LCA as a support decision-making tool in nanocomposite material additive manufacturing sector

Anastasia Gkika, Foteini Petrakli, Natalia Sieti, Anestis Vlysidis, Elias Koumoulos*

IRES—Innovation in Research & Engineering Solutions, Rue Koningin Astritlaan 59B, 1780 Wemmel, Belgium

***Contact: epk@innovation-res.eu**

Abstract

Innovative materials developed and demonstrated through European research projects need to be assessed for their carbon footprint and climate mitigation potential compared to commercial alternative solutions. Life Cycle Assessment (LCA) is a standardised methodology (ISO 14040/44) to assess, evaluate and quantify potential environmental impacts of such innovative materials. When used in the early stages of a Research and Innovation (R&I) project, LCA can support the design phase by identifying environmental impacts and hotspots across the supply chain. Due to their enhanced functionality, Nano-enabled materials (NM) are the next generation of materials used in several everyday applications. However, little information exists on their environmental impact. Research efforts on potential impacts of released nanoparticles to climate change are still at its infant stage and commercial LCA databases lack NM data; valuable and reliable LCA results depend on the quality of underlying data.

To illustrate the above, this study performs a 'cradle-to-gate with end-of-life' LCA across the supply chain of 3D printed composite filaments with different NMs. Filaments consisting of three polymer matrices (PA, PP and PLA) in combination with different NMs (multiwall carbon nanotubes (MWCNTs), graphene oxide (GO) forms, graphene nanoplatelets(GNPs)) produced at lab scale, have been examined.

Waste treatment of nanocomposites are treated as plastic waste, as of today. Although EU Directives on plastic waste demands recycling of engineering materials, recycling of nanocomposites is limited. LCA enables to assess different End-of-Life treatment options, providing insights into designing for recycling towards circularity. In this context, further research on this issue is required and collaboration between LCA practitioners and the waste management community.

Results suggest that LCA studies are deemed necessary to develop knowledge on environmental impacts of nano-enabled materials and support decision making.

Keywords: Life Cycle Assessment; Sustainability; Innovative materials & processes; Nanomaterials

1. Introduction

Additive manufacturing (AM) is an attractive key technology for rapid prototyping in modern industry, offering on-demand manufacturing, flexibility and high-effectiveness for component fabrication (1). Last decades, 3D printing, also known as additive manufacturing, has evolved and covers a number of different technologies, while various industrial sectors, such as aerospace, military, automotive, medical, and construction industries taking apply it more and more (2), (3), (4). Thermoplastics are favored as 3D printed polymers due to their excellent mechanical properties, ease of processing and the possibility of recycling. Polylactic Acid (PLA), a sustainable biodegradable polymer, and Acrylonitrile butadiene styrene (ABS) are the two most widely used polymers in 3D printing fabrication. Other thermoplastics such as polyamides (PA), polypropylene (PP), polystyrene (PS) and polyester are also keen for AM feedstock and suitable to produce mechanical parts due to their advanced properties (durability, abrasion resistant). This family of polymers have the potential to be infused with conductive carbon-based nano-additives (Carbon Nano Tubes (CNTs), GO, GNPs, etc.) for the production of 3D printed multi-functional composites (5) (6) (7) (8) . Due to their unique properties, carbon -based nanomaterials (NMs) have been extensively used in novel applications. At the same time, increasing CO_2 levels in the atmosphere have generated widespread global concern regarding climate change (9).

In Europe, one of the top priorities of the Green Deal, and the new Action Plan for Circular Economy is circular and sustainable design of products. For this reason, LCA is an invaluable tool, as it can be used in the early stages of an R&I project, to support the design phase by identifying environmental hotspots across the supply chain, while ensuring desired properties and functionalities of composite materials. However, only few studies exist concerning their environmental impact (10). This challenge is widely addressed in Research & Innovation (R&I) projects through developing carbon based NMs for innovative functionalized nano-composite filaments for conductive composites products and using the LCA approach to assess their environmental sustainability and performance. Even though, thermoplastic manufacturing is an industrialized process, technologies for producing (carbon based)-nanomaterials are still incumbent. Recent studies have shown that various routes can lead to environmental emissions during the different stages of carbon nanomaterial production (11) (12) (13) (14) (15) (16).

In this context, LCA plays an important role in assessing potential impacts of these new technologies, thereby helping to guide research and innovation activities to achieve environmentally compatible, sustainable products that could follow the circular economy concepts (17).

Up to date, the 75% of the plastic waste in Europe is recycled (32% recycling & 43% energy recovery) and the 25% is landfilled (18). Therefore, recycling of nanocomposites is an issue to be considered when producing nano-enhanced products. The 3D printing filament market is projected to grow at a compound annual growth rate of 28,1% up to 2025[1], estimated at USD 739 million in 2020. The global growth rates of carbon nanotubes and graphene markets are projected to 10.7%[2] and 38.7%[3], respectively, up to 2027. In this context, large quantities of nano-enabled products will be produced and their avoidance from ending up in Municipal Solid Waste Incineration (MSWI) plants should be projected. Research studies that have investigated the presence of NMs in MSWI indicate that current regulations on waste incineration emissions do not adequately address nanomaterials (19) (20). LCA enables to assess End-of-Life treatment options but also identify trade-offs across the supply chain of a product, providing insights into designing for recycling towards circularity.

Thus, this LCA on 3D printable, nano-enhanced composite filaments could provide insights in regard to the potential environmental impacts on the life cycle environmental impacts of nano-enabled composite materials to support decision-making towards sustainable 3D printed objects (21). Novel nanocomposite materials need to be assessed for their carbon footprint and climate mitigation potential, at the early stage of their development.

2. Methodology

The study is carried out following the general framework and requirements provided in ISO 14040:2006 - *Environmental management – Life Cycle Assessment- Principles and framework* (22) and ISO 14044:2006 - *Environmental management – Life Cycle Assessment – Requirements and guidelines* (23).

2.1. Goal and scope

The goal of the present study is to perform LCA on functionalized nano-composite filaments and use the assessment results to support decision-making for sustainable, conductive filament production.

Three polymer compounds were chosen for assessment based on 3D printable filament production in the additive manufacturing system with smart functionalities (i.e. PLA, PA and PP). The functional unit (F.U.) considered is 1 kg of nano-enabled polymer filament.

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[1] https://www.marketsandmarkets.com/Market-Reports/3d-printing-filament-market-267169690.html
[2] https://www.alliedmarketresearch.com/carbon-nanotube-market
[3] https://www.grandviewresearch.com/industry-analysis/graphene-industry

The guiding principle for the choice of PLA, PA, PP as the polymer compounds was their prevalence in the AM sector being the most widely used polymers in 3D printing fabrication. This information was combined with the identification of the most-used NM fillers) as per available literature.

Based on literature, carbon-based nanomaterials as fillers in polymer matrices have attracted considerable interest due its unique extremely high electrical conductivity, environment stability, thermal conductivity, and good mechanical strength. These unique properties make nanofillers suitable for improving existing energy-related devices and paving ways for new generation of smart energy devices (24) (25; 26) . Much effort has been done in this direction as for instance Behzad Shirkavand Hadavand et al. (27) examined different weight percentages of pure and treated multi-walled carbon nanotubes (MWCNTs) (0.1–0.3 wt%) dispersed in the epoxy polysulfide resin. They have found that there is significant difference between acid treated and untreated MWCNTs in mechanical properties of epoxy polysulfide nanocomposites (27). In addition, M. Abdalla et al. investigated that 0.1 wt% - 0.3 wt% of amino-functionalized multi-walled carbon nanotubes dispersed in different resins. In all cases, epoxy with MWCNTs showed improved performance while the maximum improvement was obtained in 0.2 wt% MWCNT-COOH modified epoxy samples (28). A. Badran A Lsafee et al. also examined untreated MWCNTs with different weight percentage (0.1, 0.5, 1, 2, 3, 4 and 4.5) % wt. in order to develop MWNT/epoxy composite samples by hand lay-up method. The electrical conductivity of multiwalled carbon nanotubes (MWNT)/epoxy composites is investigated from 2x10-5 for pure epoxy to 1x10-2 for the concentration 4.5% wt. of MWCNTs (29).

Moisala et al. (30) studied the electrical and thermal conductivities of epoxy composites containing 0.005–0.5 wt% of single-walled (SWNTs) or multi-walled (MWNTs) carbon nanotubes. They found that the electrical percolation threshold of the MWNT composites was <0.005 wt%, while the thermal conductivity of the same samples increased as a function of the filler material. The electrical percolation thresholds were higher (0.05–0.23 wt%) in the SWNT composites, but the thermal conductivity was lower than that of the pristine epoxy.

Although less literature has been identified for Reduced graphene Oxides (rGOs), those were used as thermally conductive fillers by Yun Seon Lee et al. (31) for the preparation of the heat-dissipation polymer composites. Concentrations of 1, 2 and 3 wt% of rGO were investigated.

Finally in the case of Graphene Nanoparticles (GNPs) reinforced composites Mohammad Rahat Rahman et al. (32) investigated different conditions for the nanocomposites with 0.1 wt% loading of the fillers. Results shown that GNPs reinforced composites did not present the percolation threshold even with 5 wt% (with the ratio to the weight of epoxy) loading of the GNPs.

To summarize, in the present study, the incorporation of carbon-based nanomaterial (CNTs, rGO and/or GNPs) as nanofillers into different polymeric matrices: Polylactic Acid (PLA), Polyamide (PA) and Polypropylene (PP), suitable for AM processing technologies, are investigated from an environmental point of view using LCA. Hence, this paper aims to fill a knowledge gap by quantifying the potential environmental impacts of carbon-based nanoparticles (CNTs, rGO and GNPs) dispersed in thermoplastic matrices (PLA, PP and PA) and report some open challenges that need to be collectively addressed to facilitate sustainable nano-enabled products in line with the European Green Deal in a circular economy.

The formulation of the conductive nano-enabled polymer filament with a steady nanomaterial dispersion 3% wt in the polymer matrices, has been examined based on the frequency of repetition of such value across the identified literature stated in the Introduction section.

Table 1 Different loadings (ranges) of C based NMs reported in literature

rGO (w%)	GNPs (w%)	CNTs (w%)
0.09 (33)	0.1 (32) (34)	0.1 (35)
0.13 (36)	0.13 (36)	0.3 (28) (27)
0.2 (37)	0.3 (38) (39) (34)	0.5 (35) (29)
0.3 (39)	0.5 (39)	1.0 (29) (35) (28)
0.25 (38) (39) (34)	1.0 (36)	2.0 (35) (29)
0.5 (39)	2.14 (29)	**3.0** (35) (29)

1.0 (31)	**3.0** (40)	4.0 (29)
1.5 (41)	5.0 (32)	4.5 (29)
2.0 (31)	6.0 (36) (42)	
3.0 (31)	21.0 (28)	

As a result of this analysis, the nano-enabled polymer filaments mentioned in Table 2 are assessed in the LCA.

Table 2 Investigated products per functional unit

Product name (Filler 3%)	NM technology, scale	End-of-life (shares%)
PLA -GNP	Expanded, exfoliated graphite pulverized, lab scale	Incineration (100%)
PLA -GO	Hummer's method, mild bath sonication, lab scale	
PLA -CNT	Fluidized bed CVD, lab scale, (N_2 /20 bead cycles)	
PA -GNP	Expanded, exfoliated graphite pulverized, lab scale	Incineration (35%) Landfill (10%) Recycling (55%)
PA -GO	Hummer's method, mild bath sonication, lab scale	
PA -CNT	Fluidized bed CVD, lab scale, (N_2 carrier gas/20 bead cycles)	
PP -GNP	Expanded, exfoliated graphite pulverized, lab scale	Incineration (35%) Landfill (10%) Recycling (55%)
PP -GO	Hummer's method, mild bath sonication, lab scale	
PP -CNT	Fluidized bed CVD, lab scale, (N_2 carrier gas/20 bead cycles)	

This study performs a 'cradle-to-gate with end-of-life' LCA across the supply chain of 3D printed composite filaments with Nano Materials such as CNTs, rGO and GNPs. The system boundaries encompass the production of raw materials (NMs and thermoplastic polymers), the extrusion process for the composite filament manufacturing, and end-of-life (EoL) management, excluding the use phase.

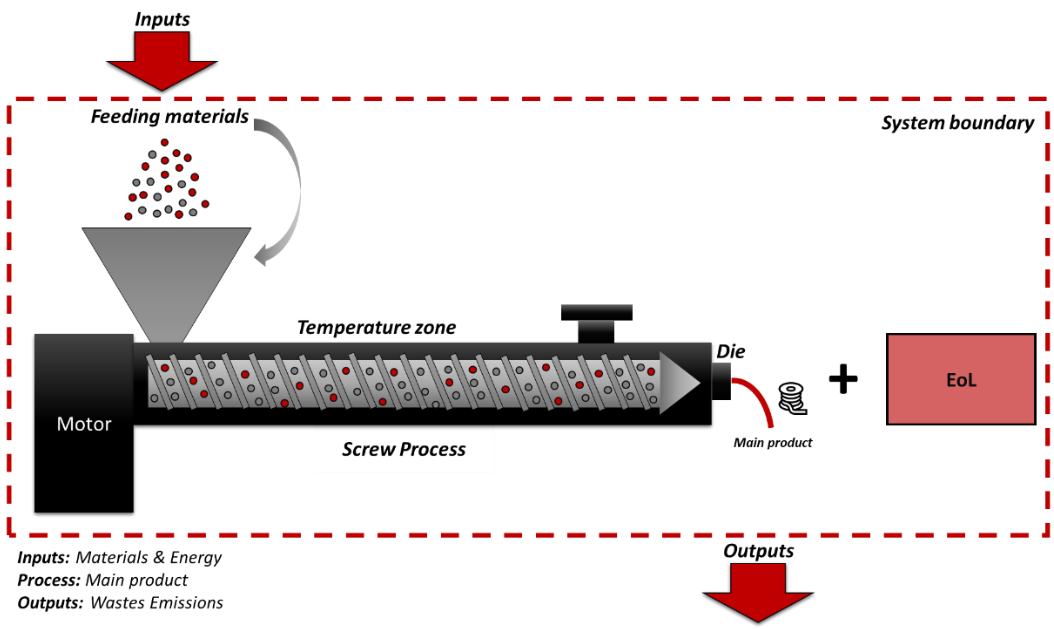

Figure 1 System boundaries of the examined LCA study

2.2. Inventory Data

Data were mainly collected through open access literature. Background life cycle inventory data were sourced from ecoinvet v3.6 (43) where available and supplemented by data from literature as detailed below. Background data were adjusted for EU conditions with respect to electricity mix.
The production of PLA, PP and PA is an industrialized process and data is available on commercial material databases. In this study, data are sourced from ecoinvent 3.6 as PLA, PA and PP granulates. For PA, nylon 6-6 was selected as a proxy from ecoinvet v3.6. The production of these polymers is considered not to change in the following decade and therefore, background system is modeled at status-quo condition.

2.2.1. Production of Nanomaterials

Because from a product life cycle perspective, CNT production technologies can vary in terms of its impact, to complement this LCA study, the selection methodology of 'high quality' CNT (excluding MWCNTs) synthesis data inventory is described.
Teah et al. (16) investigated the life cycle Greenhouse Gas (GHG) emissions of produced CNTs via three lab-scale CVD synthesis methods. The GHG emissions of CNT production were quantified using LCA methodology and hotspots were identified towards technological improvements. Findings show that configurations that include selection of oxidative additives (CO_2 or H_2O), growth modes in reactors (2D flat-plate or 3D spherical), catalyst deposition methods (sputtering or CVD), and purging gases (Ar or N_2) significantly change the impacts. Also, on-substrate CVD method has high environmental impact therefore is more suitable for ensemble use in planar devices, whereas the fluidized-bed CVD methods are more applicable for bulk use.
Healy et al. (44) investigated an unspecified catalytic CVD method concluding that continuous processes, such as fluidized bed chemical vapor deposition (CVD), seem to be the most promising methods for industrial levels of bulk production of nanotubes. Expecting technology advancements, the authors identified high GWP impact for a predicted yield at lab-scale, can be reduced to a similar case for on-substrate CVD (16)
Gavankar et al. (45) and Kushnir and Sanden (46) are not considered here as the prior provides no inventory data, while the latter assesses Cumulative Energy Demand (CED) for an alternative technology.
Summarizing, although LCAs of CNTs are scarce, it should be noted that (16) provide the most inclusive information in both reviewing prior literature but also providing inventory data and assessing the life cycle GHG emissions of

single-wall CNTs (SWCNTs) for the most common synthesis methods (Pure Carbon Nanotubes Synthesized via On-Substrate and Fluidized-Bed Chemical Vapor Deposition). As a result, a step-based methodology was developed for selecting representative inventory data based on desired characteristics (**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**).

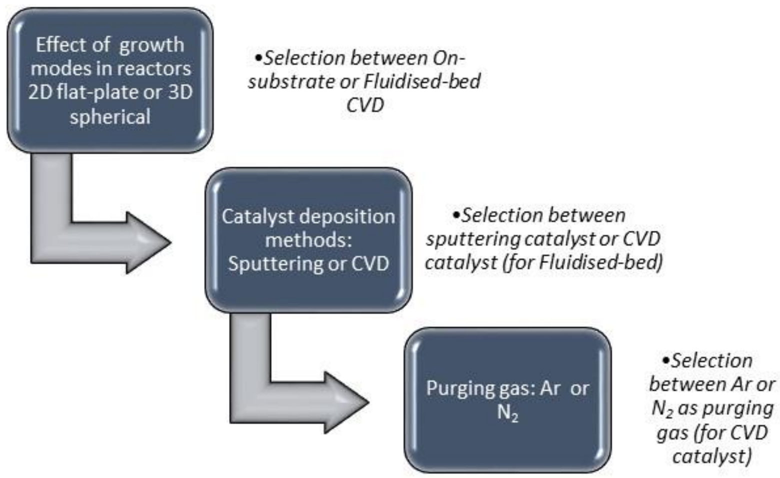

Figure 2 Reduced Global Warming Potential (GWP) for three main configurations of CNT (adapted by (16)

As seen in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.** and described by (16) given the high environmental impact of on-substrate CVD method, it is more suitable for small scale applications, while the fluidized-bed CVD methods are more applicable for bulk use. It should be noted that Japan data were used for electricity generation, while Ecoinvent v3.4 data were used for the background system.

More information on the Life Cycle Inventory data is provided based on the above step-based process, with the main selection criterion being the fact that CVD-based methods are considered the most commercially viable option due to cost, simplicity of operation, ease of scalability, hence is considered the most representative technology (47).

Due to the significant variation in environmental impacts depending on selected production technology combined with the limited and not updated present literature on environmental evaluation of CNTs, in this study, chemical vapor deposition (CVD) is selected as the most promising way to produce carbon nanotubes. This selection was combined with the best-case scenario adapted from (16) for the CNTs (on a lab scale), and the choice of N_2 as a carrier gas and 20 times of substrates cycle.

Graphene is still an emerging carbon-based nanomaterial and there is limited information on the potential environmental impacts of its production routes. The most patented processes are: exfoliation (39%), chemical vapour deposition (38%), and epitaxial growth (7%) (48). Arvidsson's (13) review on environmental life cycle assessment studies of graphene production focused on five different routes: chemical reduction of graphite oxide, ultrasonication exfoliation, thermal exfoliation, CVD and epitaxial growth. As the functional unit is not identical in the reviewed studies, direct comparison between the results is rather difficult. Cossuta et al. (15) performed a comparative LCA of three graphene production routes: electrochemical exfoliation, chemical oxidation (with subsequent chemical or thermal reduction) and chemical vapour deposition (CVD). The cradle-to-gate LCA study indicated that the chemical oxidation process followed by thermal reduction is the least impacting route to produce large quantities of reduced graphene oxide. Complementary to this study, prospective LCA was conducted to estimate the impacts on hypothetical commercial scale, with results indicating that the least impacting scenario remains the chemical oxidation with thermal reduction route.

Serrano-Lujan et al. (12) studied the environmental impacts of Hummers and Marcano methods, as these are considered two of the most successful approaches for producing high-performance rGO. In total, seven production routes for reduced graphene oxide were assessed. Two functional units were proposed in the study: 1 kg of reduced graphene oxide to allow comparison and an application-specific functional unit normalized by conductivity.

Hummer's production method showed lower cumulative energy demand per kg of graphene production. Impacts ranked by the application-specific unit showed that Hummers' method is better suitable for bulk applications of graphene, while Marcano's method would be better for thin film electronic applications.

Pizza et al. (11) studied the life cycle assessment of high-quality nanocomposites made of thermally conductive graphite nanoplatelets (GNPs), excluding the nano-waste generated and the nanoparticles emissions. The study focused mainly on the energy requirements for the nanocomposite manufacturing and the primary energy for the GNPs production. Results indicated the energy-intensive production process of GnP filler (1,879 MJ/kg), while the manufacturing of 1kg of epoxy composite with 5.8 wt% of filler assuring a thermal conductivity of 1 W/mK and a lifetime of 30 years requires 303 MJ. The life cycle inventory of GnPs included the mechanism from the graphite separation into intercalated graphite flakes to microwave expansion and pulverization by ball milling until the production of graphite flakes platelets with high aspect ratio.

In this study, LCI data derived from (12) for Graphene oxide (GO) production, complementing the LCI with a personal communication and Pizza (11) for Graphene Nanoplatelet production (GNP).

2.2.2. Manufacture of the composite filament

The resources used in the manufacturing process considering extrusion, were from Ecoinvent v3.6 for plastic film extrusion modified to include only steps for screw extrusion.

2.2.3. End-of-life management

At the EoL stage, the study considers that most products are not biodegradable but can be treated via disposal to landfill, incineration, or recycling processes. Due to different rates of EoL management across Europe and throughout the years, EoL pathways for 2030 based on the European strategy for plastics (49) in a circular economy in 2030 are considered based on Maga et al. (50). Specifically, the EU strategy for Packaging and Packaging Waste (51), demands that by the year 2030, the recycling rate of plastics in packaging is 55%, while according to the Circular Economy Package, landfilling is reduced to 10% maximum. Consequently, the remaining 35% max, will be covered by incineration.

Based on the above, the EoL management pathways considered in the study are summarized in Table 3.

Table 3 EoL management pathways considered in the study

EoL pathway	**PP (%)**	**PA (%)**	**PLA (%)**
Share to incineration	35	35	100
Share to landfill	10	10	0
Share to recycling	55	55	0

2.3. Alternative EoL treatment scenarios

Further studies by Boldrin et al., (52) and Hansen et al., (53), on predicted disposal paths for waste containing NMs present in municipal waste indicate that the majority will end up in recycling (>50%), while incineration and landfill tends to range between 13-38% and 8-29%, respectively. Previous studies estimated that most of the waste contaminated with NMs would be landfilled (60-91%) or found in sludge (19-52%) (54), (55).

Due to inherent variations regarding EoL treatment pathways, three alternative scenarios are assessed for the worst-case filament towards climate change mitigation, incl.:

- 100% recycling
- 100% landfill
- 100% incineration

2.4. Life Cycle Impact Assessment

For calculating the environmental impacts, the International Life Cycle Data (ILCD) method (56) was used as it is recommended by the Joint Research Centre (JRC) of the European Commission. However, only global warming potential (GWP) is presented in this study, based on the Intergovernmental Panel on Climate Change's (IPCC) 2007 report for a 100-year period.

3. Results

Results suggest that LCA studies are deemed necessary to develop knowledge on environmental impacts of nano-enabled materials and support decision making.

3.1. Environmental impacts of products

The environmental impacts of the nine products are detailed in Figure 3 for the greenhouse gas (GHG) emissions excluding biogenic carbon impact category considered. Overall, the fillers are found to increase the total impacts of the product, while the polymers have a much lower relative contribution. This applies significantly for CNT and GO, whereas the picture changes, with the polymer contributing considerably when considering GNPs. All impacts are expressed per functional unit of 1kg of nano-enabled polymer filament.

More specifically, the filament with the highest impact is PA-GO with 13.21 kg CO_2 eq. (Figure 3). All GO-based filaments perform worse than the CNT-based alternatives for Global Warming Potential (GWP), while GNP-based filaments are the most climate-friendly. The rest results range from 2.32 kg CO_2 eq. (PP-GNP) to 11.82 kg CO_2 eq. (PA-CNT). In terms of contribution analysis, for GWP, the main contributor comes from the filler, except in the case of PA.

In the case of polymers, when the scope is 'from cradle to gate', PLA performs best at 1.07 kg CO_2 eq./kg PLA, followed by 2.11 kg CO_2 eq./kg PP and lastly 8.36 kg CO_2 eq./kg PA. That is due to because of carbon capture from the atmosphere, PLA being derived from renewable resources contrary to other petroleum-based thermoplastics. However, when considering the EoL of the polymers, on a 'cradle to grave' approach for 1 kg of polymer, PP performs best with 1.87 kg CO_2 eq./kg PP, followed with PLA at 2.34 kg CO_2 eq./kg PLA while PA performs worse for GWP at 4.68 kg CO_2 eq./kg PA. For the case of PLA, the biogenic carbon balances out since the amount of CO_2 incorporated in PLA is released to the atmosphere by thermal treatment during the EoL stage.

For the fillers, impacts considering a 'cradle to gate' approach rank the NMs as GNP (17.2 kg CO_2 eq./kg GNP) <CNT (246 kg CO_2 eq./kg CNT) <GO (293 kg CO_2 eq./kg GO).

As also seen in Figure 3, the EoL stage contributes significantly in the case of PA where the negative value means the polymer materials being recycled avoid the release of potential GHG emissions.

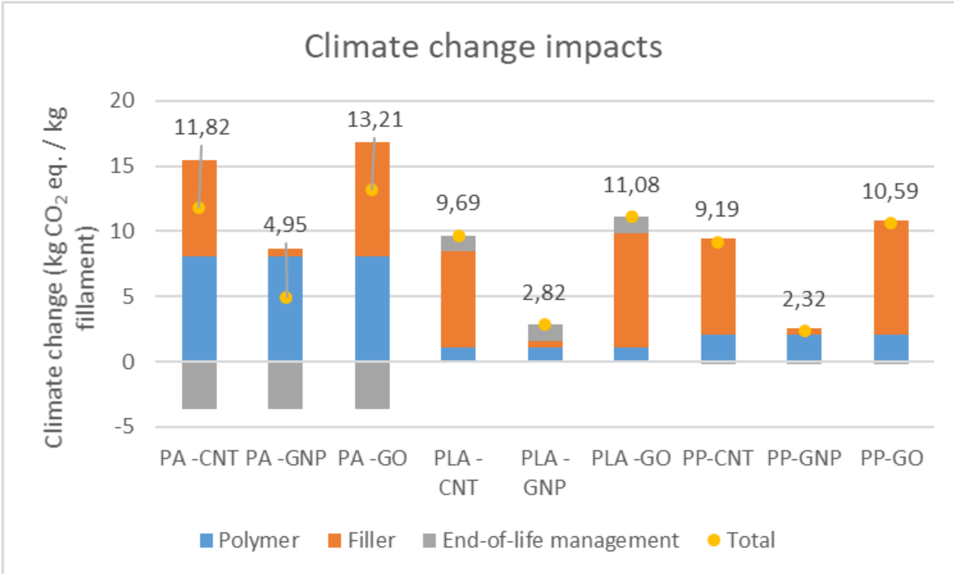

Figure 3 Contribution to Global Warming Potential (GWP) impacts of the filaments considered in the study

3.2. Environmental impacts of alternative EoL treatment scenarios

As seen in Figure 3, the filament with the highest impact is PA-GO with 13.21 kg CO_2 eq. However, as EoL management pathways considered in the study yield environmental benefits and are based on future estimates, we now compare EoL options for the worst performing filament.

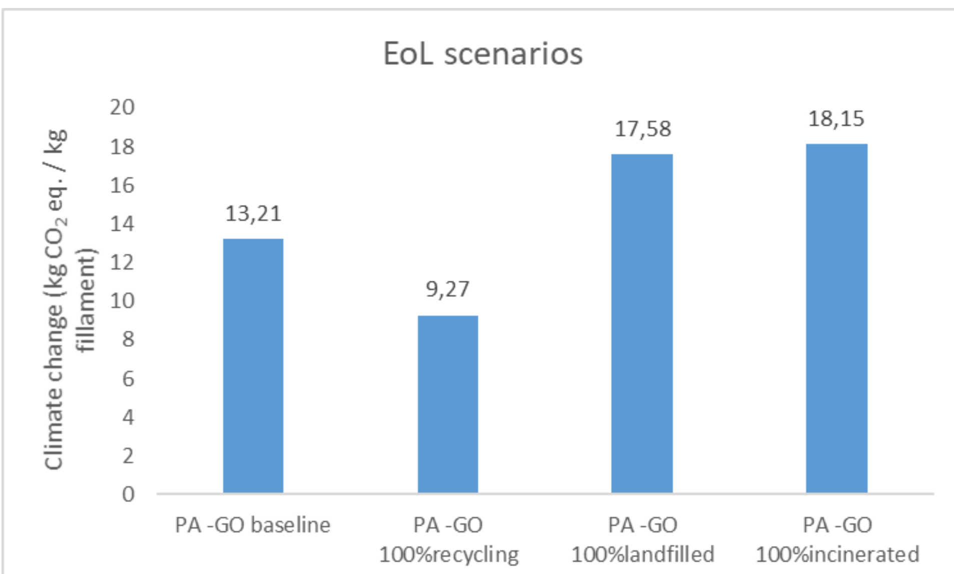

Figure 4 EoL scenarios for the worst performing filament in terms of GWP impacts

Therefore, the PA-GO filament baseline shows a reduction of 30% for the 100% recycling option and an increase of 33-37% for landfill and incineration respectively (Figure 4). The absolute ‘cradle to grave’ values per kg of PA-GO filament are displayed in Figure 4 ranging from PA-GO 100% recycling (9.27 kg CO_2 eq./ kg PA-GO filament) < PA-GO baseline (13.21 kg CO_2 eq./ kg PA-GO filament) < PA-GO 100% landfilled (17.58 kg CO_2 eq./ kg PA-GO filament) < PA-GO 100% incinerated (18.15 kg CO_2 eq./ kg PA-GO filament).

As nano-enabled products are not specific-labelled, sorting and separation of the waste streams containing NMs remains a challenge for sustainable waste management. Hence, according to Musee (57) new forms of challenges to the “nano-waste or nano-pollution” management pathway from nanotechnologies might mean the current waste paradigm is either inadequate or inappropriate. Few studies on the incineration of waste containing CNTs indicate that if temperatures are kept constantly high at the incinerator, CNTs are most likely to be destroyed. If not, CNTs will end up in bottom ash (58). This means that nano-waste or “nano-pollution” mean: (1) manufactured by-products containing single NMs, (2) end-of-life (EOL) forms of nano-products, and (3) individual waste materials contaminated with produced NMs (52).

Bouillard et al. (59) on their study investigating incineration of CNT containing polymers (acrylonitrile butadiene styrene with a 3 wt.% content of MWCNTs), showed that at upstart of the incineration process where low temperatures (450 ºC), are achieved, CNTs are released. This result points to the importance of running solid waste incinerators continuously in order to reach high temperatures and destroy the CNTs.

Additive manufacturing has a significant role in improving resource efficiency as the nature of the process means that less material waste is created. However, as it is growing with a rapid pace, the waste community must anticipate recycling and EoL management opportunities and collaborate with LCA practitioners towards zero waste and circularity.

4. Conclusions and recommendations

This study considered the life cycle climate change impacts that arise from producing and disposing nano-enabled 3D filaments, considering nine different filaments encompassing three alternative polymers, three nanomaterials and their combinations. This study has been carried out to provide a basis for the LCA, Additive Manufacturing and waste community to build on this area.

The results showed that, filaments analyzed for GWP, range from 2.32 kg CO_2 eq. (PP-GNP) to 13.21 kg CO_2 eq. (PA-GO). The key hotspots across filaments were GO or CNTs fillers, while in the case of PA as polymer – nylon is energy-intensive, which causes emission of greenhouse gases leading to global warming production (more than other plastic-based fibres).

As PA bring a significant climate change impact, the EoL treatment pathway plays a significant role in reducing climate change across its life cycle. When alternative EoL treatment scenarios are analyzed for the worst-performing filament (PA-GO) an approximate ± 30% variation occurs based on treatment pathway. Recycling performs as the best option amongst the scenarios in this case.

Authors have discussed and interpreted the results in relation to the research questions and it is found that following this case study LCA proves as a useful decision tool to assess potential environmental impacts across the supply chain of novel materials.

Literature identified provide data on NM however data significant variations in terms of environmental impacts are observed (CNT ranges in literature and for GO inventories are limited and uncertain). This shortcoming highlights the necessity to work towards LCI database for nanomaterials and best available techniques for NM production. Further studies must be headed towards that direction.

Additionally, given that the additive manufacturing sector is targeting efficiency reaching zero-waste is of imminence. However, as the study highlights, when taking into consideration three alternative EoL scenarios no reduction is observed in absolute impacts except the case of recycling. It must be borne in mind here that LCA does not take into consideration potential nanoparticle emissions at EoL during either recycling, incineration, or disposal pathways, hence design should touch upon broader environmental and societal issues.

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