Review of LCA Studies on Plastics

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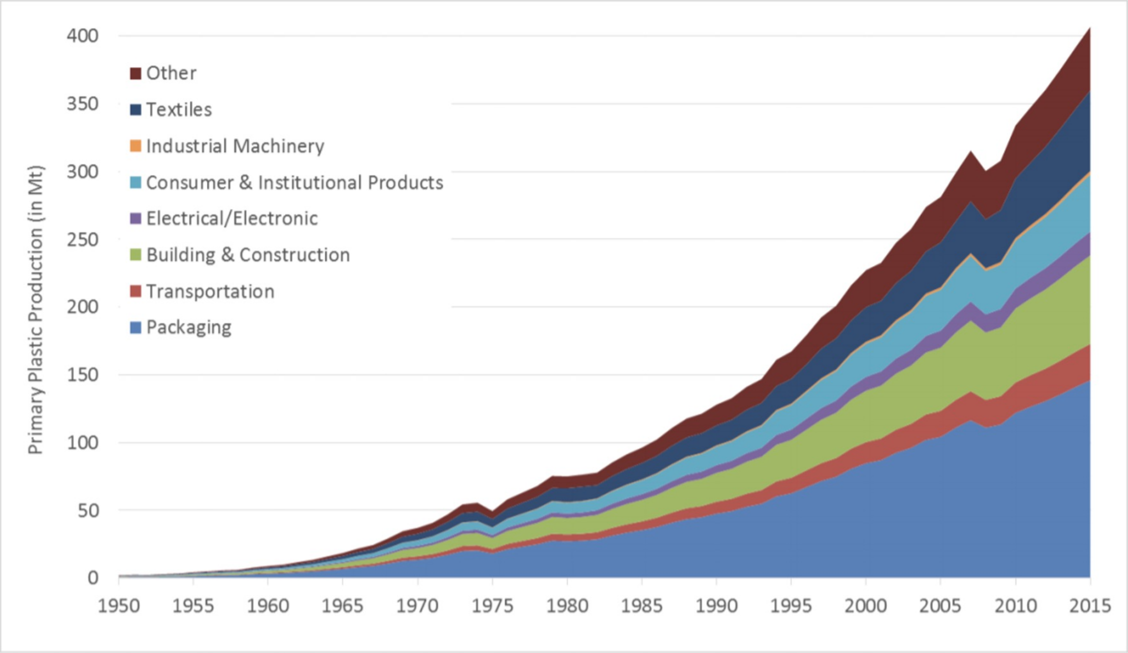
1. Introduction

Background

Plastic serves as a key material in our daily lives throughout the economy due to their durability, versatility, and low cost.

However the production, consumption, and end life management of plastics raised environmental concerns



Global primary plastics production (million metric tons)

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Objectives

1. Review existing research and activities related to LCA in plastic material and plastic-based products
2. Identify the challenges and gaps in current studies, standards, tools, and other resources
3. Discuss the current research gaps that are being filled by ongoing initiatives and those yet to be addressed

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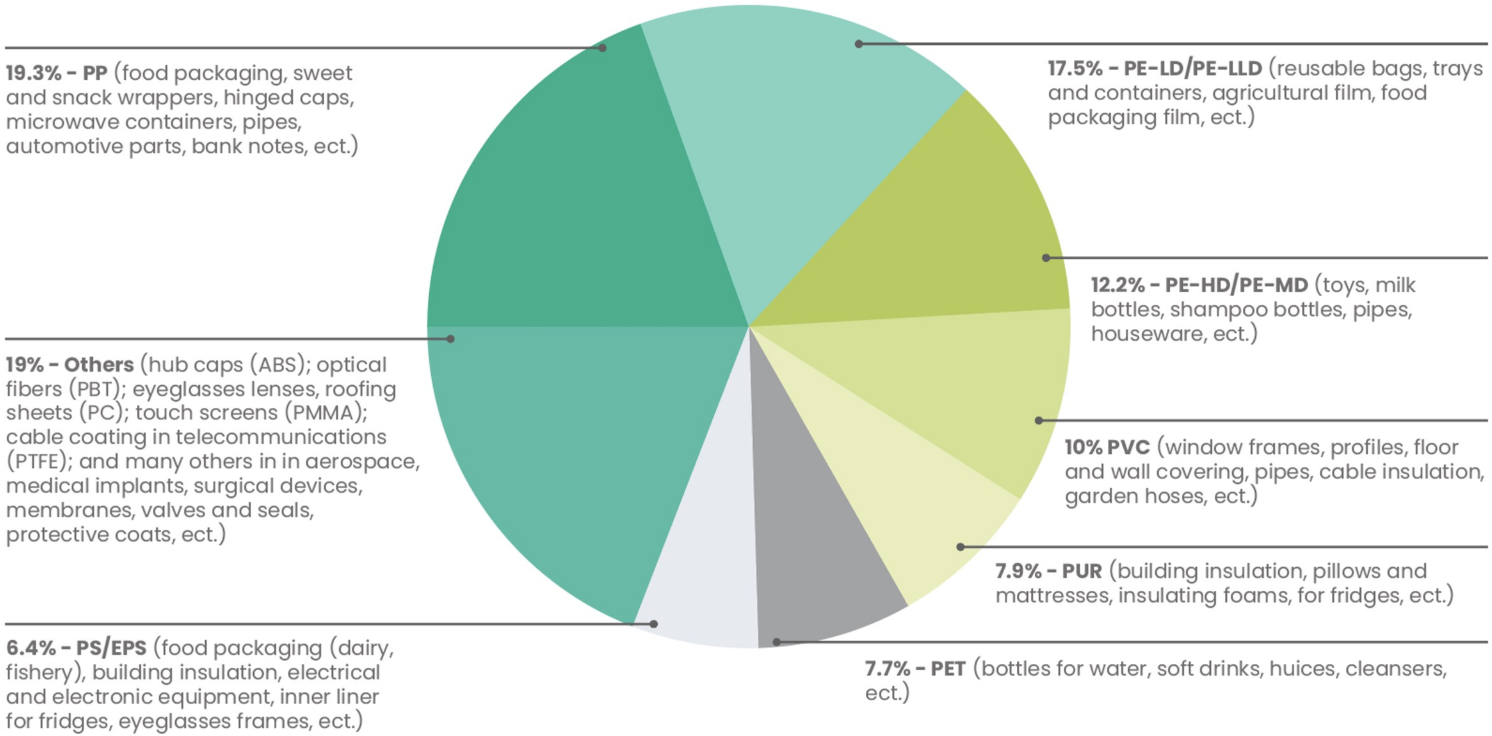
Distribution of plastics demands by resin types



Overview of terms

Terms	Description
Polymer	A large molecule composed of monomers typically connected by covalent bonds.
Plastic	A colloquial term for wide range of synthetic or semi-synthetic polymers.[1]
Bioplastic	While exact definitions vary, it generally refers to both biodegradable plastics and bio-based plastics.[19]
Compostable plastic	Plastic that is capable of biodegrading at elevated temperatures in soil under specified conditions and time scales, usually only encountered in an industrial composter (standards apply).
Degradable plastic	Plastic that is capable of a partial or complete breakdown as a result of e.g., UV radiation, oxygen attack, biological attack, which implies an alteration of the properties, such as discoloration, surface cracking, and fragmentation.[19]
Microplastic	The generic term for small pieces of plastic the longest dimension of which is under 5 mm.[20]
Bio-based plastic	A type of plastic derived from biomass such as organic waste material or crops grown specifically for the purpose, which may or may not be biodegradable.[19] It applies to both naturally occurring polymers and natural substances that have been polymerized into high molecular weight materials.
Biodegradable plastic	Plastic that is capable of biodegrading under biological process of organic matter, which is completely or partially converted to water, CO_2/methane, energy, and new biomass by microorganisms (bacteria and fungi).[19]
Fiber reinforced plastic	Composite material made of a resin matrix reinforced with fibers to enhance the mechanical properties [21]

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*Not all bio-based polymers are biodegradable. The non-biodegradable plastics produced by renewable resources are still considered “carbon-neutral”.

2. Review of Plastics LCAs

Relevant LCA databases

Source of Data	Description
US LCI database	National Renewable Energy Laboratory (NREL) created the US Life Cycle Inventory Database to provide gate-to-gate, cradle-to-gate, and cradle-to-grave accounting for plastic environmental impacts
Ecoinvent	Life cycle inventory database encompassing around 18,000 processes including energy supply, agriculture, transport, chemicals, construction, and waste treatment.
Plastics Europe	Association of plastic manufacturers in the European plastic industry.
Gabi Plastics Extension Database	Gabi provides life-cycle inventory data on mass plastics (e.g. PE with various densities, PP, PS), vinyl polymers (e.g. PVC, PVAL), technical plastics (e.g. ABS, PMMA, PTFE), polyamide (e.g. PA 6, PA 6.6, PA 6.12), special plastics (e.g. PPS, PEEK, SMA)
USEEIO database	The Environmental Protection Agency (EPA) provides an LCA database on US products and services. This database includes datasets for multiple plastic products (e.g. plastic bottles).
Comprehensive Environmental Data Archive (CEDA)	CEDA is an extensively peer-reviewed suite of environmentally extended input-output databases first launched in 2000. These are designed to assist various environmental systems analyses including life cycle assessments (LCA), carbon, energy, water, waste, and toxic impact assessment throughout the supply chain.
CarbonMinds	CarbonMinds has developed a CM.CHEMICAL database from a regionalized model of the global chemical industry, built from plant-level. The database provides life cycle inventory datasets for national averages of consumption, production and per technology.
The GREET Model	The GREET model is developed by the Argonne National Laboratory to address the life-cycle emissions of various fuel-vehicle combinations. Since plastic is widely used in automobile manufacturing, this model includes LCA data for plastic resins and products.

Relevant LCA databases

- These databases provide LCIs of several hundred plastic materials
- Temporal and spatial system boundaries vary
- The level of aggregation / resolution also varies
- Overall, Europe is better represented
- Limited coverages in additives and bio-based plastics.

Packaging

- Largest portion of primary non-fiber plastic production (**42% in 2015**)
- Short product life-time: mostly less than 1 year
- **Common uses:** bags, bottles, take-away food containers
- **Materials:** HDPE, PET,PP, PS, PLA, PE, cotton, paper
- **Important factors on environmental impact:** Use pattern, weight, geographical context and waste management practices

Packaging

- Impact category is important the assessment
  - PLA vs.PET bottles
  - PLA bottles have lower global warming potential, fossil energy use, and human toxicity
  - PET bottles have lower impact in acidification and eutrophication categories

Agriculture

- **Common uses:** Greenhouses, mulching, irrigation systems, crop transportation
- Mulch film makes up 41% of agricultural plastic use
  - Mechanic recycling is challenging due to contamination with soil, stones and biological waste
  - Biodegradable film 25-80% less impact depending on the impact categories and the end-of-life scenario compared to nonbiodegradable PE film

Building and Construction

Replacement materials for concrete: Fiber reinforced plastics (FRP), Polypropylene (PP) fiber

- Compared to traditional steel reinforcing mesh (SRM), recycled PP fiber consumed 99% and 91% less water and fossil fuel, respectively. Moreover, it produced 93% less CO_2 equivalent and 97% less PO_4 equivalent.

Replacement for copper: polyethylene (PEX)

- Cross-linked polyethylene (PEX) may be used for plumbing as a replacement for copper, and it consumes 42% less CO_2 equivalent, and contains 47% less embodied energy

Building and Construction

Replacement for flowing and sewer pipes: Polyvinyl chloride (PVC)

- Life-cycle energy consumption and GHG emissions from PVC are lower than similar materials, but there is also a higher rates of exposure to health hazards such as toxic mold growth, and heavy metals.

Insulation material: Extruded polystyrene (XPS)

- 57% CO_2 equivalent more than fiberglass, and 2.8 times the CO_2 equivalent of corkboard. Moreover, it produced 50% and 29% more SO_2 equivalent than fiberglass and corkboard, respectively.

Automotive

Plastics are widely used in automotive sector, because plastics have:

- Light weight
- Greater design flexibility
- Cost-effective

Reinforcements are often used to enhance material property

- Typical filler or reinforcement materials include talc, clay, natural fiber, carbon fiber, and glass fiber.
- Different reinforcement materials have different environmental impacts
    - Cotton reinforced PP has the worse environmental performance due to its cultivation process with significant environmental impacts

Consumer goods

- **Common uses:** Toothbrushes, wipes, nappies, feminine products, and other personal care products
- Johnson & Johnson toothbrush case study:
  - Pre-consumption plastic waste in toothbrushes
  - Lower environmental impacts and the production cost
- Drivers of environmental impact for single-use and reusable nappies and feminine products
  - Single-use products: Production phase
  - Reusable products: Use phase
- Cultural context affects the adoption of alternative materials and user behavior

Electronics

- Additives in the composition make it difficult to recycle and reuse
  - Low recycling efficiency
- **Printer panels:** Additives are the biggest contributors to cradle-to-gate GHG emissions of a printer's GHG emissions (up to 40%)
- **Laptops** : The recycled content of the product should be above a certain percentage depending on the metal, replacing the primary metal production for metals to be a better option than plastics

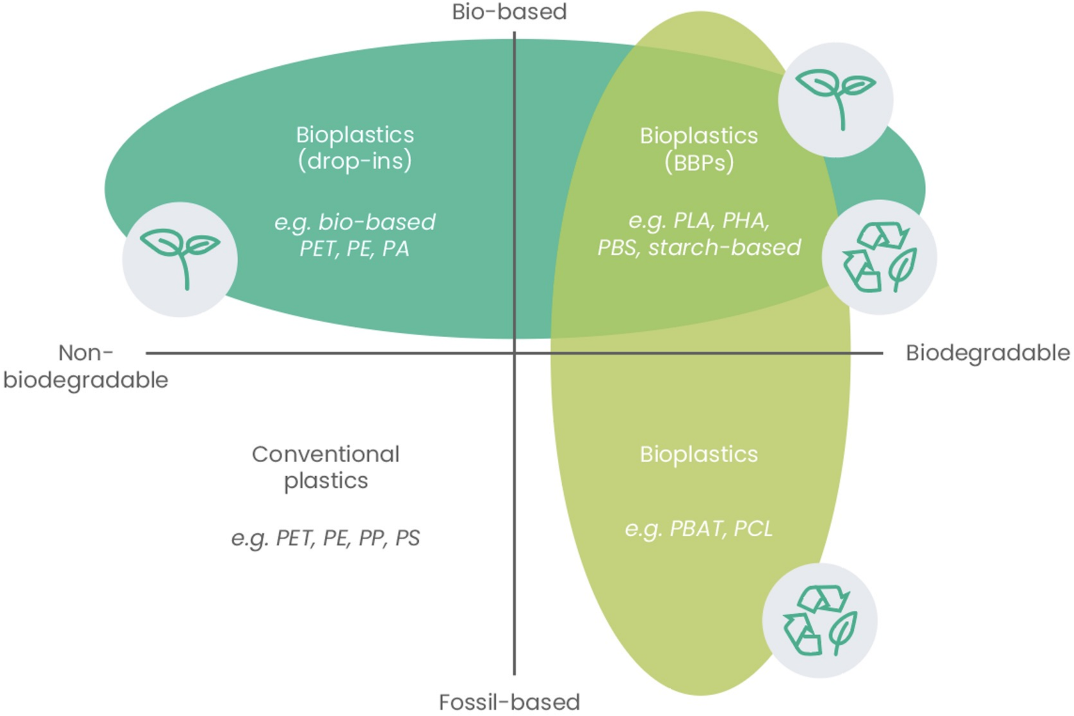
Additives

- Additives can be categorized into functional additives, colorants, reinforcements, and fillers.
- Few LCA studies have incorporated additives, especially functional additives, into their scope.
- Including additives into plastic LCA studies are challenging since:
  - There are a large number of potential substances;
  - Some additives will alter the characteristics of the product, which requires more data for a comprehensive analysis;
  - The impact of plastic additives also depends on the end of life (EOL) treatment for the product, which is also a blindspot in plastic LCA.

Material origin and biodegradability properties

Bioplastics is divided into three main groups:

1. Bio-based or partly bio-based, non-biodegradable plastics, such as bio-based PE, PP, or PET, and bio-based technical performance polymers such as PTT or TPC-ET;
1. Plastics that are both bio-based and biodegradable, such as PLA and PHA or PBS;
1. Plastics that are based on fossil resources and are biodegradable, such as PBAT.



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Concerns of bioplastics

Using bioplastics may reduce climate impacts but may result in other environmental tradeoffs:

- Use of fossil-derived pesticides and fertilizers in large-scale agricultural products
- Feedstock of energy- and chemical-intensive crops
- Environmental impacts of land use change
- Ecosystem services damage due to excessive harvesting

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3. Challenges and Gaps in Plastics LCAs

Challenges

1. Lack of reliable, high-quality regional data on plastics
   - Asia has emerged as an important contributor to global plastic production yet no much LCI data is available..
   - Region-specific emission factors are needed to accurately represent the background energy mix scenarios and end-of-life treatment options.
2. Lack the assessment of impacts from microplastics
   - Health impacts of microplastics are still not well understood
3. Not all additives are well-studied using an LCA approach.
   - Some additives will alter the characteristics of the product (e.g. prolonged lifetime, reduced fire risk), and such characteristics need to be embedded in the cradle-to-grave LCA for accurate results.

Challenges

4. No publicly available tool with which manufacturers and researchers can assemble reliable LCIs of plastics.

5. Challenging to model of plastics' end-of-life treatment
   - Waste collection rate, type and severity of contamination, and accessible recycling technologies vary widely across geographies and times.

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4. Conclusions and Recommendations

Conclusions

1. The environmental impact of plastics is receiving lots of public's attention.
2. LCA is well suited to evaluate plastics' life-cycle environmental impacts, while further development in data and impact assessment is needed to address the public's concerns on plastics.
    - For example, the impact of plastics on marine and terrestrial ecosystems have been neither fully understood nor incorporated into LCIA.
    - The fate, transport, and exposure of plastics in the environment including their degradation pathways are not fully understood.

Conclusions

3. Many LCAs have been conducted on LCA, but due to the differences in system boundaries, completeness of the study, assumptions made, and base years used, etc. the results are not directly comparable.
4. While plastics are produced globally, where Asia has emerged as the main production outlet, existing LCIs focus on Europe.
5. LCI data on additives are scarce.
6. As a result, representative LCAs for widely used plastics are scarce.

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Recommendations

1. Harmonized and transparent LCA data that represent other continents than Europe is needed.
2. A protocol or standard to build representative LCAs of plastics needs to be developed.
3. We recommend incorporating LCA research into on-going and relevant research at NIST
   - The prediction of service life of plastics with the consideration of additives
   - Standardization and the method of identifying additives used in plastics

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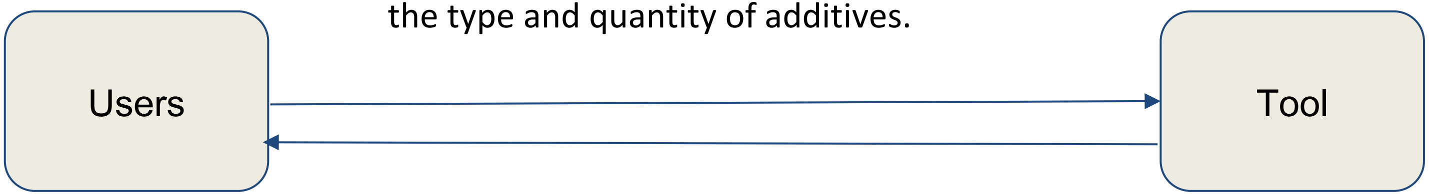
Recommendations

4. Develop reference LCIs for major plastic materials, additives, and prevailing processes to enable rapid and reliable LCA of plastics
5. Develop a life-cycle screening tool focusing on plastics life-cycle.

Life-cycle screening tool

Users enter information of: polymer type, country of production, energy mix, feedstock mix, EOL scenarios, and the type and quantity of additives.



The tool provide results of: greenhouse gas emissions, human health impacts, and ecological toxicity of plastics.

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