PERSPECTIVE

Plastics' metabolic potential as biotechnological carbon sources: A review and future goals

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ABSTRACT

The plastic dilemma necessitates immediate action, particularly when it comes to the end-of-life of plastics. Microbial metabolism may create new avenues for recycling mixed plastic fragments, which are currently challenging to recycle. These carbon sources may be employed in biotechnology to upcycle plastic waste into useful goods like bioplastics and bio surfactants, thanks to breakthrough methods for degrading polymers to oligo- and monomers. We summarized well-known monomer breakdown routes and calculated potential yields for compounds of industrial importance. We generated replacement scenarios for current fossil-based synthesis methods for the same products using this knowledge. As a result, we draw attention to fossil-fuel-based goods for which plastic monomers might be a viable carbon source. The (in-)efficiency of the petrochemical routes (i.e., carbon, energy usage) defines the possibility of biochemical plastic upcycling, not the maximum yield of product on substrate of the biochemical route. Our findings might be used to guide future metabolic engineering efforts aimed at creating a more sustainable plastic economy.

Key Words: *Plastic; Microbiology*

INTRODUCTION

The global plastic issue is a reality. We confront a tremendous problem with 4.8 billion tons of plastic in poorly managed landfills, up to 400 Mt of new plastic generated in 2020, and less than 10% of this new plastic recycled even once (less than 1% recycled twice). While the issue of plastic in the environment has sparked public debate in a number of nations, the future remains bleak. Even under a "ambitious" react-now scenario, 20 to 50 Mt of plastic will be disposed of into aquatic environments per year by 2030. Another issue posed by the growing usage of plastic, which is expected to reach 1000 Mt by 2050, is the utilization of fossil resources. Indeed, by 2030, the chemical sector is expected to have the fastest growth rates in terms of fossil resources (International Energy Agency, 2018). By 2050, yearly greenhouse gas emissions would have reached 6.5 Gt CO2 equivalents. Surely, the poor contribution of definitely less than half a percent of plastic generated from renewable carbon sources, i.e., biomass, CO2, and waste streams, will not affect the overall situation. Sugar as a carbon source, on the other hand, is gaining traction, as seen by Polylactic Acid (PLA) made from Lactic Acid (LA). TotalCorbion has announced the construction of a new PLA production plant in Europe with a yearly capacity of 125,000 t PLA, as well as additional developments across the world, particularly in China. Microbial polyesters (Poly-3-hydroxybutyrate (PHB) and Polyhydroxyalkanoates (PHA) with diverse monomer compositions) have a manufacturing capacity of 5000 tons per year. While it's encouraging to see bioplastics eventually succeed, their contributions to the plastics sector are now insignificant.

Fair pricing of CO2, including its climatic effect, as adopted for other industrial sectors in the EU Emissions Trading System, will be critical to the development of a sustainable plastics economy. In a recent editorial, Wei et al. called for a zero-fossil-resource plastic economy based on the "6 R" principles of rethinking, refusing, reducing, reuse, recycling, and replacing. For manufacture and end-of-life plastic treatment, such a future plastic economy will rely in part on biological technology. Importantly, any plastic that may wind up in the environment should be provided with an emergency degrading mechanism to prevent the accumulation of plastic trash. Rubber, in the form of microscopic particles from tyre wear, might be an example, since it is estimated that 100,000 tons of rubber are lost to the environment each year in Germany alone, with no substantial accumulations or sinks discovered too far. Indeed, Cadle and Williams (1980) estimated a half-life of roughly 16 months, and vulcanized rubber is biodegradable, indicating such an emergency disintegration. While atmospheric oxidation appears to be the primary process, two evolutionary distinct enzyme systems capable of attacking the double bond in rubber have been identified. However, reliable studies that measure the environmental impact of tyre wear are critically needed. While environmental plastic degradation has been studied for decades and investigated by ISO guidelines like as ISO/DIS 23832 and ISO 14855–2, degradation to oligomers and monomers for use as microbe substrate has gotten less attention. The European Union launched the "European Strategy for Plastics in a Circular Economy" in 2018, with the goal of supporting plastic-based biotech. In this context, the MIX-UP initiative aims to transform the typical linear plastics value chain into a sustainable, biodegradable one. We discuss the current state-of-the-art of two potential approaches for obtaining oligomers and monomers in this section: 1. Enzymatic plastic breakdown and 2. Pyrolysis plastic degradation. We are aware of the extensive efforts in chemical plastic recycling, with exciting examples such as combined polymer degradation and monomer hydrogenation (hydrogen lysis) of PET and PLA to the corresponding diols. The chemical breakthrough in PET recycling resulted in fast hydrolysis at room temperature, a catalytic problem that was not expected to be addressed so quickly or at all. In addition, certain modified PE-like polymers with performance attributes similar to PE but equipped with activatable bonds for innovative end-of-life choices were proposed. The advancements in chemical plastic recycling, on the other hand, are outside the scope of this analysis.

Biotechnological techniques have been offered as a sustainable option for plastic recycling in recent years. Direct microbial DE polymerization of the polymer, which may also occur in plastic-contaminated settings, is the simplest process for depolymerizing plastics. Enzymatic DE polymerization of more resistant polymers, such as PET, necessitates the use of specialized enzyme reactors under particular operating conditions, such as higher temperatures. Unspecific oxidases (e.g., laccases, peroxidases) may breakdown polymers with very resistant C–C bonds in their backbones over time, albeit at very low rates or not at all depending on the environmental circumstances. Technically, these plastics may be depolymerized by pyrolysis, which produces a condensate, or pyrolysis oil. These many approaches are explained in the following section, beginning with microbial degradation and going via enzymatic cleavage to pyrolytic plastics breakdown.

Upcycling (bio)chemicals is frequently thought to be ecologically friendly. Waste treatment, on the other hand, is a complicated process that might have unintended environmental implications. Chemical recycling of plastics, in particular, may have negative environmental consequences as compared to other waste treatment options such as mechanical recycling or burning in a cement kiln. We analyzed the environmental implications of several waste

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treatment strategies to discover potentially favorable biochemical upcycling routes. The Global Warming Effect (GWI) as an environmental indicator is our emphasis. Garbage treatment, in general, and recycling/upcycling, in particular, serve two purposes: the first is to eliminate waste, and the second is to create value goods from waste. Chemicals from biochemical upcycling, polymers through mechanical recycling, or heat and power from trash incineration might all be useful goods. When waste treatment is used to produce these items instead of the traditional method, waste treatment benefits the environment. The most common method of producing a chemical is known as conventional production. These production routes are now mostly reliant on fossil fuels. Thus, the difference between the benefit of avoided production GWIavP and the impact of waste treatment GWIWT is the net global warming impact GWInet of waste treatment.

CONCLUSION

With the growing number of plastics generated, recycling solutions must take precedence over landfilling and incineration. Polyesters, such as PET, are potential candidates for biotechnological plastic breakdown. Furthermore, pyrolysis oils can be used as microbial substrates. Theoretical maximum yields of important compounds from plastic monomers have been demonstrated to differ significantly. The evaluation of substituting typical recycling techniques with a biotechnological approach, on the other hand, revealed that the product yield on carbon is less of a determinant of potential maximum yields than the resource efficiency of the current chemical synthesis pathway. As a result, this research helps to direct biotechnological plastic waste valorization toward compounds such as isoprene, 1,4-BDO, caprolactam, and succinic/adipic acid. Furthermore, the examined products malate, itaconate, propylene glycol, 1,3-propanediol, and 1,4-BDO have potential climate advantages that are unaffected by the plastic substrate utilized, making them a promising candidate for mixed plastic fraction valorization. Because mechanical and chemical recycling are already extremely competitive for some plastics, the biochemical upcycling pathway should focus on plastic kinds and plastic mixes that cannot be recycled using existing technologies. In the other direction, this research can help with the creation of bio based plastic goods that are especially designed for biochemical upcycling as an end-of-life solution. This evaluation intends to focus on the advancement of biochemical upcycling in order to optimize its contribution to addressing today's massive amounts of plastic and future technology solutions. Overall, we expect that our findings will help to direct biochemical upcycling research in the most sustainable direction possible, uncovering several metabolic engineering potentials.