few conflicting data present in Table 1, like those of references [5] and [17], may be explained by factors such as type of use phase, system boundary, type of End of Life (EoL) treatment, and use of recycled materials. For example, a given phase can generate a higher relative impact, even though this may not be true when the whole Life Cycle is considered. Or distinct systems boundaries can lead to substantial differences in the overall environmental impact. Also, recycled polymers are normally preferable to virgin ones, since their use saves resources and reduces emissions. This beneficial effect of polymers is obtained in spite of the energy consumption and potential gaseous emissions that are necessarily associated to the recycling process.

Table 1. LCA studies comparing traditional materials and polymers.

Material	Global Warming Potential	Total Energy Use
W(su); CB(su); P(r) [5][1]	P(r)≈W(su)<CB(su)	P(r)≈W(su)<CB(su)
G; P [6][1]	P<G	P<G
G; P [7][1]	P<G	P<G
PET; rPET [8][2]	rPET<PET	-
S; HDPE [9][3]	-	HDPE<S
CB(su); PP(r) [10][1]	CB(su)<PP(su)	
S; A; PPC [11][3, a]	PPC≈<A<S	-
Current P version; Prototype version	Prototype<Current	-
PE; PP; PVC [13][4]	PE<PP<PVC	-
A; PPC[14][4, c]	PPC<A[d] A<PPC[e]	-
CB(su); PP(r) [15][1]	PP(r)<CB(su)	PP(r)<CB(su)
EPS; CB [16][1]	CB<EPS[d] EPS<CB[e]	-
rPaper; PS [17][1]	rPaper<PS	-

Applications: [1]Packaging; [2]Construction; [3]Automotive; [4]Consumable product.

[a]Clay reinforced virgin PP; [b]Prototype plastic version based on compatible and recyclable polyolefin; [c]PP composite with virgin PP and recycled tyres' rubber granulate; [d]System boundary up to the manufacture stage, "cradle-to-gate" analysis; [e]System boundary up to the EoL stage, "cradle-to-grave" analysis.

Key - A: aluminium; CB: cardboard; EPS: expanded polystyrene; G: glass; HDPE: high density polyethylene; P: plastic; PE: polyethylene; PET: polyethylene terephthalate; PP: polypropylene; PPC: polypropylene composite; PS: polystyrene; PVC: polyvinyl chloride; r: reused; rPaper: recycled paper; rPET: recycled polyethylene terephthalate; S: steel; SS: stainless steel; su: single-use; W: wood

3. LCC of polymers and polymer composites

According to the Society of Environmental Toxicology and Chemistry (SETAC) working group on LCC, there are three different types of LCC [18]: conventional LCC, environmental LCC and societal LCC. An overall vision of this taxonomy is depicted in Figure 1, together with the corresponding economic aspects. Conventional LCC, to a large extent the historic and current practice of many practitioners, including governments and firms, is based on a purely economic evaluation. It considers the costs associated with a product that are born directly by a given actor, but often neglects external costs. Environmental LCC summarizes all costs associated to a product LC that are directly covered by one, or more, of the actors involved in its LC. It includes the externalities that are anticipated to be internalized in the decision-relevant future. Societal LCC uses an expanded macro-economic system and incorporates a larger set of costs,

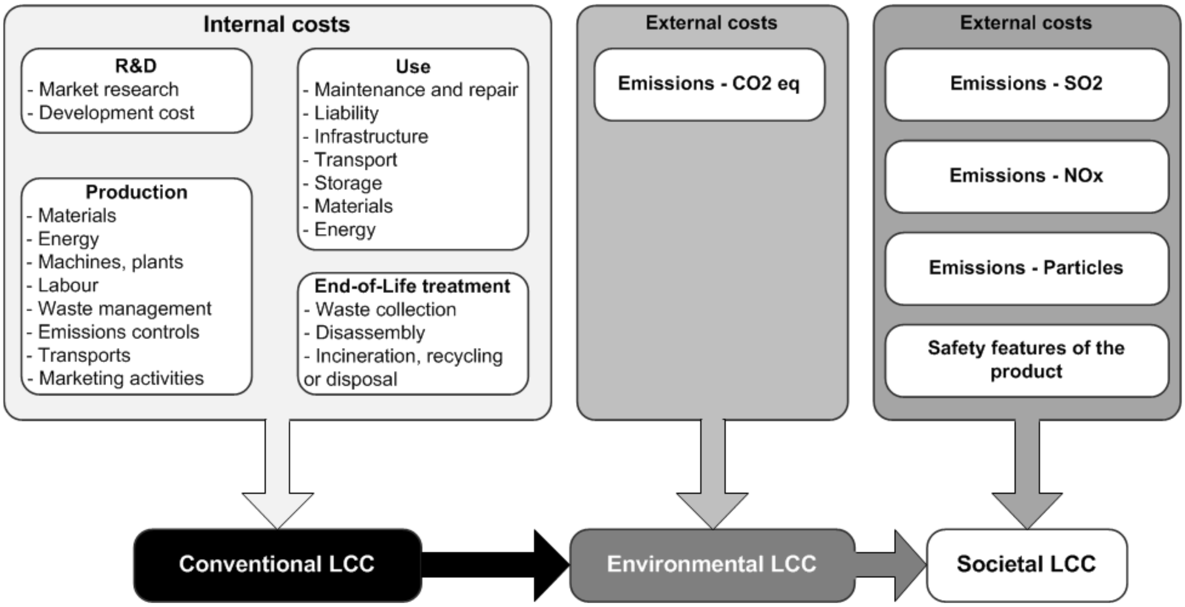

Fig. 1. The three types of Life Cycle Costing studies and corresponding economic aspects.

namely some emissions and safety features.

Societal LCC also involves, as opposed to conventional and environmental LCC, governments and other public bodies that could be indirectly affected through externalities. It includes all of environmental LCC plus additional assessment of external costs, usually in monetary terms. The main difference between conventional cost accounting and LCC consists in the latter accounting for “hidden” or “less tangible” costs, including costs for environmental protection [19].

Initially limited to financial costs analysis, LCC presently incorporates environmental costs (externalities) in the evaluation, an important innovation of the last two decades, either through environmental cost-benefit assessment or multicriteria approaches [20-22]. The costing of external effects reveals something about the potential taxes and other expenses that the companies and consumers may be charged with. There are at least three reasons why a company should incorporate external social costs in its accounting [19]: avoiding the “regulatory treadmill” (to be prepared for future regulatory issues, industry managers may wish to begin accounting for such external costs now); international competitiveness (in today's increasingly global economy, often the highest environmental standards for products become the global standards for companies that wish to compete internationally); and accountability beyond responsibility (business is under increasing pressure to protect the environment, regardless of what formal regulatory mandates are in place). Transversal to the reasons described is the general adoption of the “polluter pays principle” (the polluter shall pay for the environmental damage he or she causes). While external costs are real costs and should be considered, they are often difficult to quantify as they are borne by society as a whole, and often involve goods that are not traded in markets and consequently lack a clear market value [19].

Literature reporting the LC economic assessment of polymers and polymer composites is scarcer than that reporting their LC environmental assessment. In fact, the main focus of most studies is the evaluation of environmental impacts, the economic and social assessment being a secondary objective. Table 2 summarizes published LCC studies comparing traditional materials, conventional polymers and polymer composites. Analysis of these studies shows that the LCC methodology is still controversial, since different methods of economic assessment were used in most of them. Undoubtedly, greater efforts should be made to standardize methods and tools in LCC, following the recent publication of a code of practice on environmental life cycle by SETAC [23]. Further to this, all the studies reviewed were limited to a financial cost analysis, excluding externalities. Automotive applications were highly studied, since the use phase of cars is highly energy intensive. As a consequence, the use of lighter materials (vis. polymer composites) may result in substantial savings.

Table 2. LCC studies comparing traditional materials, conventional polymers and polymer composites.

Material	Economic analysis method used	Cost results
W(su); CB(su); P(r) [5][1]	LCC (excludes externalities)	P(r)<W(su)<CB(su)
GFRP[a]; NFRP [24][2,b]	Economic analysis (semi-quantitative, excludes externalities)	NFRP<GFRP
GFRP; NFRP[c] [25][2]	Economic analysis (excludes externalities)	NFRP<GFRP
SS(r); SS(su); FRP(su) [26][3]	LCC (total cost of ownership -TCO, excludes externalities)	SS(r)<SS(su)< <FRP(su)
GFRP[d] ; NFRP[e][27][4]	LCC (excludes externalities)	NFRP<GFRP
S; A; PPC [11][2, f]	Economic analysis (technical cost modelling -TCM, excludes externalities)	PPC≈A<S
PP; LDPE; GFRP[g]; PPC[h] [28][1,2,5]	LCC (excludes externalities)	PP≈PPC PPC<LDPE PPC<GFRP
SS; A; HCFRP; FCFRP[29][2]	Economic analysis (TCM, excludes externalities)	FCFRP<HCFRP≈ ≈A<SS
M; S; GMT; SMC; GFRP; CFRP [30][2]	Economic analysis (TCM, excludes externalities)	SMC<GFRP<GMT< <M<CFRP<S
Auto CFRP; OOA; CFRP[31][2]	Economic analysis (TCM, excludes externalities)	OOA≤Auto
GFRP[i]; NFRP[j] [32][2]	Economic analysis (qualitative, excludes externalities)	NFRP<GFRP

Applications: [1]Packaging; [2]Automotive; [3]Medical; [4]Construction; [5]Agricultural

[a]Unsaturated polyester glass fibre composite; [b]Jute fibre unsaturated polyester composite; [c]Untreated and treated jute fibre unsaturated polyester composite; [d]Epoxy vinyl ester glass fibre composite; [e]Epoxy vinyl ester glass fibre and hemp fibre composite; [f]Clay reinforced virgin PP; [g]30 wt% glass fibre reinforced virgin PP; [h]Nanoclay silicate reinforced virgin PP; [i]Glass fibre reinforced virgin PP; [j]Curauá fibre reinforced virgin PP.

Key - A: aluminium; Auto: autoclave; CB: cardboard; CFRP: carbon fibre reinforced polymer; FCFRP: full CFRP composite; FRP: fibre reinforced polymer; GFRP: glass fibre reinforced polymer; GMT: glass fibre mat thermoplastic; HCFRP: hybrid CFRP composite; LDPE: low density polyethylene; M: magnesium; NFRP: natural fibre reinforced polymer; OOA: out-of-autoclave; P: plastic; PP: polypropylene; PPC: polypropylene composite; r: reusable; S: steel; SMC: glass fibre and unsaturated polyester resin sheet moulding compound; SS: stainless steel; su: single-use; W: wood.

The results depicted in Table 2 are once more consistent, and generally agree with those in the previous Table. They evidence that the use of polymers and polymer composites has the lowest (or a similar) economic impact in all but one of the studies reviewed. The one conflicting result [11] may be explained by the type of use phase. Conventional material products may be preferable to composite ones when they can be reused a number of times large enough to mitigate the higher material cost. Although not the main subject of this work, it is also of note that the use of natural fibers has a high potential to decrease materials' cost.

4. Conclusions

The overarching conclusion of the present study is that polymers and polymer composites often have environmental economic advantages over conventional materials. It was also found that while the Life Cycle Assessment methodology is already stabilised, efforts must still be made to standardize methods and tools in Life Cycle Costing studies.

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