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A Comprehensive Assessment of Conventional Propylene and Policy Recommendations for Bio-based Alternatives in Polymer Production

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Abstract:
This research explores the environmental impact of propylene production, especially conventional polypropylene (PP) which constitutes 16% of the global plastic industry. The production methods, including steam cracking and fluid catalytic cracking, significantly contribute to both greenhouse gas emissions (28%) and fossil resource use (23%). In response, the paper advocates for a transition to bio-polypropylene, foreseeing global market growth from $94.8 million in 2021 to $996.9 million in 2028, with a compound annual growth rate of 39.9%. Bio-polypropylene offers a reduced carbon footprint and better alignment with production sustainability goals. However, the paper also addresses potential challenges in this transition, including impacts on food security and increased water consumption for cultivation of bio-mass. The research recommends strategic policy interventions, such as Pigouvian tax and subsidies, to facilitate a gradual shift, emphasizing the importance of balancing economic feasibility and environmental sustainability.

Keywords: Propylene, Polymer Production, Pigouvian Tax, Subsides, Polypropylene, Carbon Footprint

Introduction

This research investigates the environmental consequences of conventional polypropylene (PP) production, a prevalent polymer with challenges in recycling and a significant environmental footprint. The study scrutinizes propylene production processes and highlights their environmental impact, including climate change, resource depletion, water use, human toxicity, and pollution. In response to these concerns, the paper explores the potential of bio-polypropylene, derived from renewable biomass sources like corn and other agricultural feedstocks, as a sustainable alternative. While bio-polypropylene offers promise in reducing the carbon footprint of polymer production, challenges arise in terms of food security and resource demands. To ease a sustainable transition, the research proposes strategic policy interventions.

Background

Conventional polypropylene (PP) is the second largest polymer industry, accounting for approximately 16% of the whole plastic industry [1]. By 2019, PP and its blends had appeared as a significant product category, generating revenues exceeding $124.01 billion (about $380 per person in the US) with a compound annual growth rate (CAGR) of 5.2% [2]. The Asian Pacific region, notably India, China, and Japan, dominates PP production, contributing $39.95 billion in 2020 alone [3]. Polypropylene finds diverse applications including items such as medical components, washing machine drums, battery cases, and bottle caps, talc-filled variants supply added rigidity, particularly at higher temperatures, making them suitable for applications like jug kettles. Additionally, PP is used in oriented polypropylene (OPP) films for packaging items like crisps and biscuits, as well as in the production of fibers for applications in carpets and sports clothing. [17] Especially during crucial times like the COVID-19 pandemic, there is a surge in output, resulting in billions of facemasks. This increase in output posed as significant environmental challenges are issues related to the management of municipal solid waste (MSW) and hazardous waste. [4] as they relied on raw materials derived from petrochemicals, which are non-biodegradable. Conventional polypropylene can take a staggering 30 years to degrade [1]. According to some researchers, the degradation rate of plastics is extremely low, it takes 60 to 1000 years to degrade under the natural environment. [31]. This results in environmental damage when they are discarded [5].

The thermoplastic polymer has appeared as a popular choice in many industries owing to its excellent strength, minimum gas permeability, biocompatibility [13] and its ability to flexibility multi-use it in single layer films or as a part in multi-layer films. However, the environmental impact of polypropylene (PP) has garnered increasing concern and significant attention attributed to its limited recycling rate of merely 1%, resulting in the majority ending up in landfills [14]**.** The high resistance of this substance to biodegradation has resulted in extensive pollution over both land and sea [15]. According to some studies [16], the disposal of polypropylene waste in landfills ranges from 22% to 43%.

Overview of Polypropylene Production Process

Production Process of Propylene

Propylene, a vital feedstock in the petrochemical industry, is primarily produced through several key processes. Among the prominent methods are steam cracking, fluid catalytic cracking (FCC), olefin catalytic cracking, propane dehydrogenation, oxidative dehydrogenation, and metathesis processes.

Steam Cracking

Steam cracking stands as the largest plant in petrochemistry, focusing on the production of unsaturated compounds, including olefins, dienes, and aromatics, from oil fractions[18]. The weight yield of propylene typically ranges from 15% to 20%, depending on the hydrocarbon feedstock, except for ethane cracking, which yields proportionally less propylene. Steam cracking, however, has limitations related to relatively low propylene yield and a propylene-to-ethylene product ratio typically below 0.5 (molar). The residence time is extremely brief (approximately 0.08–0.25 seconds), and the cracking temperature is notably high (around 750–850°C) [19]

Fluid Catalytic Cracking (FCC)

The Fluid Catalytic Cracking (FCC) process, originally conceived in the 1940s for high-octane gasoline production, has undergone substantial evolution. It now additionally yields light gases enriched with olefins. Recent advancements in petrochemical FCC processes have resulted in amplified production of light olefins, catering to the burgeoning demands of the petrochemical industry. A noteworthy innovation in this domain is the commercialized UOP RxPro process, which remarkably augments propylene yield, surpassing conventional FCC processes by achieving over 20 weight percent compared to the latter's 5 weight percent. The UOP RxPro process seamlessly integrates a petrochemical FCC with specialized separation techniques, thereby perfecting selectivity towards propylene and liquid products. [20] [21]

Steam Enhanced Catalytic Cracking

Steam Enhanced Catalytic Cracking (SECC) is an advanced refining process that improves upon conventional catalytic cracking of light feeds into light olefins. This innovative technology is used at lower temperatures than steam cracking but higher than Fluid Catalytic Cracking (FCC), leading to significantly increased yields of both ethylene and propylene. The introduction of steam serves multiple critical functions: it helps reduce coke formation on catalysts, enhancing their longevity, and promotes the efficient gasification of coke deposits. Additionally, steam plays a pivotal role in easing the cracking of hydrocarbons, inhibiting biomolecular reactions that may hinder the process, and favoring the production of propylene, a vital building block in the petrochemical industry. This integration of steam and catalytic cracking processes shows great promise in revolutionizing the production of light olefins, thereby addressing the growing demand for essential materials used in products like plastic packaging, bottles, and automotive components. [22] [23]

Olefin Catalytic Cracking

Sinopec's Olefins Catalytic Cracking (OCC) process stands as a significant stride forward in olefin production. This method, seamlessly integrated with Methanol-to-Olefins (MTO) plants, adeptly transforms low-value C4/C5 by-products into high-quality ethylene and propylene suitable for polymer production. OCC shows impressive selectivity, yielding around 55-60% propylene and 15-20% ethylene. At the heart of this innovation lies the catalyst, composed of full crystalline eolite Socony Mobil-5 zeolite. This material plays a pivotal role in easing the controlled cracking of hydrocarbons, ensuring a high yield of desired olefins. The reaction unfolds at a temperature range of 550-600°C, running at optimum pressure. This controlled environment is key to perfecting product distribution. By harnessing the OCC process, Sinopec not only enhances the efficiency of ethylene and propylene production but also maximizes the use of feedstock, particularly C4/C5 by-products. This integrated approach harmonizes seamlessly with Methanol-to-Olefins (MTO) plants, exemplifying a holistic strategy towards olefin production. The OCC process uses advanced catalyst technology, with the full crystalline ZSM-5 zeolite leading the charge. This catalyst's unique properties drive the conversion process, ensuring a high proportion of ethylene and propylene, pivotal components in polymer manufacturing.

Moreover, the OCC process is notable for its operational conditions. Executed at temperatures between 550-600°C and under ambient pressure, this method strikes a balance between efficiency and feasibility. This controlled environment enables precise control over the cracking reactions, further enhancing product yield. [24] [25]

Propane Dehydrogenation and Oxidative Dehydrogenation

The dehydrogenation of propane to propylene is carried out industrially at 550–650°C near atmospheric pressure. This process is influenced by rapid catalyst coking and needs continuous regeneration. The most used catalysts are based on Pt-Li/Al_2O_3 (refers to a type of catalyst used in the dehydrogenation of propane to propylene) or chromia-alumina Cr_2O_3-Al_2O_3 doped with potassium. [20]

Metathesis Process to Produce Propylene

The Metathesis Process for Propylene Production, developed by Phillips Petroleum Co., involves the conversion of a mixture of ethene and 2-butene into propene. This process, known as the Phillips triolein process, employs a heterogeneous catalyst system and runs at temperatures exceeding 260°C and 30-35 bar pressure.

The reaction occurs in a fixed-bed reactor over a combination of WO3/SiO2 (the metathesis catalyst) and MgO (an isomerization catalyst). Within this system, 1-butene is isomerized to 2-butene as the original 2-butene is consumed in the metathesis reaction. The conversion rate of butene exceeds 60% per pass, with a selectivity for propene surpassing 90%. The reactor undergoes regular regeneration.

Commercially, the Phillips triolein process has been integrated into various plants. Lyondell Petrochemical Co. implemented this process in Channelview, Texas, producing 136,000 tons of propene annually. BASF FINA Petrochemicals in Port Arthur, Texas, also enhanced propene production compared to ethene through the integration of the OCT process.

This process has gained global prominence. Mitsui Chemicals in Japan is set to increase its propene capacity by 140,000 tons per year using OCT technology. Shanghai Secco Petrochemical in Cajoling, China, and Petrochemical Corp. in Singapore, among others, are adopting the OCT process for increased propene output. Overall, the Metathesis Process for Propylene Production stands as a pivotal advancement in the petrochemical industry, offering an efficient alternative route for propene production to meet the rising global demand. [26] [27]

Environmental Implications of Conventional Polypropylene Production

This section aims to assess the environmental implications associated with the production of conventional polypropylene, highlighting key impact categories and their respective contributions. The statistics used in this analysis are drawn from the Environmental Life Cycle Assessment of polypropylene conducted by Christian Moretti, Martin Junginger, and Li Shen. [28]

Climate Change (28%):

The production and combustion of LPG (18%) and hydrogen production (21%) are major contributors to greenhouse gas (GHG) emissions, making climate change a significant concern in the life cycle of conventional polypropylene.

Fossil Resource Use (23%):

The extraction and use of fossil fuels for processes like steam cracking and hydrotreatment contribute to resource depletion and environmental degradation.

Water Use (11%):

The high-water consumption in processes such as steam cracking and hydrotreatment raises concerns about water scarcity and potential environmental impacts on local water systems.

Human Toxicity (Cancer and Non-cancer effects):

The production of certain chemicals during the hydrotreatment process can lead to human toxicity, particularly in terms of cancer and non-cancer effects. Additionally, electricity and phosphoric acid production are notable contributors to non-cancer effects.

Particulate Matter (5%):

Particulate matter emissions during the production process pose risks to air quality and human health, causing mitigation strategies.

Ozone Depletion (1%):

Although ozone depletion has a relatively minimal impact, it is important to consider its contribution to stratospheric ozone layer depletion.

Terrestrial and Marine Eutrophication (2%):

The release of excess nutrients into terrestrial and marine environments can lead to ecosystem imbalances, affecting biodiversity and water quality.

Acidification (5%):

Acidification of soil and water bodies due to acidifying substance emissions is a concern associated with conventional polypropylene production.

Bio-Polypropylene: A Sustainable Alternative for Conventional Polymer Production

Bio-polypropylene, derived from renewable biomass sources, presents a notable advancement in sustainable polymer technology. Its use as an alternative is possible as both bio-based Polypropylene (bio-PP) and conventional Polypropylene (PP) show similar chemical and physical properties [10] [11].

Like conventional-polypropylene, the bio-based polypropylene (Bio-PP) market is growing due to an increased adoption of 'sustainable solutions' in many industries. Biobased plastic products offer two prominent advantages over their conventional counterparts: firstly, they conserve fossil resources by using annually renewable biomass, thereby contributing to carbon neutrality. Additionally, certain bioplastics have the supplementary characteristic of biodegradability, which opens new possibilities for resource recovery at the conclusion of a product's lifecycle. [12]

Bio-PP is experiencing an increasing demand, especially in emerging economies such as India, Indonesia, China, and Brazil [6]. The global market for bio-based polypropylene is expected to experience significant growth, with projected revenues increasing from $94.8 million in 2021 to $996.9 million in 2028, showing a compound annual growth rate (CAGR) of 39.9% during this period. [7]. Bioplastic production accounts for approximately 1% of the total global plastic production, which amounts to around 360 million tons per year. [8] Bioplastics are produced from renewable feedstocks, mainly from crops like corn, sugar beet, or castor plants [9]. Bio-based does not mean the plastic is bio-degradable, meaning that the extent to which the plastic can degrade solely depends on the chemical structure and not the raw material it is made from. [12]

The transition to bio-polypropylene carries the potential for significant positive impacts on global sustainability. There is expected reduction in carbon footprint compared to conventional petrochemical-based polymers, aligning with broader efforts to mitigate climate change. Lessons from organic farming systems, keeping higher soil organic matter, reveal the potential for improved drought tolerance and ecological resilience, emphasizing the environmental benefits associated with sustainable agricultural practices in bio-polypropylene feedstock production. Moreover, the shift signifies a change toward renewable resource use in polymer production, addressing concerns related to finite fossil resources.

Environmental and Economic Repercussions of Transitioning to Bio-polypropylene

Reduced Carbon Footprint:

The shift to bio-polypropylene results in a substantial reduction in the carbon footprint compared to conventional polypropylene. For instance, conventional corn ethanol production, a comparable bio-based process, involves significant energy inputs, emitting pollutants and contributing to environmental degradation. The environmental benefits of bio-polypropylene are clear in the potential reduction of air pollution and greenhouse gas emissions, aligning with these sustainability goals.

Land and fossil fuel use:

The transition to bio-polypropylene, particularly concerning land use changes for cultivating bio-based feedstocks, carries significant repercussions for global poverty and food security. With approximately 17% of cropland worldwide dedicated to irrigation, the cultivation of crops for polymer production demands careful consideration. The data reveals that worldwide malnourishment affects over 3.7 billion people, highlighting the critical need for basic foods. Shifting extensive land resources towards growing feedstocks for polymer production rather than essential food crops poses a direct threat to food availability and affordability.

Global cropland per capita is diminishing to less than 0.22 ha, worsening concerns about distributing limited arable land for bio-based polymer feedstocks.

Urbanization and other human activities contribute to the reduction in available cropland, further restricting the resources available for food production.

The production of 9 t/ha of corn for bio-based feedstocks requires about 7 million liters of water. This adds pressure to worldwide water resources, which are already becoming limited. The decline in world irrigation poses a direct threat to food production, as water demand intensifies with the increased cultivation of bio-based feedstocks.

The U.S., consuming about 22% of the world's fossil energy output, is heavily dependent on fossil fuels for agriculture and food production.

The decline in fossil fuel supplies, coupled with the increasing global demand for biofuels, raises concerns about the economic feasibility of bio-based polymers. [30]

Consequences for Poverty and Food Prices:

Finally, the global malnourishment rate, affecting 56% of the population, emphasizes the urgency of addressing basic food needs. The potential shift of arable land from food crops to bio-based feedstocks may worsen malnourishment rates, especially in regions heavily reliant on agriculture for sustenance. Devoting cropland to bio-based polymer feedstocks can contribute to an increase in food prices, as the competition for limited resources intensifies. The transition may lead to a scenario where food becomes more expensive, worsening existing challenges related to poverty and hunger. [29] [30]

Water Consumption and Energy Requirements:

Bio-polypropylene offers advantages in water consumption compared to conventional petrochemical processes. The production of irrigated wheat, a conventional crop, requires significantly more energy

(14.3 million kcal/ha) and water (5.5 million liters) compared to rainfed wheat (4.2 million kcal/ha). Assessing water usage patterns across the cultivation and processing stages of bio-based feedstocks is crucial. Additionally, bio-polypropylene's promise of reduced energy consumption should consider the comprehensive energy requirements from cultivation to polymer processing for a holistic evaluation. [29]

Production Costs and Market

Economic repercussions are central to the transition to bio-polypropylene. Irrigated wheat, which involves high energy input, is economically less viable compared to rainfed wheat. The economic feasibility of bio-polypropylene is intricately linked to feedstock prices, processing technologies, and market dynamics. Considering the economic landscape is vital, especially as subsidies for conventional corn ethanol exceed $6 billion annually. [30]

Policy recommendations

Pigouvian Tax for Conventional Propylene Production:

In the pursuit of sustainable polymer production, especially propylene, a significant shift from conventional petrochemical methods to bio-based alternatives is imperative. For this transition, the implementation of a Pigouvian tax appears as a strategic policy tool, aligning economic incentives with environmental goals. The roots of environmental economics trace back to pivotal moments in the 1960s, where economists such as Allen V. Kneese pioneered concepts like effluent charges and tradable pollution rights. These ideas laid the groundwork for addressing externalities and pollution-related challenges. [32]

The introduction of a Pigouvian tax involves a phased increase in levies on businesses engaged in conventional polypropylene production. This gradual approach ensures that industries have time to adapt to the changing economic scene, encouraging a smooth transition to bio-based alternatives. By taxing the environmental impact, it encourages businesses to explore and adopt more sustainable practices. The foremost benefit lies in providing businesses with financial motivation to explore and adopt sustainable bio-based polypropylene production. As taxes on conventional methods increase, the cost advantage shifts in favor of bio-based polymer production, driving firms towards more sustainable practices.

Industries accustomed to conventional production methods may initially show reluctance due to the familiarity and efficiency of existing systems. The substantial investments in infrastructure for conventional polypropylene, as well as with the advancements in technology specific to this method, contribute to the hesitancy in accepting the change. Government intervention should acknowledge the challenges posed by the existing technological advancement and efficiency levels reached. [33]

The agricultural sector plays an essential role in food production and in fostering sustainable practices across various industries. This section explores the potential of using subsidies as a strategic tool to ease a gradual shift in the polymer production sector. Drawing insights from recent studies on the Common Agricultural Policy (CAP) in the European Union, it becomes clear that subsidies can be instrumental in steering transitions within sectors. The breakdown of agricultural subsidies into distinct components, such as decoupled payments and investments in knowledge and innovation, proves the nuanced approach that policymakers can adopt. [34]

Like Pillar I decoupled agricultural payments, decoupling subsidies from conventional polypropylene production can encourage producers to explore bio-based alternatives. This approach allows for a gradual transition without disrupting economic stability. [35]

Pillar I of the Common Agricultural Policy (CAP) in the European Union focuses on supplying direct income support to farmers, stabilizing agricultural markets, and implementing measures like the Basic Payment Scheme and greening initiatives. It plays a key role in ensuring income stability and market resilience for farmers. Pillar, I complement Pillar II [35], which emphasizes rural development, environmental sustainability, and broader agricultural investments. Mirroring the positive impact observed in Pillar II payments on physical capital investments in agriculture, subsidizing research and innovation in bio-based polymer production can enhance efficiency. This strategy not only promotes economic growth but also positions the industry as a hub for sustainable practices. Transitioning to bio-based polypropylene can significantly reduce the carbon footprint of the polymer industry. Agricultural subsidies can incentivize the adoption of eco-friendly practices, aligning with sustainability goals. With growing consumer awareness and demand for sustainable products, industries adopting bio-based polymers stand to gain a competitive edge. Subsidies can help offset initial costs, making bio-based polymers more economically practical.

An essential part of this policy implementation involves the allocation of federal funding towards research and development initiatives focused on advancing bio-propylene production technologies. These resources would be directed towards projects aimed at refining and maturing the technological processes involved in bio-propylene production. By supplying financial support for innovation, the government eases the development of more efficient and sustainable methods for propylene production, ensuring the long-term viability of the bio-based approach.

While these policy interventions hold immense potential, it is imperative to anticipate and address potential consequences. The increased demand for biomass feedstock may lead to heightened costs within the agricultural sector, potentially resulting in higher prices for food products. This, in turn, may exert inflationary pressures on the broader economy. Striking a balance between promoting bio-propylene production and managing potential impacts on the agricultural sector will be crucial in ensuring a successful and sustainable transition towards eco-friendly propylene production methods.