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TRANSITIONING TO SUSTAINABLE PLASTICS: PHA PRODUCTION FROM GREENHOUSE GASES

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ABSTRACT

The shift from synthetic to biodegradable polymers has been impeded by the high cost of carbon feedstock. The use of alternative feedstocks such as greenhouse gases (CH4 and CO2) is a promising approach, with AirCarbon^{TM} from New Light Technologies demonstrating a high potential.

TRANSITIONING TO SUSTAINABLE PLASTICS: PHA PRODUCTION FROM GREENHOUSE GASES

Perfect Peace Sunday*

1. INTRODUCTION

The Production and distribution of petroleum-based plastics have grown significantly worldwide since their first introduction in the 1950s. Plastics, due to their numerous uses and applications have become deeply ingrained into man's activities and different stages of technological advancement. Despite their harmful effects on environment, it seems impossible to eliminate the use of petroleum-based plastics entirely. Unfortunately, most of these Petroleum-based plastics are not biodegradable and can persist in environment for decades. To address this synthetic plastics menace, there has been expensive and risky existing alternatives such as plastic waste incineration, landfilling, and recycling which only transfer the problem from one phase to another. To address this non-biodegradability of plastics there is urgent need to transition fully from petroleum-based to more environmentally friendly and biodegradable plastics such as biobased plastics made from Polyhydroxylalkanoates (PHAs) polyesters [1], [2].

Plastic contamination takes place in two stages: during manufacturing (resulting in carbon emissions) and at the end of their lifespan (leading to pollutants and physical risks), negatively affecting both the surroundings and the ecosystem. An alternative solution that could substantially decrease carbon emissions and energy production demands is to substitute petroleum-derived polymers with bio-based polymers. The figure below shows the reduced impact of bio-based/biodegradable polymers on the environment relative to some commercial petroleum-based polymers [3].

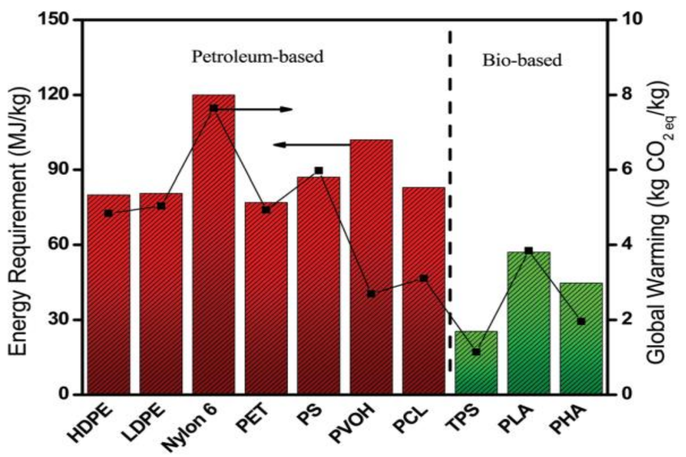

Fig. 1: Production energy and CO_2 emissions of petroleum-based and bio-based polymer
Source: Meereboer et al. 2020

PAHs or Polyhydroxylalkanoates are biopolymers produced by various kinds of bacteria including gram-positive bacteria such as Bacillus megaterium. The discovery of Polyhydroxylbutylrate (PHB) a type of PHA, can be attributed to the bacteriologist Maurice Lemoigne who first discovered the production of polyhydroxylbutylrate (PHB) from bacterium Bacillus mega-bacterium. Since then, more than 100 known PAHs have been identified from different kinds of bacteria in the environment. Out of the known biobased biopolymers, PHAs are considered superior due to their ability to biodegrade in both soil, fresh water, and marine environments within a short period of time [4] according to standards set by American Society for Testing of Materials (ASTM) and the International Standards Organization (ISO). In contrast, Polylactic acid (PLA) and other competing biobased polymers can persist in marine environments for thousands of years. The launch of Mirel in 2007, marked a new era in market share for biopolymers. Mirel is a biobased biopolymer produced from the fermentation of corn sugar using genetically engineered bacteria. The 'Miracle of Nature' product, as it was termed by the company Metalibox Inc., has a track record of delivering 80% dry weight PHAs and can provide 200% reduction in greenhouse gas emissions along with over a 95% reduction in the use synthetic polymers [5]

Considering the adverse environmental effects caused by synthetic plastics, scientists have devised alternative biodegradable polymers to be used in plastic production. Among them is PHA, which is both biodegradable and biobased. However, the shift from synthetic to biodegradable polymers has been impeded by the high cost of feedstock [2][6]. Hence, this study was undertaken to explore various alternative feedstocks for PHA production, with a particular focus on harnessing greenhouse gases like methane and CO_2. This research also explored the feasibility of replacing fossil fuel plastics with eco-friendly plastics made from newly discovered PHA.

2. FEEDSTOCK AND COMMERCIALIZATION CHALLENGE

Since the discovery of PHA, advances have been made to improve the yield of PHA for large scale commercialization. The amount of PHA produced by micro-organisms cannot meet the demand for transition from fossil fuels to biodegradable polymers. To overcome the challenge of low yield and high cost of extracting PHA from micro-organism, researchers have developed more controlled and efficient methods to produce PHA. Methods such as synthetic biology, system biology, morphology engineering and next-generation industry biotechnology have been developed for a more efficient and sustainable synthesis of PHA[1]

Even with this improvement in yield and cost, PHA cannot compete with petroleum-based polymers commercially in terms of price and application due to high cost of downstream processes such as purification, extraction and refining of PHA polymers from bacteria culture. Moreso, the cost of acquiring the carbon source used as feedstock for the bacteria contributes to 30-40% of the final cost of the PHA polymer [2], [6]. Another promising solution has been the utilization of biogas such as methane and CO_2 from waste streams as a low-cost feedstock in PHA production. Methane (CH_4) and CO_2, significant greenhouse gases, generated from sources such as wastewater treatment plant, agricultural activities, landfills, waste, fossil fuels extraction processes, plastic polluted sites etc can be captured and utilized as a feedstock for PHA production. This approach doesn't only solve the problem of high cost of carbon feedstock, but also sustainable and helps mitigate greenhouse gas emissions [6].

In addition to using *type 11 methanogens* in low-cost PHA production from CH_4, *phototrophic cyanobacteria* have also been explored as potential alternative for low-cost PHA production from CO_2 in the presence of light [2], [7], [8]. However, Research has shown that the efficiency of photoautotrophic production of PHA from cyanobacteria is significantly lower compared to the PHA production process reported by numerous chemoheterotrophic microorganisms[9].

Although the high cost of PHA production feedstock is a major challenge, there is also a problem of inconsistent polymer properties resulting from the use of pure strains in production. Poly-3-hydroxybutyrate (PHB), a dominant naturally produced type of PHA has limited application due to its brittle nature and low thermal stability. To produce copolymers, PHA with better mechanical and chemical properties, pure strains need to be replaced with mixed cultures in PHA production[10].

Previous studies such as Karthikeyan et al., in 2015 investigated the production of methanotrophic PHA/PHB from methane. They highlighted that the production of fossil fuel plastics consumes a significant amount of 270 million tons of oil and gas annually and results in high greenhouse gas emissions. PHA/PHB can be synthesized from various organic materials such as wheat bran, whey, molasses, cane starch, and vegetable waste. Just like other research works have reported, bioplastics have great environmental benefits, but their relatively high production costs compared to petrochemical-derived plastics remain a challenge [1], [2], [6] . One potential solution to reduce the cost of bioplastics is to use CH_4 as a carbon resource for PHA/PHB production, given the large amount of CH_4 released into the atmosphere as a greenhouse gas. Technoeconomic analyses were conducted to explore the effective utilization of 295 million tons of CH_4 under different possible scenarios, including conventional biofilter systems. The results showed that scenario 4, which involves the coculturing of PHA/PHB-producing strains of CH4 oxidizers and CO_2 fixers, has the potential to be the most effective in terms of PHA/PHB production. Furthermore, the authors presented the process leading to the conversion of methane to PHA/PHB by methanotrophic bacteria to involve a series of enzyme-catalyzed reactions that produce methanol, formaldehyde, and formate as intermediates. [11].

Studies have also investigated the use of waste streams such as molasses, whey, and crude glycerol to produce PHA as well as edible and non-edible oils. In recent years, the price of edible oils increased significantly due to increasing demand for cooking oil and biodiesel production, leading to a shift towards using non-edible oils and waste/spent cooking oils as feedstocks for PHA production. The use of waste streams to produce PHAs is a sustainable approach that can contribute to reducing waste and reliance on non-renewable resources. But the challenge with waste streams is their limitations in terms of their availability and distribution. Microorganisms such as *Escherichia coli* and *Pseudomonas oleovorans* have been reported from whey production. molasses has been reported using different microorganisms such as *Azotobacter vinelandii* and *Bacillus sp. JMa5*. *Pseudomonas putida KT2442* was shown to produce medium chain length PHA from glycerol in the early nineties. Other microorganisms, such as *Methylobacterium rhodesianum* and *C. necator*, have also been used in fermentative PHB production using glycerol and casein hydrolysates as carbon and nitrogen sources, respectively [10], [12].

E.B Vea et al., discussed the sustainability of PHA-based plastics by evaluating their environmental impact throughout their entire life cycle. The authors identified methods to optimize PHA yield, thickness, and material choice to improve their environmental performance. The use of wastewater or organic waste streams as a feedstock for PHA production to reduce the carbon footprint of the process was recommended. They also suggested the use of thinner PHA films for packaging applications to reduce material use and emissions. Finally, they proposed that PHA can be blended with other bioplastics, such as PLA or starch-based materials, to improve its mechanical properties and enable broader applications. The study found that the stability of PHA has an impact on its environmental performance, with slower degradation scenarios performing better for impact categories related to climate change. Increasing PHA yield and reducing the thickness of underlying materials can also improve the environmental performance of PHA-based plastics. Though the authors stated that the study was limited by the variability and uncertainty of parameters used for modelling life cycle inventories, the choice of Life cycle inventory (LCI) database, and the deficiencies in the impact assessment method [13].

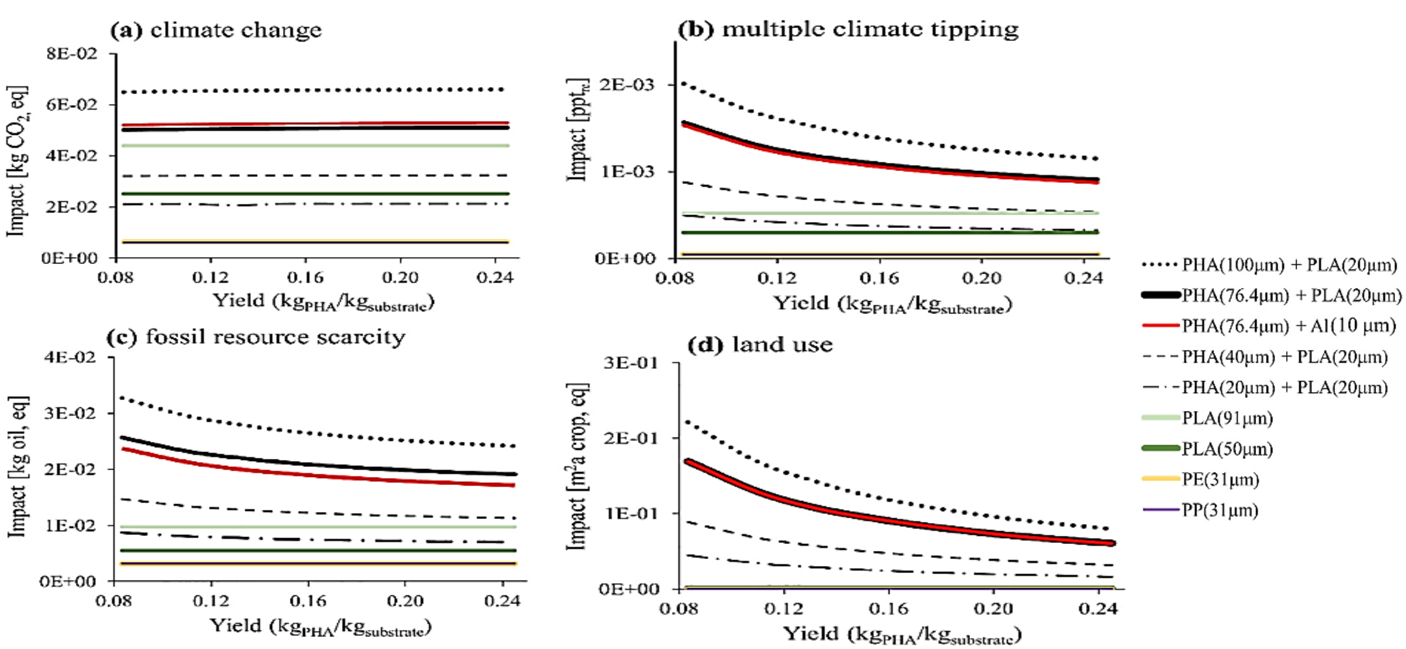

Fig. 2: impact scores for climate change, multiple climate tipping, fossil resource scarcity, and land use, as influenced by PHA yield, and the type and thickness of underlying materials. The yield in the x-axis refers to PHA-based plastics only [13].

3. A NEW ERA IN PHA PRODUCTION

M. Koller and A. Mukherjee in 2022 conducted research to examine the commercialization attempts of PHA by various companies from the past to 2021. The trend for carbon feedstock over time has been sugar (mostly sucrose and glucose) as well as a few attempts using oil from plants seed and crude biogas, which was used by Mango Material. However, New Light Technologies LLC, was seen as a new player having brought an entirely different approach to commercialization of PHA utilizing CH_4 and CO_2 from greenhouse gases to produce P(3HB) homopolyester marketed under the trade name "AirCarbon^{TM}. The process for AirCarbon production involves the use of renewable energy and a regenerative biocatalyst known as "Newlight's 9X biocatalyst" which consumes greenhouse gases such as air and CO_2 to synthesize and accumulate P(3HB) homopolyester [4].

This Southern California-based USA company utilizes natural ocean microorganism to produce AirCarbon [14]. The company invited Carbon Trust, an independent organization with a mission to accelerate transition to a sustainable, low carbon economy, to calculate and certify the cradle-to-gate carbon footprint of AirCarbon. The results of the footprint analysis revealed that AirCarbon has a carbon-negative cradle-to-gate product carbon footprint. Meaning that AirCarbon removes more carbon from atmosphere than it emits during its entire lifecycle from raw material extraction to manufacturing, distribution, use and disposal stages [15]. AirCarbon is fully biodegradable and compostable both industrially and domestically making it a circular material. According to the company, modern recycling has been challenging due to the complexity involved in it. AirCarbon aims to revolutionize the recycling industry by emulating nature's way of recycling; anaerobically breaking down plastics into greenhouse gas and using that gas to make new AirCarbon [14]. AirCarbon, according to New Light Technology, is a regenerative, carbon-negative material that will replace synthetic plastic and fibers and solve plastics pollution and climate change [15]. However, such bold statements and claims from the company have raised questions about whether AirCarbon can truly help transition the world from fossil fuel-based plastics to renewable plastics and bring an end to the lingering plastic pollutions and climate change debates.

Vaclav Smil, a renowned energy expert, argues that the shift from fossil fuels to renewable energy is likely to follow a gradual and prolonged path, like previous large-scale energy shifts in history. He highlights several key drivers of energy transition, which have been instrumental in driving transitions in the past, such as the transition from coal to fossil fuels. These drivers include:

- Shortage of old energy sources.
- New sources being cheaper and more reliable than old sources.
- New sources being less polluting than old sources.
- New sources have better energy density and portability than old sources.

Bringing Smil's arguments home to the plastic industry, the world might not be currently experiencing a shortage in fossil fuels. However, the need for energy transition in the world today, especially in the plastic industry, is driven by the urgency to save the environment and climate from pollution[16]. Plastic industries have been one of the major contributors of environmental pollution, from raw materials extraction down to disposal. Transitioning to renewable plastics will be a critical step towards reducing climate change and pollution. Failures in previous attempts to commercialize and transition to renewable plastics were due to the second point outlined by Vaclav Smil while every other point was checked. However, with the advent of the world first commercially scaled carbon capture technology from New Light Technology, which can produce high-performance thermoplastics from CO_2 and CH_4 emissions that can match the performance of oil-based plastics and out-compete on price[17], there is a possibility of transition to renewable plastics happening faster than historical transition trends.

4. CONCLUSION/PERSONAL REMARKS

One major barrier to the commercialization of PHA has been the high cost of feedstock. However, with the discovery of greenhouse gases such as CH_4 and CO_2 as efficient alternative feedstock for PHA production, the possibility of transitioning to more sustainable plastics has become more realistic. New Light Technologies' AirCarbon, an innovative PHA, has demonstrated the potential of this approach. Nevertheless, the current technologies for producing PHA from greenhouse gases are still limited, and significant challenges remain to be addressed before widespread commercialization can be achieved. One critical area of research is the development of more efficient bioreactors and production processes that can fully exploit the potential of this new approach [18]. With continued innovation and investment in this area, it is possible to achieve a cleaner and more sustainable future for the plastic industry.

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* Sunday Perfect Peace