ECONOMIC AND ENVIRONMENTAL IMPACTS OF POLY(3-HYDROXYPROPIONATE)

Posmik, Daniel Christian; Heiges, Jessica; Shyong, Jocelyn

Abstract

Despite the low cost and convenience of single-use, non-biodegradable plastic packaging, these polymers negatively impact the environment and aquatic health. Novomer poly(3-hydroxypropionate (P(3HP)) is a biodegradable polymer that reduces environmental and aquatic health impacts while exhibiting attractive properties at a relatively low cost. With the goal of assessing end-of-life efficiency, data was collected to estimate the monetary drawbacks of the current plastic industry. Cost and performance data were assessed comparatively, and the cost of waste management was briefly examined. Currency is adjusted for inflation and given in 2020-$. A Life Cycle Assessment (LCA) was performed according to the ISO 14040 framework using SimaPro 9.0. A more holistic understanding of the entire life cycle cost of single use plastic packaging will lead the way to more sustainable consumption habits in an increasingly circular economy.

1. Introduction

Single-use plastic packaging consumption is rising at unprecedented levels globally.[1] This consumption has enormous negative environmental and aquatic health impacts both upstream (activities prior to consumer use) and downstream (activities after consumer use). Broadly speaking, the impacted environments are air, land, and water pollution due to (i) upstream (e.g. oil extraction), (ii) conversion (refineries and manufacturing), and downstream processes (e.g. waste handling and disposal). Pollutants from these process harm natural environments as well as the health of the communities working in those facilities and living near them[2].

There are numerous mechanisms in play to reduce solid waste generated from single-use plastic packaging consumption. Waste generation is a systems issue, so the pairing of mechanisms like local and state legislations with waste infrastructural improvements, is incredibly important. An additional, emerging mechanism, is the change of the composition of single-use packaging to biodegradable sources as the consumption practice of such convenient and affordable goods like single-use packaging is not likely to trend lower without government intervention.[3]

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[1] Ryan, A Brief History of Marine Litter Research, in M. Bergmann, L. Gutow, M. Klages (Eds.), Marine Anthropogenic Litter, Berlin Springer, 2015; Plastics Europe

[2] Goldenman, G., Fernandes, M., Holland, M., Tugran, T., Nordin, A., Schoumacher, C., & McNeill, A. (2019). The cost of inaction: A socioeconomic analysis of environmental and health impacts linked to exposure to PFAS. Nordic Council of Ministers.

[3] Mulder, K., & Knot, M. (2001). PVC plastic: a history of systems development and entrenchment. Technology in Society, 23(2), 265-286.

2. The Problem with end-of-life disposal

2.1 General Concerns

Plastic Solid Waste (PSW) management strategies include landfilling, incineration[4], recycling[5], and open dumping[6]. Each of these methods has benefits and drawbacks,[7] as well as require either large upfront costs or ongoing maintenance costs, land space needs, collection processes, and strong municipality support, which is why end-of-life treatment is not consistent from region to region[8]. In South Asia, 75% of waste is dumped in comparison to only 18% in East Asia and Pacific. North America has the highest recycling rate (33.3%), trailed by Europe and Asia (20%). Furthermore, globally, a little over 30% of waste is "leaked" into the natural environments, meaning it is not captured by managed processes[9]. The mismanagement of waste has become a topic of increasing concern. It implies the improper disposal of waste, resulting in heightened pollution and unfavorable byproducts. Regions projected to have the highest rates of mismanagement by 2025 include China, Southeast Asia, and India.[10] These countries exhibit poor waste collection, with rates as low as 44% in Sub-Saharan Africa (in the US, by contract, collection rates are at 100%).[11] The large volumes of improperly disposed waste lead to environmental and economic damages. Examples include the accumulation of waste in the oceans[12] and the disruption of marine and terrestrial ecosystems, thus negatively impacting local economies either reliant on those ecosystems for production and survival or reliant on them for other commerce, such as tourism. The import of foreign waste is another cause of waste mismanagement. The combination of poor waste processing infrastructure and waste imports overwhelm the waste processes systems of low-income countries[13]. In a global cascading effect, developing countries are the destination of millions of tonnes of plastic waste from around the world.[14]

[4] Includes gasification and pyrolysis
[5] Recycling refers to mechanical recycling; unless otherwise stated
[6] Open dumping includes intention (e.g. littering) and unintentional (e.g. "leakage" from the other waste processing approaches).
[7] Antelava, A. et al. (2019). Plastic solid waste (PSW) in the context of life cycle assessment (LCA) and sustainable management. Environmental Management (New York), 64(2), 230-244.
[8] Kaza, Silpa, Lisa Yao, Perinaz Bhada-Tata, and Frank Van Woerden. What a Waste 2.0: A Global Snapshot of Solid Waste Management. Urban Development Series. Washington DC: World Bank, 2018.
[9] World Economic Forum. 2016. The New Plastics Economy: Rethinking the future of plastics.
[10] Jambeck, J. R.et al. (2015). Plastic waste inputs from land into the ocean. Science (American Association for the Advancement of Science), 347(6223), 768-771. doi:10.1126/science.1260352
[11] Kaza, Silpa, Lisa Yao, Perinaz Bhada-Tata, and Frank Van Woerden. What a Waste 2.0: A Global Snapshot of Solid Waste Management. Urban Development Series. Washington DC: World Bank, 2018
[12] Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., … & Noble, K. (2018). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Scientific Reports, 8(1), 4666. Available at: https://www.nature.com/articles/s41598-018-22939-w.
[13] Jambeck, J. R.et al. (2015). Plastic waste inputs from land into the ocean. Science (American Association for the Advancement of Science), 347(6223), 768-771. doi:10.1126/science.1260352
[14] Brooks, A. L., Wang, S., & Jambeck, J. R. (2018). The Chinese import ban and its impact on global plastic waste trade. Science Advances, 4(6), eaat0131. Available at: http://advances.sciencemag.org/content/4/6/eaat0131.

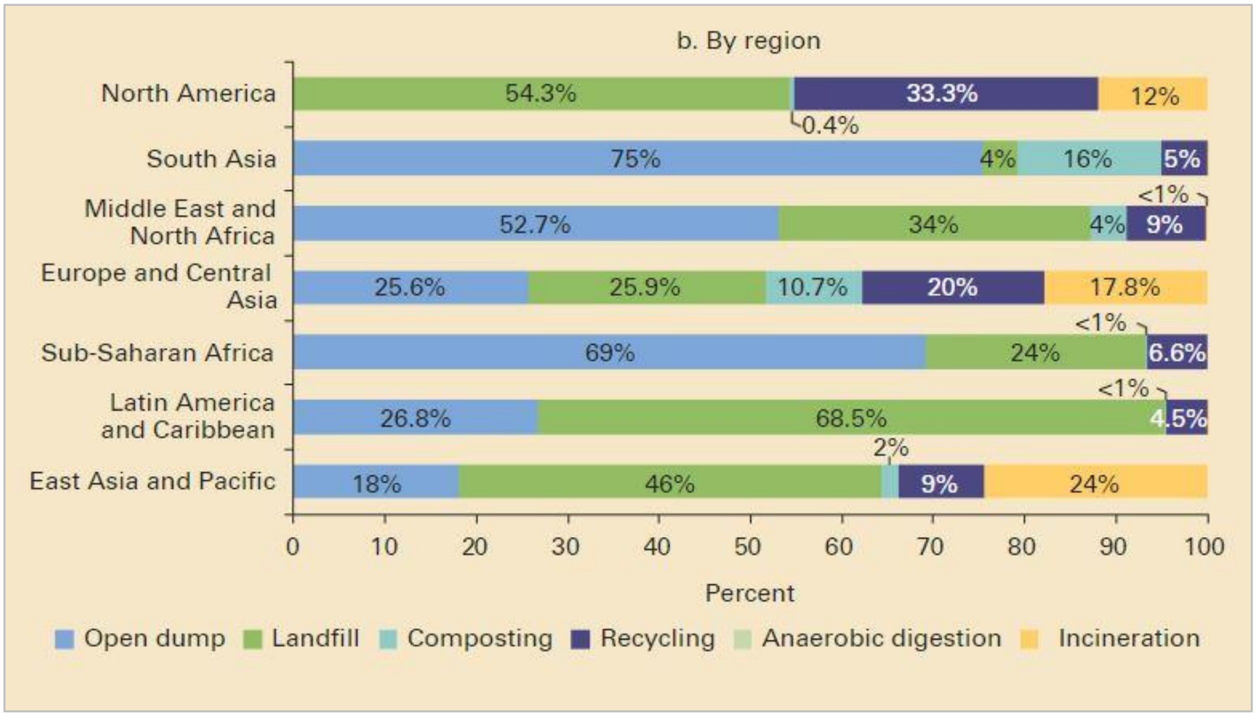

Figure 1: Post-consumer plastic waste disposal by region[15]

2.2 Environmental Impacts

Single-use plastic packaging degradation by landfill, incineration, recycling, and open dumping have different negative impacts on the environment. Polyolefins, the largest source of single use plastics are generally stable under ambient conditions. However, the landfilling process releases leachates and additives (e.g. plasticizers, fillers, and colorants), which seep into surrounding watersheds and soils[16]. These can impact the environment, as well as marine and terrestrial ecosystems. Additionally, landfills require substantial land use and have the potential to contaminate surrounding areas for decades[17].

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[15] Kaza, Silpa, Lisa Yao, Perinaz Bhada-Tata, and Frank Van Woerden. What a Waste 2.0: A Global Snapshot of Solid Waste Management. Urban Development Series. Washington DC: World Bank, 2018.

[16] Dikes-Hoffman, L.S., Pratt, S., Lant, P.A., and Laycock, B. (2018). The Role of Biodegradable Plastic in Solving Plastic Solid Waste Accumulation. Plastics to Energy: Fuel, Chemicals, and Sustainability Implications. Plastics Design Library: 2019, Pages 469-505. ttps://doi.org/10.1016/B978-0-12-813140-4.00019-4.

[17] Electronic Code of Federal Regulations. (2016), Title 40: Protection of Environment PART 258 - Criteria for Municipal Waste Landfills, §258.61 Post-closure care requirements. In https://www.ecfr.gov/cgi-bin/text idx?SID=3cabaf93350b92ea3dca1c18fc78541f&pitd=20160201&node=sp40.25.258.f&rgn=div6#se40.25.258_161.

Incineration consumes relatively large amounts of electricity and heat[18]. Incinerated PSW may result in toxic ashes and solid waste, with dangerous human health impact[19]. Incineration ranks high for global warming (CO2), acidification (SOx), and eutrophication (NOx) potential. Although there is an opportunity to capture the heat for energy production, the amount of energy needed to operate the incinerator results in minimal net gains in energy production[20]. It is the most environmentally harmful method of PSW management.

Based on 2015 data, only 9% of potentially recyclable material was recycled (Geyer et al., 2017)[21]. Recycling has considerable global warming (CO2), acidification (SOx), and eutrophication (NOx) potential[22]. Furthermore, plastics can typically only be recycled once – and even then, they are "downcycled" into less valuable products – because of the decreased quality of materials after the recycling process[23]. Although recycling does not exceed the environmental damages of incinerated PSW, it does leads to solid waste and potentially toxic waste residues.

Finally, there is opening dumping. Opening dumping is more common in low-income countries where waste collection coverage is lower (39% on average) and little to no waste management infrastructure is in place[24]. The act of open dumping means placing waste in unmanaged natural environments such as land and waterways. "Leakage" is also categorized as open dumping, which occurs either intentionally (e.g. littering) or unintentionally (e.g. items catching in the wind during waste collection routes)[25]. Open dumping is particularly harmful to the public health of communities and the well-being of ecosystems.

2.3 Economic Factors

The economic impact breaks down macroeconomic factors, international economics, cost and revenue factors, and cost externalities for each end-of-life waste path. The macroeconomic situation is in part dependent on the global economic recovery owing to the pandemic. Due to oversupply and reduced global demand, oil prices are projected to remain

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[18] Rudolph, N., Kiesel, R., & Aumnate, C. (2017). Understanding plastics recycling: Economic, ecological, and technical aspects of plastic waste handling. München: Hanser.
[19] CIEL. (2019). The Hidden Cost of A Plastic Planet. Plastic & Climate. https://www.ciel.org/wp-content/uploads/2019/05/Plastic-and-Climate-FINAL-2019.pdf
[20] CIEL. (2019). The Hidden Cost of A Plastic Planet. Plastic & Climate. https://www.ciel.org/wp-content/uploads/2019/05/Plastic-and-Climate-FINAL-2019.pdf
[21] Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7), e1700782. Available at: http://advances.sciencemag.org/content/3/7/e1700782.
[22] Life Cycle Impacts for postconsumer recycled resins: PET, HDPE, and PP (2018), The Association of Plastic Recyclers, Franklin Associates, A Division of Eastern Research Group (ERG)
[23] World Economic Forum. 2016. The New Plastics Economy: Rethinking the future of plastics.
[24] Kaza, Silpa, Lisa Yao, Perinaz Bhada-Tata, and Frank Van Woerden. What a Waste 2.0: A Global Snapshot of Solid Waste Management. Urban Development Series. Washington DC: World Bank, 2018.
[25] World Economic Forum. 2016. The New Plastics Economy: Rethinking the future of plastics.

low. This leads to a devaluation of plastic waste, as the virgin material is now cheaper to produce. This is likely to result in continued waste mismanagement and a decreasing global recycling rate. The international outlook is dominated by China's action as a global player. In 2016, the world exported 7.13 million tonnes of plastic to China. This changed with the import ban (Operation National Sword), reducing the quantity imported from 7.13 million tonnes (2016) to 0.05 million tonnes in 2018[26]. The 99.4% reduction due to the import ban illustrates the fragility of global plastic waste flows. By 2025, 71.14 million tonnes of plastic waste are projected to be displaced as a result of the China import ban[27]. Cost and revenue factors for landfilling, incineration, and recycling differ from each other. Rudolph et al.[28] compares cost and revenue factors for waste management facilities of each method with the help of a model. Various revenues, cost factors, and external factors are incorporated. Incineration is the most profitable path, estimating total normal profit[29] at $88.96[30] per tonne[31] of incinerated resin. Recycling yields a loss of $9.76 per tonne of resin, with landfilling trailing at a loss of $23.10 per tonne. Additionally, externalities such as pollution are an additional economic consequence of industrial activity. These marginal social costs per tonne (MSC/tonne) for carbon-dioxide are estimated between $1,000 and $2,000 MSC/tonne[32]. GHGs like nitrous oxide are estimated at $16,000 MSC/tonne[33].

3. The Bioplastic Market

The global bioplastic market value is projected to increase from $6 billion in 2016 to nearly $20 billion by 2026[34]. Generally, the market drivers are political support, labeling[35],

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[26] Staub Colin (2019), China: Plastic imports down 99 percent, paper down a third, Resource Recycling in https://resource-recycling.com/recycling/2019/01/29/china-plastic-imports-down-99-percent-paper-down-a-third/; O'Neill, K. (2009;2005;). The environment and international relations. Cambridge, UK; New York;: Cambridge University Press. doi:10.1017/CBO9780511805974.

[27] Brooks, A. L., Wang, S., & Jambeck, J. R. (2018). The Chinese import ban and its impact on global plastic waste trade. Science Advances, 4(6), eaat0131. Available at: http://advances.sciencemag.org/content/4/6/eaat0131.

[28] Rudolph, N., Kiesel, R., & Aumnate, C. (2017). Understanding plastics recycling: Economic, ecological, and technical aspects of plastic waste handling. München: Hanser.

[29] Total normal profit excludes opportunity cost

[30] All currency is adjusted to inflation and given in 2020-$

[31] Tonne refers to the metric tonne (1,000kg)

[32] Ackerman, F., & Stanton, E. A. (2012). Climate risks and carbon prices: Revising the social cost of carbon. Economics, 6(10), 0_1,1-26. Retrieved from https://search-proquest-com.proxy.libraries.uc.edu/docview/1010282298?accountid=2909; Division of Behavioral and Social Sciences and Education, National Academies of Sciences, Engineering, and Medicine, Board on Environmental Change and Society, & Committee on Assessing Approaches to Updating the Social Cost of Carbon. (2017). Valuing climate damages: Updating estimation of the social cost of carbon dioxide National Academies Press. doi:10.17226/24651

[33] Marten, A. L., & Newbold, S. C. (2012). Estimating the social cost of non-CO2 GHG emissions: Methane and nitrous oxide. Energy Policy, 51, 957-972. doi:10.1016/j.enpol.2012.09.073

[34] PR Newswire. (January 13, 2020). Market value of bioplastics worldwide in 2018 and 2026 (in billion U.S. dollars) [Graph]. In Statista. Retrieved July 30, 2020, from https://www-statista-com.proxy.libraries.uc.edu/statistics/981762/market-value-bioplastics-worldwide/.

[35] The European Committee for Standardization (CEN) has published the standards EN 16640 and EN 16785-1 on the subject of the 'biobased' element of bioplastics.

consumer behavior, and leadership of big brands.[36] Similar to the conventional plastic industry, key markets can be divided into three segments: 1. high value, low volume applications (3D printing, medical device coatings, pharmaceutical excipients); 2. moderate value, moderate volume applications (specialty foams, superabsorbent polymers, coatings); and 3. low value, high quantity applications (packaging). These segments differ in economies of scale. Bioplastic production capacities are projected to increase by 415,000 tonnes or 17% from 2018 to 2024[37]. The three largest production capacities by market segment in 2019 are flexible packaging (663,000t), rigid packaging (476,000t), and textiles (237,000t).[38] Globally, Asia leads with a production capacity share of 45%. Europe (25%), North America (18%), and South America (12%) trail behind Asia[39].

4. Novomer P(3HP)

4.1 P(3HP) Versatility

Novomer P(3HP) lines up favorably within the bioplastic market due to its versatility. P(3HP) can be produced from fossil-based or bio-based carbon monoxide (CO) and ethylene oxide (EO) via a beta-propiolactone intermediate. P(3HP) can fit into existing waste management infrastructure. P(3HP) is a good candidate for Chemical Recycling to Monomer (CRM). As discussed in Coates and Getzler (2020)[40], CRM constitutes an almost perfect reclamation of monomer from resin. Post-consumer waste is converted into monomers that can be re-, up-, or downcycled. Tertiary recycling of P(3HP) resin to acrylic acid via thermolysis is an example for this type of recycling. In theory, CRM is one of the most favorable end-of-life strategies within a circular economy with respect to efficiency. This is due to its marginal waste products and high-quality yields.[41] In the current development contexts, CRM still faces market barriers. These include economies of scale[42], high capital investments, favorable ROI not possible within small-scale operations, high research and development (R&D) expenses, and low-cost fossil feedstock[43].

Novomer P(3HP) experiences favorable biodegradation properties. The aerobic biodegradation of P(3HP) under controlled composting conditions has been tested. P(3HP) biodegrades completely in just over 70 days, with water and carbon-dioxide as byproducts. After 90 days, P(3HP) measures a pH of 9.3, Total Solids (TS) percentage of 61.1%, and Volatile Solids percentage of 27.1%. Incineration of P(3HP) leads to low ash residue with low toxicity.[44]

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[36] European Bioplastics, nova-Institute (2019), from https://www.european-bioplastics.org/market/.
[37] European Bioplastics, nova-Institute (2019), from https://www.european-bioplastics.org/market/.
[38] European Bioplastics, nova-Institute (2019), from https://www.european-bioplastics.org/market/.
[39] European Bioplastics, nova-Institute (2019), from https://www.european-bioplastics.org/market/.
[40] Coates, Geoffrey W., & Getzler, Yutan D. Y.L. Chemical recycling to monomer for an ideal, circular polymer economy, Nature Review, Springer Nature Limited (2020).
[41] Coates, Geoffrey W., & Getzler, Yutan D. Y.L. Chemical recycling to monomer for an ideal, circular polymer economy, Nature Review, Springer Nature Limited (2020).
[42] favorable ROI not possible within small-scale operations
[43] (trend with decreasing value) does not guarantee profitability of operations
[44] Final Report on Aerobic biodegradation under controlled composting conditions of Poly(propiolactone)

The Novomer Glacial Acrylic Acid (GAA) Thermolysis process refers to the upcycling of P(3HP) through CRM. The conventional process to GAA involves two-step oxidation of propylene at high temperatures followed by a complex sequence of separations including aqueous or solvent absorption, distillation to crude acrylic acid, and further distillation or crystallization to yield the GAA product. The Novomer cost model[45] for thermolysis estimates total variable cost, excluding the cost to source recovered P(3HP) raw material, at approximately $50/tonne. Adding other direct costs, taxes, insurance, and depreciation, the total cost of production for Novomer GAA thermolysis is approximately $150/tonne[46]. Due to COVID-19 market disruptions, conventional GAA has plummeted from >$2,000/tonne to $1,000-$1,200/tonne[47]. However, even in today's low cost virgin acrylic acid market environment, the Novomer process from recovered P(3HP) appears favorable relative to the incumbent process.

4.2 Environmental Factors

4.2.1 P(3HP) LCA

A cradle-to-gate life cycle assessment (LCA) was conducted using SimaPro 9.0 within the ISO 14040 framework to evaluate the environmental impact of Novomer fossil-based and bio-based P(3HP) against alternate fossil-based and bio-based polymers. The standard unit was defined as 1 kg of polymer, assuming comparable end use. Base case geography was defined as a European P(3HP) production scenario. Life cycle inventory data was derived from internal process modeling, the Ecoinvent v3.5 database, USLCI, and other external partner or literature sources.

The ReCiPe 2016 Midpoint (H) method was used to assess climate change impact, with modifications to account for biogenic carbon uptake and emission in cradle-to-gate comparison of fossil and bio-based products. The single-issue Cumulative Energy Demand (CED) method was also used.

The climate change impact breakdown for 100% fossil-based P(3HP) production is shown in Figure 3 in kg CO_2 equivalent/kg polymer. The fully fossil-based P(3HP) scenario uses CO from steam methane reforming and EO from steam cracking of naphtha. Feedstock impacts (CO and EO) comprise more than half of the calculated climate change impact here; many alternate pathways to CO and EO exist corresponding to a partially or fully bio-based P(3HP) product and lower climate change impact.

[45] Source: Kyle Sherry (2020)
[46] Source: Kyle Sherry (2020)
[47] Source: Kyle Sherry (2020)

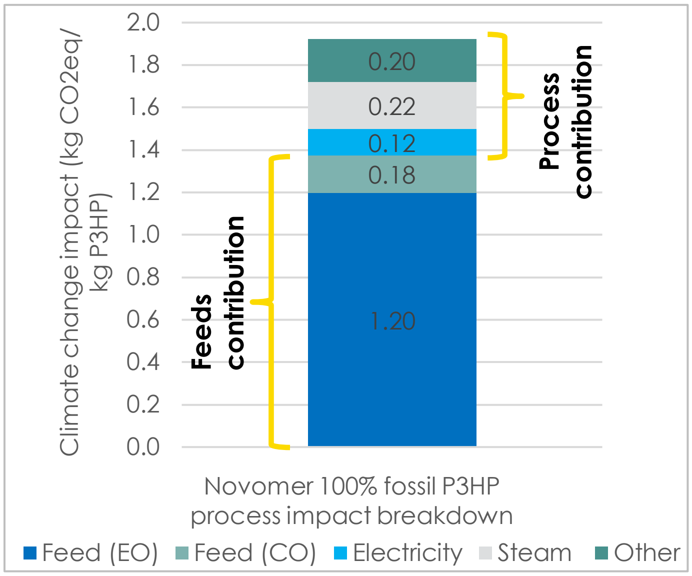

Figure 2: Biodegradable 100% fossil-based P(3HP) climate change impact breakdown

P(3HP) climate change impact and cumulative energy demand comparison with conventional fossil-based plastics are seen in Figure 3 and Figure 4. Fossil-based P(3HP) has a climate change impact comparable to or lower than non-biodegradable alternative virgin thermoplastics shown (LDPE, HDPE, PP, PET, PS)[48], and a similarly comparable cumulative energy demand. The base case for 100% bio-based P(3HP) involves CO from solid oxide electrolysis of CO_2[49] (assumed biogenic, i.e. derived from sequestration at a point source such as ethanol fermentation) and EO from oxidation of maize ethanol[50]. The climate change impact of bio-based P(3HP) varies depending on choice of biomass feedstock and process route. Ranges of climate change impact values for alternate bio-based feeds selection are shown, including pathways to CO from biomass gasification and EO from lignocellulosic ethanol.

P(3HP) climate change impact is likewise compared against alternate bio-based polymers (PLA[51] and PHAs including P(3HB) and PHBH[52]) in Figure 4. Climate change impact for both fossil and bio-based P(3HP) is within the range of values for the PHA processes modeled and slightly higher than that of PLA. P(3HP) cumulative energy demand as seen in Figure 5 is lower than the corresponding value calculated for P(3HB) and PHBH variants in addition to PLA, due partially to the higher steam and electricity consumption in PHA and PLA conversion processes from respective feeds, shown in Figure 6.

[48] LCI for fossil-based thermoplastics from PlasticsEurope eco-profiles (global production basis)
[49] LCI for CO production via solid oxide electrolysis based on Haldor Topsoe eCOs™ technology
[50] LCI for EO production via maize ethanol from Ecoinvent, USLCI, discussions with industry partners
[51] LCI for PLA from maize is from NatureWorks
[52] LCI for P(3HB) from sucrose and PHBH from Harding 2007, Chen 2001, Akiyama 2003; referenced against Jiang 2016, Chen 2012, and other literature.

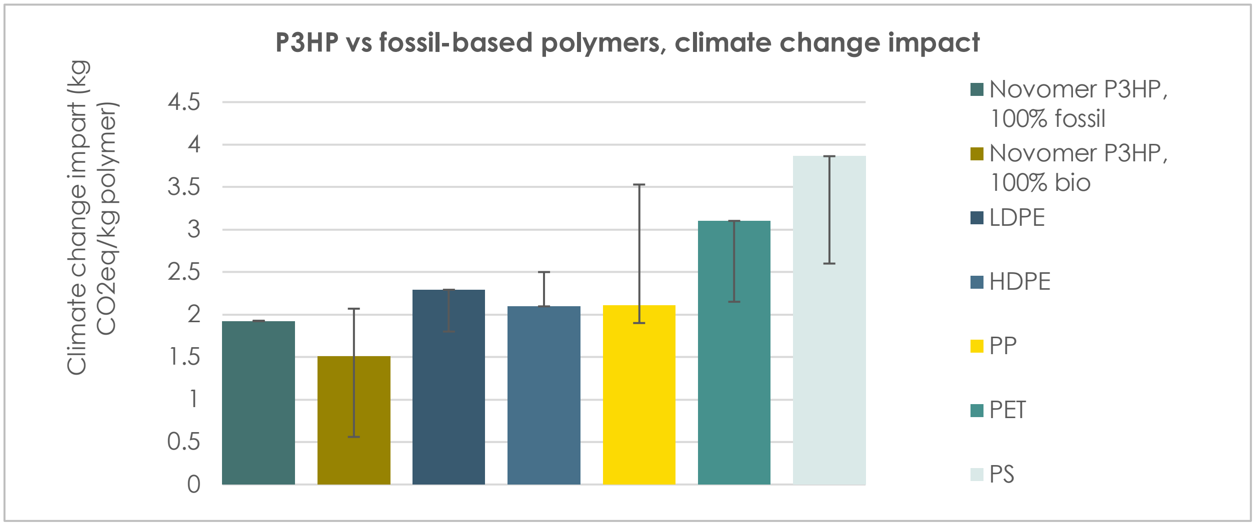

Figure 3: Climate change impact of biodegradable fossil and bio-based P(3HP) compared with non-biodegradable fossil-based polymers

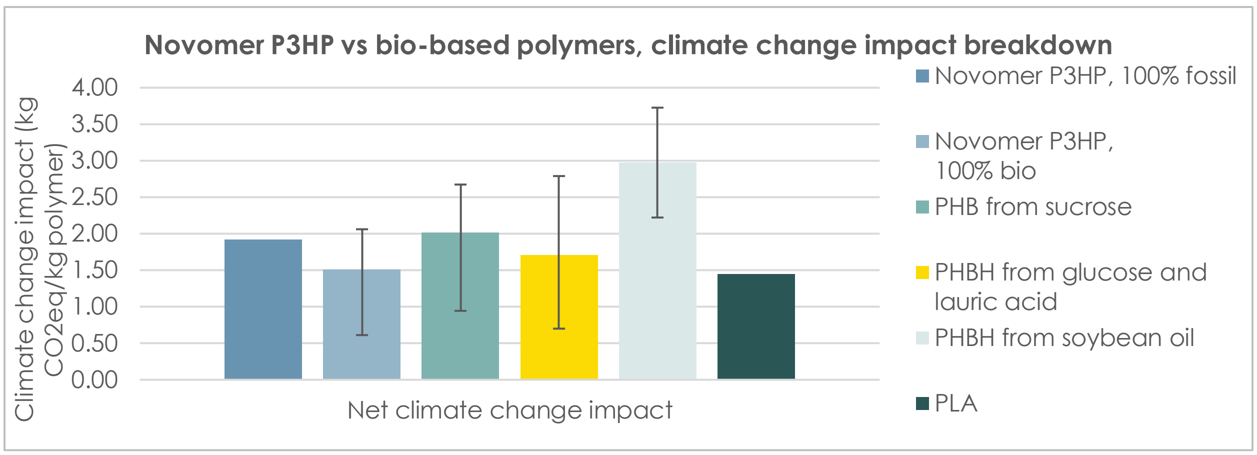

Figure 4: Climate change impact of biodegradable fossil and bio-based P(3HP) compared with-alternate bio-based polymers

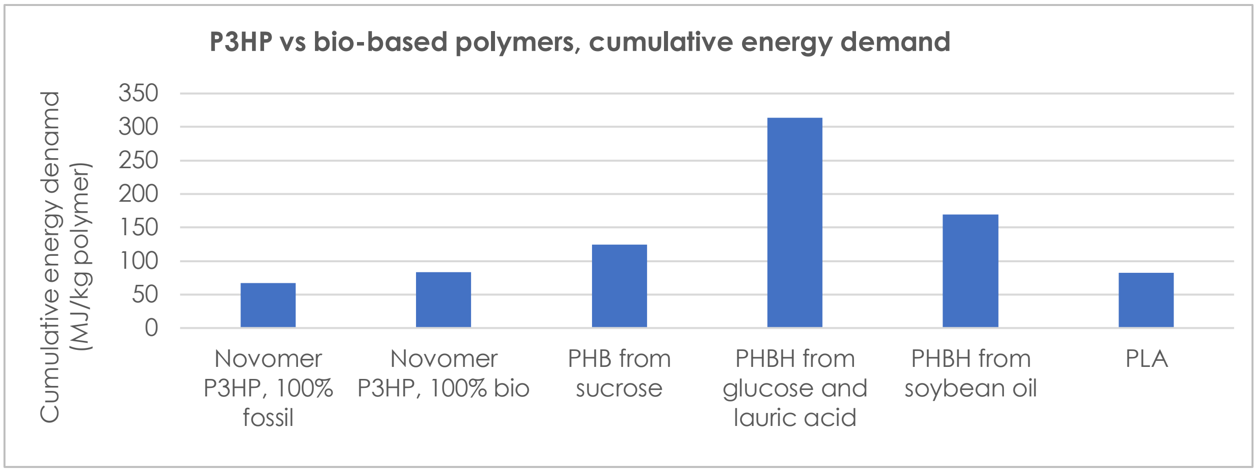

Figure 5: Cumulative energy demand (CED) of biodegradable fossil and bio-based P(3HP) compared with alternate bio-based polymers

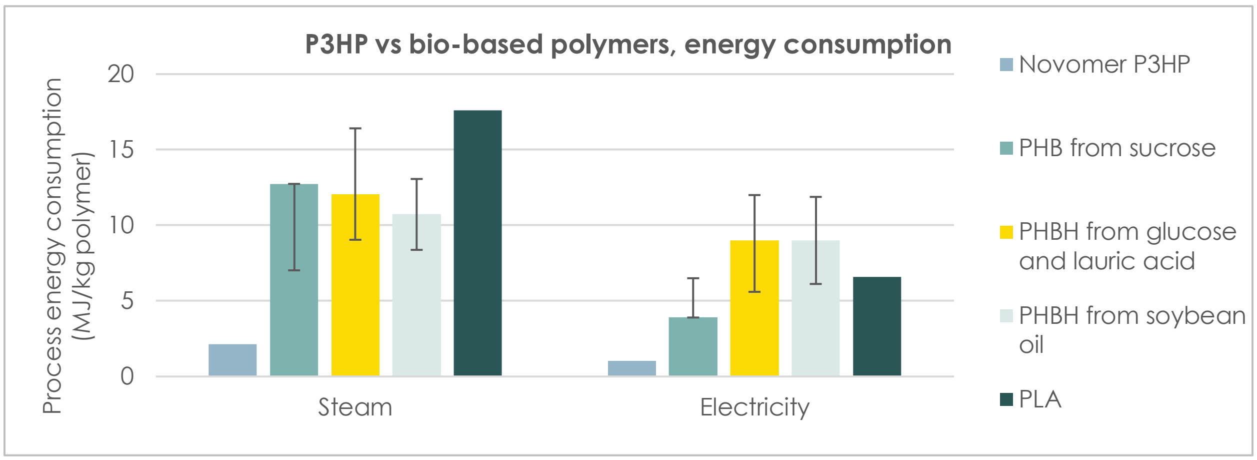

Figure 6: Process steam and electricity consumption for P(3HP) and alternate bio-based polymer production

4.2.2 GAA LCA

P(3HP) material may additionally be upcycled to GAA via thermolysis of the P(3HP) waste stream, extending the overall material life cycle and offsetting the disadvantages of single-use thermoplastic applications. GAA produced in this manner is substantially free of furfural and acetic acid impurities.

Cradle-to-gate LCA was conducted for Novomer GAA from P(3HP) compared to GAA from two-step propylene oxidation[53], using a European production scenario. Functional unit was defined as 1 kg of GAA (>99.5% purity). Climate change impact and cumulative energy demand in Figure 7 for upcycled GAA are calculated in two ways, firstly using the recycled

[53] LCI for conventional GAA from two-step propylene oxidation is from Nexant 2014

content/"cut-off" model where downstream waste P(3HP) to GAA production is assumed burden-free due to secondary usage, and secondly using the 50/50 allocation methodology[54] where process impacts from virgin P(3HP) production are allocated to P(3HP) and upcycled GAA equally. Ranges are shown for GAA values corresponding to variation in feeds selection for upstream P(3HP); the base case indicated is 100% fossil-based GAA. The climate change impact and cumulative energy demand for base case upcycled Novomer GAA are significantly lower than the conventional route to GAA in both the cut-off and 50/50 allocation models.

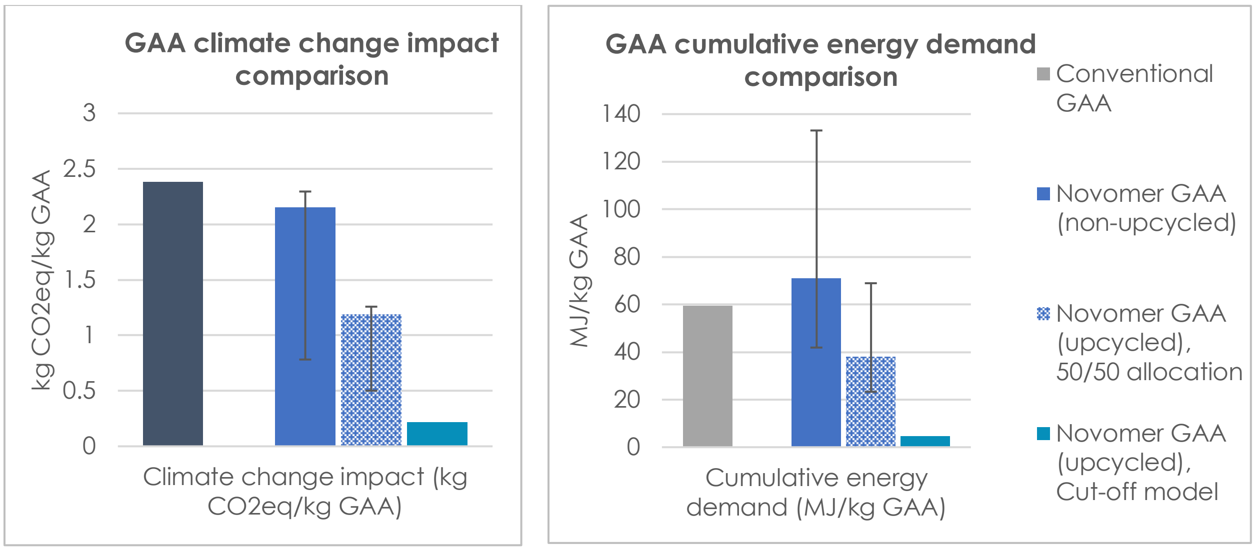

Figure 7: Climate change impact and cumulative energy demand of Novomer GAA produced from P(3HP) waste stream compared to GAA from two-step propylene

4.3 Thermomechanical Properties

P(3HP) performance within the bioplastic market is limited by the low melting point at ~85 degrees Celsius. However, P(3HP) compares favorably relative to benchmark properties for packaging films..

[54] Nicholson et al., 2009

Property	Rinnovo	PLA	Benchmark(s)
Tensile Elongation @ break (%)	400 – 800	<10	500-650 – PP
Oxygen Permeability (cm3 ·µm/m2 ·day-atm))	~100	~27,000	4 – EVOH (32% PE)
Compostability EN13432	Passed	Did not pass	Did Not Pass – PP and PE

Table 1: Thermomechanical property data

P(3HP) exhibits a relatively high elongation at break at 400-800%. P(3HP) has average tensile strength. In summary, these thermomechanical and barrier properties help identify key strengths and weaknesses of P(3HP).

4.4 Cost- and Price-competitiveness

P(3HP) competes in the bioplastic market with a wide array of polymers. In order to holistically assess market attractiveness, P(3HP) is compared to polymers that are a combination of either bio-based or fossil-based; and biodegradable or non-biodegradable.

The cost/price analysis unveils that fossil-based PE has a cost-advantage over biopolymers due to economies of scale and low oil prices. The cost of P(3HP) consists mostly of the beta-propiolactone (bPL) feedstock price at approximately 90% of the product cost. PBAT and P(3HB) both have energy-intensive, high-cost production processes. Polymers like Bio-PE and P(3HB) can use agricultural byproducts as feedstock. Although the use of waste as feedstock is sustainable, the land requirements to produce sugar cane, corn, grains etc. remains high.

The Compound Annual Growth Rate (CAGR)[55], confirms the previous observation of bioplastic market growth. Especially the bio-based polyethylene market is projected to grow drastically at 19%. In summary, P(3HP) lines up favorably when compared to four other polymers.

[55] The CAGR time intervals differ slightly from one another. All describe the next 4-5 years however with either 2019,2020,2012 as the base year

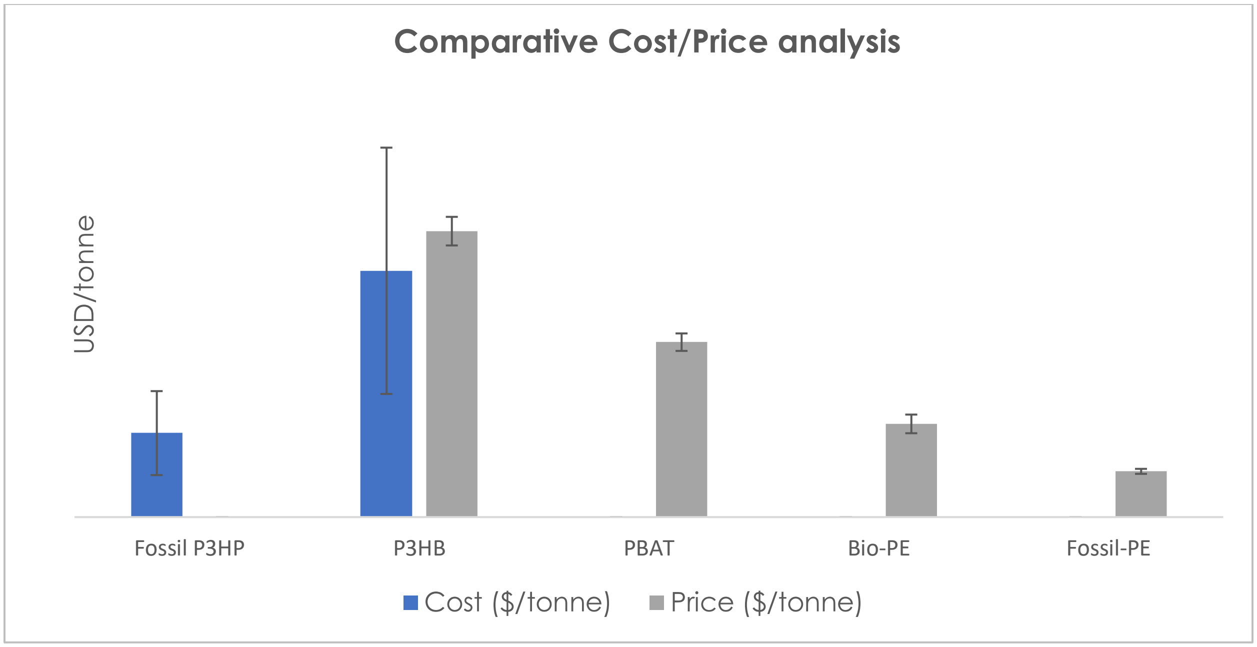

Figure 8: P(3HP) Cost and Price Comparison[56] [57] [58] [59] [60] [61]

5. Summary

The bioplastic industry is projected to grow rapidly due to preferable economic and environmental factors[62]. Bioplastics constitute a favored environmental alternative to conventional[63] polymers due to poor waste management systems, lack of economically favored recycling infrastructure and environmental impacts of polyolefins. Within the bioplastic

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[56] P(3HP) Cost Data: Kyle Sherry (2020).

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ABBREVIATIONS

3D	Three dimensional
B2B	Business to Business
Bio-PE	Biobased Polyethylene
bPL	Beta-propiolactone
CAGR	Compound Annual Growth Rate
CED	Cumulative Energy Demand
CN	China
RER	Europe
Deg C	Degrees Celsius
CO	Carbon-monoxide
CO2	Carbon-dioxide
CRM	Chemical Recycling to Monomer
EO	Ethylene Oxide
GAA	Glacial Acrylic Acid
GHGs	Greenhouse Gases
HDPE	High density polyethylene
HHI	Herfindahl-Hirsch Index
kg	Kilogram
LCA	Life Cycle Assessment
ISO	International Organization for Standardization
LDPE	Low density polyethylene
MPa	Megapascal
N/A	Not applicable
NOx	Nitrous Oxide
P(3HP)	Poly(3-hydroxipropionate)
P3HB	Poly(3-hydroxybutyrate)
PBAT	Polybutylene adipate terephthalate
PCL	Polycaprolactone
PET	Polyethylene terephthalate
PHBH	Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate)
PLA	Polylactic acid
PEA	Poly(ethylene adipate)
PP	Poly(propylene)
PPL	Poly(propiolactone)
PS	Polystyrene
PSW	Plastic Solid Waste
R&D	Research and Development
ROI	Return on Investment
SOx	Sulfur [x]-oxide
t	tonne
TS	Total Solids
U.S.	United States of America
USD	United States Dollar
USLCI	United States Life Cycle Inventory Database