INTENSIFICATION AND SCALE-UP OF WASTE PLASTIC UPCYCLING TO LUBIRCANTS

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Abstract

Polyolefin packaging waste constitutes approximately 70–80% of all U.S. plastic waste, presenting a significant environmental challenge due to its accumulation in landfills and leakage into the biosphere. Conventionally practiced mechanical recycling, incineration, or pyrolysis do not address the issue of polyolefin waste. Novel solutions, like closed-loop chemical recycling of polyolefins to new polymers via ethylene and propylene intermediates, suffer from unfavorable economics due to stiff competition from fossil-derived incumbent polyolefins. Open loop catalytic processes offer to upcycle waste polyolefins into value-added lubricants, waxes, and surfactants with much more compelling economic incentives. Our research at NYU Tandon School of Engineering tackles the problem of chemical upcycling from a reaction engineering and process design standpoint.

One of the most prospective open-loop reactions is polyolefin hydroconversion to lubricants, which requires 200-300 °C and 30-50 bar H_2. Supported metal nanoparticles and sulfides catalyze hydrogenolysis in the melt phase, but the reaction rate and whole process scale-up are limited by the low thermal conductivity and diffusivity in polyolefin melt. This leads to significant thermal and mass transfer gradients, the development of hot spots, and coking. The batch or semi-batch operation studied so far exacerbates these issues, resulting in low activity and high selectivity for low-value by-products, like methane.

Our approach leverages a slurry bubble column reactor setup to induce vigorous mixing and convention within the plastic melt. We explore how gas holdup the correlation between engineering parameters, like column gas holdup, bubble size distribution, sparging intensity, and reactor performance. We add continuous operation capability, allowing simultaneous overhead product removal and feeding of fresh plastic from the bottom. Finally, we demonstrate process robustness using real-world packaging waste contaminated with antioxidants, fire retardants, and other additives. This work establishes a framework for scalable, economically viable polyolefin waste upcycling to lubricant base oil.

Introduction and Motivation

The global adoption of plastic started in the mid-20th century and substantially changed multiple industries, replacing traditionally used materials like steel, paper, and aluminum.[2] Plastic transformed packaging, construction, healthcare, and consumer goods manufacturing. An increase in plastic production coupled with its low cost strongly incentivized its application in short-life-lifecycle products with little to no attention paid to the end-of-life.[3] This distortion led to extensive landfilling of discarded plastic (75%) with some contribution from mechanical recycling (~10-15%).[4] Global shipments of waste plastic culminate in disproportionate landfilling in developing countries, where plastic leaks into aquatic environments and causes air pollution if incinerated.[5]

The current imbalance in plastic use and disposal calls for new ways to recycle or upcycle plastic waste, diverting it from landfills. Plastic goods, especially packaging, are highly engineered materials with customer-specific properties, so it is challenging to recycle them even with proper waste collection infrastructure. Mechanical recycling has a very low energy and carbon footprint and was traditionally applied to plastic in the past.[6] In the case of packaging, mechanical recycling usually leads to lower-quality material, loss of properties, and discoloration.[7]

Since short life-cycle packaging is a significant application niche for plastic (Fig. 1A), the main polymers that constitute packaging are disproportionately represented in the waste stream. More specifically, polyethylene (PE) and polypropylene (PP) constitute over 60% of all US plastic waste due to their abundance in single-use packaging (Figure 1).[4] Polyolefins (PE and PP) are usually layered and mixed with multiple other additives to improve barrier and mechanical properties and ensure packaging cohesion.[8] Successful pathway for packaging waste upcycling or

recycling should address the following challenges: i) the complex nature of polymer mixtures present in packaging and other waste streams, where PE and PP are mixed with adhesives, surfactants, stabilizers, and dyes; ii) polyolefins have low thermal conductivity and high viscosity, which introduces heat and mass transfer limitation during process scale-up. Thus, the ideal plastic recycling/upcycling method should be impurity-tolerant and handle variations in waste streams. It should also lead to higher added-value products to incentivize upstream collection and recycling economically.

At the US DOE-funded Center for Plastic Innovation (Energy Frontier Research Center), our team was strongly motivated to develop a new way to recycle or upcycle plastic using well-studied alkane chemistry and catalysis. Over the past five years, that culminated in a new way of versatile plastic upcycling using **hydroconversion**.

Review of Related Work

Currently, polyolefin plastic waste is pyrolyzed thermally or catalytically at 500-600 °C, leading to pyrolysis oil and off-gas (Fig. 1B).[2] This intermediate is usually further purified and steam-cracked into a mixture of ethylene and propylene, which are standard commodity monomers and can be easily recycled back into a value chain.[9] In a recent analysis, Yadav et al.[9] compared various pyrolysis-based processes and concluded that the minimum selling price for monomer production is competitive with fossil-derived incumbents. On the other hand, naphtha as a process target has ~5x higher prices than the current market value. It appears that the economic cost associated with waste collection, pyrolysis, and purification can reduce the feasibility of any plastic recycling or upcycling process.

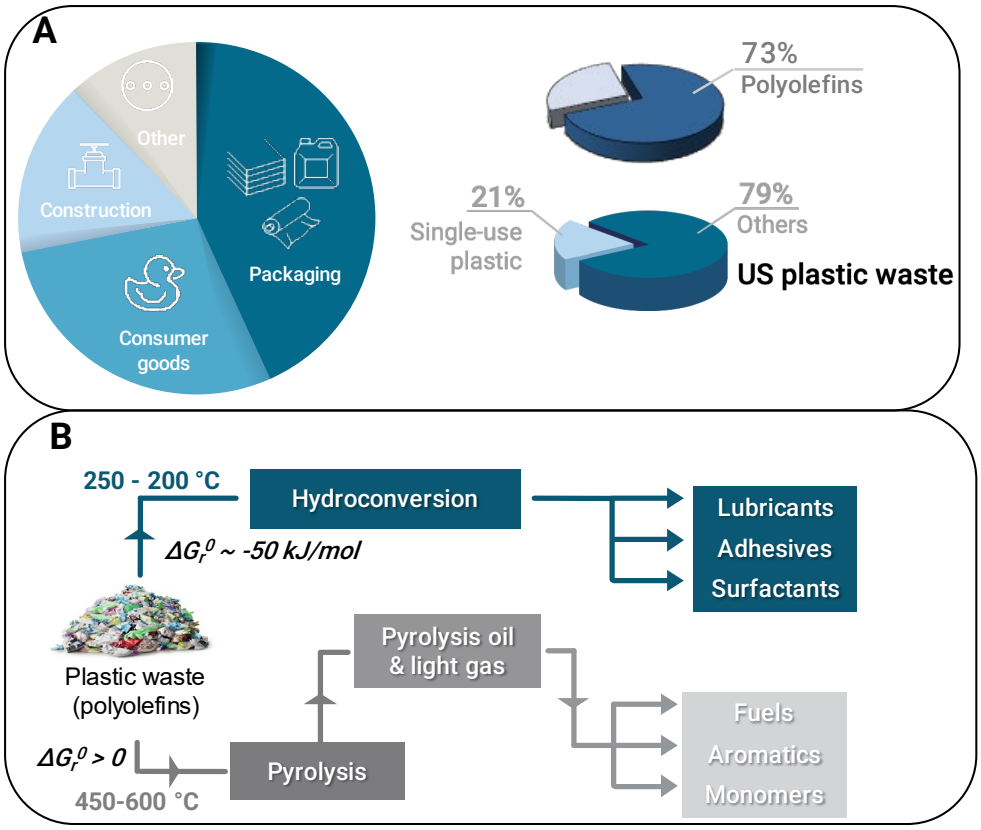

Figure 1. A – overview of main plastic applications, and composition of US waste stream: fraction of polyolefins and percentage of single-use plastic. B – typical chemical recycling and upcycling pathways for polyolefin-rich plastic waste.[2, 10]

A high-energy co-reactant, like O_2, ethylene, or H_2, can lift the thermodynamic constraint on plastic breakdown.[1] **Hydroconversion** relies on hydrogenolysis or hydrocracking to break C-C bonds in the polymer backbone and produce shorter alkanes in the fuel and/or lubricant range, which can be further upcycled into surfactants and adhesives. This approach requires much lower temperatures, in the range of 250-300 °C.[10] The process requires a catalyst, like Ru or Ni, dispersed on various supports, like acidic zeolites, WO_3-ZrO_2, or neutral silica. Furthermore, hydroconversion processes can be integrated with existing refinery and chemical manufacturing infrastructure using hydrotreatment units, facilitating rapid adoption at scale. Our research focused on various product streams, from lubricants to fuels, and on making catalysts robust in the presence of multiple additives, especially for plastic waste.

Technology Approach

Overview of Hydrogenolysis. Our work shows that hydrogenolysis of polyolefins over mono-functional metal catalysts produces lubricant oil at yields above 80%.[11, 12] Hydrogenolysis constitutes polymer binding to the metal surface followed by cleavage of C-H and some C-C bonds. Smaller alkane products are, in turn, hydrogenated and desorbed. The process is typically carried out in the presence of a transition-metal catalyst, such as ruthenium (Ru), supported on a high-surface-area material like titania (TiO_2). The reaction proceeds under mild conditions, typically at temperatures of 200-300°C and hydrogen pressures of 10-30 bar, making it more energy-efficient compared to traditional pyrolysis methods.[13]

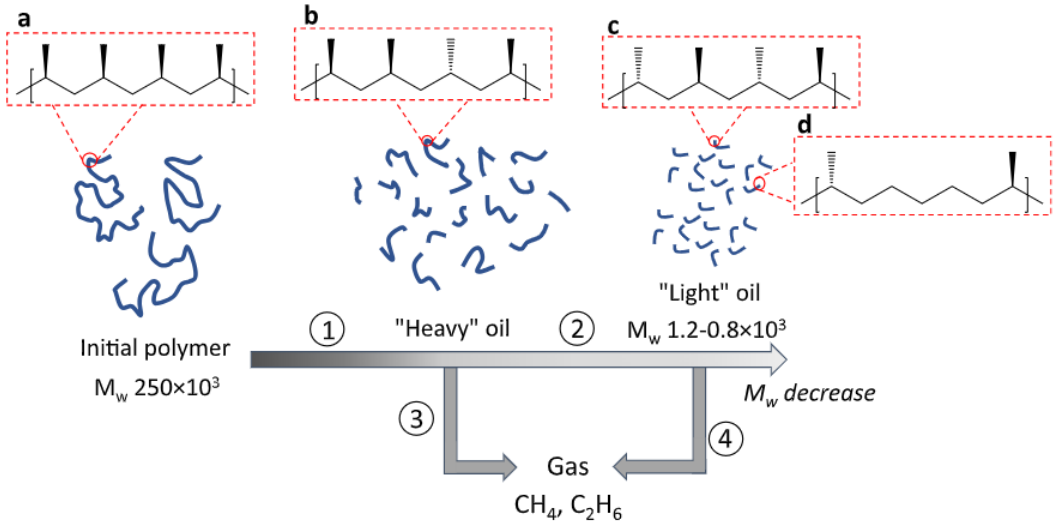

Fig. 2. Reaction Network of Successive Polypropylene Hydrogenolysis over Ru/TiO_2. [11]

The reaction scheme (Fig. 2) involves an initial cleave of C-C bonds in isotactic-PP, leading to its loss of isotacticity due to interaction with the surface. Because of the high degree of natural branching in PP and decreased stereoregularity, polymer readily forms a viscous liquid oil analogous to currently used group I lubricants. Further hydrogenolysis produces an even lighter liquid containing demethylated fragments made of CH_2 sequences. The final step of the reaction in excess H_2 involves a full conversion of PP to methane, a low-value by-product in this case.

The unique properties of Ru/TiO_2 catalysts, such as high selectivity for lubricant-range hydrocarbons and minimal methane formation, make them particularly suitable for plastic waste hydroconversion. Studies have demonstrated yields exceeding 80% for liquid products, with optimized reaction design further enhancing performance (Table 1). Key lubricant properties, such as pour point and kinetic viscosity, were compared to commercial poly-alpha olefins. A higher viscosity index (VI) reflects a smaller dependence of the lubricant's viscosity on temperature. Generally, an oil with a higher VI is desirable due to having a stable lubricating film over a wide temperature range. The VI is below 120 for Group I–III mineral oil and higher for synthetic lubricants. The plastics-derived base oils show an overall higher viscosity than polyolefin (PAO) commercial analog but a higher VI. The pour point and thermal stability of the final formulation can be easily improved using appropriate additives, while the main part of the composition may originate from waste plastic.

Table 1. Main lubricant properties of oil produced from i-PP over Ru/TiO_2 catalyst and PAO reference sample.

Sample	KV40 (cSt)	KV100 (cSt)	VI	Pour point, °C	DSC oxidation onset, °C
Light lubricant	30.3	6.2	146	-15	179
Heavy lubricant	113.5	42.2	149	-18	175
Chevron PAO6	30.8	5.9	139	-62	246

KV100 and KV40 are kinematic viscosities at 100 and 40 °C, respectively. VI: Viscosity index calculated from KV100 and KV40. Commercial PAO6 synthetic base oil manufactured by Chevron. The properties of commercial products were obtained from the specifications datasheet disclosed by the manufacturers. Reaction conditions: 250 °C, 16 h, 30 bar H_2, 2 g of i-PP. Light lubricant: 100 mg Ru/TiO_2; heavy lubricant: 50 mg Ru/TiO_2.[11]

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Figure 2 highlights the fundamental reaction network of polypropylene hydrogenolysis over Ru/TiO_2, revealing a stepwise depolymerization pathway that selectively yields lubricant-range hydrocarbons. This mechanistic insight is pivotal to the novelty of our approach, as it underpins the ability to finely tune product distribution toward high-value lubricants. As a main future direction, our work focuses on overcoming heat and mass transfer limitations of the traditionally used agitated batch reactor. A new continuous slurry bubble column reactor is designed to mitigate transport limitations inherent to viscous polyolefin melts. By combining catalyst optimization, as shown in Figure 2, with innovative reactor engineering, our process enables both high lubricant yields (>85%) and scalability, marking a significant advancement in the field of plastic waste upcycling.

Overview of Hydrocracking. When Ru metal nanoparticles are deposited on acidic support (WO_3/ZrO_2), the catalyst mainly produces diesel and gasoline-range liquids with the substantial formation of methane by-product (Fig. 3B). Substitution of the metal with Pt allows to drastically shift product distribution. In that case (Fig. 3A), the lighter gasoline fraction dominates product distribution, and selectivity to methane is negligible.[1, 14]

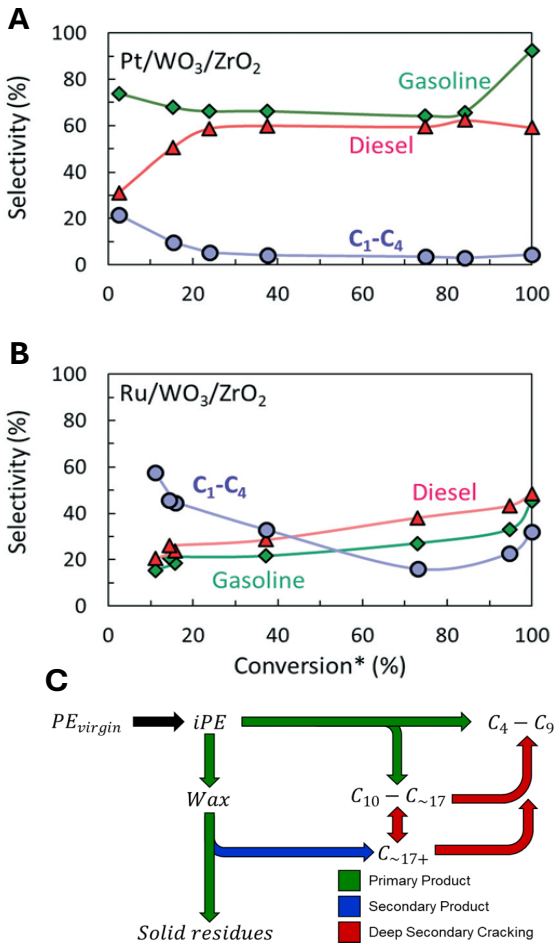

Fig. 3. Selectivity to diesel, gasoline, and light gas hydrocarbons as a function of apparent LDPE conversion for A) hydrocracking over a pure $Pt/WO_3/ZrO_2$ and B) over $Ru/WO_3/ZrO_2$; C) reaction network for polymer hydrocracking *– conversion was calculated based on the total yield of liquid products.[1]

Over $Pt/WO_3/ZrO_2$, polyolefins are converted via hydrocracking, which involves initial dehydrogenation over Pt metal followed by desorption of olefin intermediate and its diffusion to the acid sites. There, olefin is cracked into smaller olefins, which are saturated later to form alkanes over Pt metal. Due to acid-mediated cracking, almost no C_1-C_4 alkanes are produced since it cleavage over acid sites is kinetically prohibited. Interestingly, hydrocracking leads to a broad range of products. At lower reaction times, highly branched wax and liquid alkanes are formed in parallel due to extensive isomerization without C-C cleavage in the polymer backbone. Later, cracking starts to dominate over isomerization producing lighter alkanes. Results indicate that the catalyst surface is strongly pre-covered with adsorbed polymer, which excludes lighter products from further secondary cracking. We speculate that yields of wax can be maximized by removing mass transfer contains. Formation of wax may be an interesting pathway for further valorization, since it has strong adhesive properties.

Similar to hydrogenolysis, our mechanistic understanding of hydrocracking (Figure 3) allows us to fine-tune product distribution ranging from gasoline to wax hydrocarbons. The next step of our work focuses on a combination of catalyst optimization and new reactor design using bubble column.

Technoeconomic Analysis. We conducted a process simulation to compare different plastic upcycling technologies, including pyrolysis to olefins, gasification to recover H_2, hydrothermal liquefaction (HTL) in high-pressure hot water, hydrogenolysis, and hydrocracking. [13]

Table 2. Technoeconomic analysis of various technologies at 25 kt/y scale.[13]

Sample	CAPEX (MM$)	Minimum selling price, $/kg	Lowest market price, $
Pyrolysis	39.3	0.66	1.5-1.8
Gasification	35.7	2.97	2.1
HTL	15.9	0.88	0.6
Hydrocracking	44.8	0.74	0.6
Hydrogenolysis	50.8	1.67	1.5-1.8

Analysis shows that with additional process improvement and better modeling, hydrogenolysis and hydrocracking allow for profitable prices on lubricants and fuels, respectively.

Discussion

Further development of the hydroconversion process requires the selection of its niche within a broader recycling landscape. Compared to chemical recycling, based on solvent extraction methods, hydroconversion offers to process severely contaminated or mixed waste streams, especially if catalyst design is additionally improved. Our recent work on using MoS_2-based catalysts shows promising results in this direction. Additionally, we are developing new reactor design strategies that can overcome mass and heat transfer limitations, which were recently highlighted in polyolefin hydrogenolysis.[15] Overall, major challenges for hydroconversion scale-up and deployment are summarized below:

1. **Technical Challenges**:
    - Develop catalysts with higher activity to reduce reaction time; maintain high product selectivity to minimize formation of light by-products and reduce distillation cost.
    - Improve mass and heat transfer to enable process scale-up.
    - Develop feedstock pre-treatment steps to convert hard-to-recycle plastic waste streams.
    - Certification of "recyclate" lubricants and waxes may be complicated by the breakthrough of various impurities into the product stream.
2. **Economic Barriers**:
    - Enable more modular operations to reduce initial capital for plant-scale facilities.
    - Connect hydroconversion downstream of renewable hydrogen production sites to reduce the carbon footprint of the process and enable operation near urban centers without pre-existing pipeline hydrogen.
3. **Policy and Regulatory Hurdles**:
    - Inconsistent regulations on plastic waste management and chemical recycling across regions.
    - Lack of standardized definitions and certifications for recycled plastic products.
    - Investment in waste collection and sorting infrastructure conjugated with post-sorting chemical recycling/upcycling.

Industry-academia partnerships are vital in addressing these research and development needs with real-world feedstock.

Conclusions

Hydroconversion represents a new, transformative approach to the plastic waste crisis, offering a sustainable pathway to upcycle plastics via an economically viable pathway. By leveraging advancements in catalysis, process engineering, and policy support, this technology has the potential to revolutionize waste management and contribute to a circular economy. Continued innovation and collaboration will be key to overcoming challenges and unlocking the full potential of hydroconversion for a cleaner, more sustainable future.

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About the Author

Pavel Kots joined NYU Tandon School of Engineering in September of 2024 as an Assistant Professor at the Department of Chemical and Biomolecular Engineering. His research group uses chemical engineering, reactor design, and heterogeneous catalysis to address key sustainability challenges of our time. Previously, Pavel worked as a Process Development Engineer at Evonik Global Process Research, where he was involved in the scale-up of several catalytic processes. His research on plastic waste upcycling started during his time as a postdoctoral fellow at the University of Delaware.