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Biotechnological Pathways for Transitioning Oil Refineries to Bio-based Refineries

Adedeji Olalekan Iwogbemi
Department of Microbiology and Biotechnology
University of Westminster, United Kingdom

Dr. Patrick Adeel (Ph.D.)
Department of Management Sciences
University of Hertfordshire, United Kingdom

Dr. Ambrose Sunny Okorie (Ph.D.)
Department of Electronics and Artificial Intelligence
University of Portland, Oregon, USA

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Abstract: *The global shift towards sustainable energy and circular economies necessitates the transformation of traditional oil refineries into bio-based refineries. This paper explores microbial and enzymatic processes as viable pathways for this transition, focusing on the production of biofuels, bio-based chemicals, and other renewable products. A scalable biotechnological framework is proposed, supported by economic and life-cycle analyses, aligning with current trends in renewable energy integration. Case studies demonstrate the practical application and benefits of these biotechnological interventions.*

Keywords: biotechnological pathways, transitioning oil refineries, bio-based refineries

INTRODUCTION

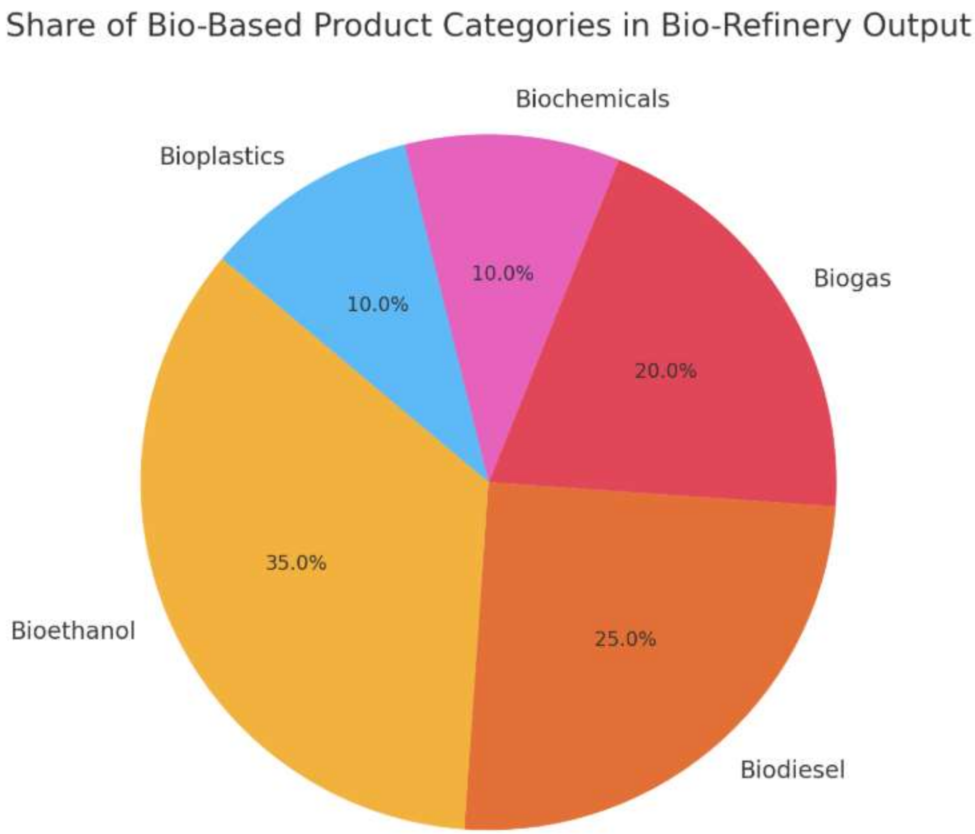
The global energy landscape is undergoing a significant transformation driven by the pressing need to mitigate climate change, reduce greenhouse gas emissions, and secure energy independence. Traditional oil refineries, which have historically played a pivotal role in global energy and chemical production, are now facing existential challenges. As fossil fuel reserves dwindle and the international community intensifies efforts to curb carbon emissions, the imperative to transition towards renewable and sustainable alternatives has never been greater. This shift is not merely an environmental necessity but also an economic opportunity that can stimulate innovation, create new industries, and drive long-term prosperity.

Bio-based refineries, which leverage biological processes to convert biomass and organic waste into fuels, chemicals, and other valuable products, present a viable pathway for reshaping the future of energy production. Unlike conventional oil refineries, bio-refineries operate within the framework of a circular economy, where waste materials are repurposed, resource efficiency is maximized, and environmental impact is minimized. This model aligns with global initiatives such as the European Green Deal and the United Nations Sustainable Development Goals (SDGs), which emphasize renewable energy integration and decarbonization across industries.

Central to the bio-refinery concept is the use of microbial and enzymatic processes that break down complex organic matter into fermentable sugars and other intermediates. These intermediates can then be converted into biofuels, bio-based chemicals, and biodegradable materials. Such processes mirror the molecular composition of petroleum-derived products, making bio-based alternatives highly compatible with existing refinery infrastructure. Moreover, advancements in synthetic biology and metabolic engineering have enabled the development of microorganisms capable of producing hydrocarbons, fatty acids, and alcohols at commercially viable scales, further strengthening the case for bio-refineries.

The transition to bio-based refineries is, however, not without challenges. Key barriers include feedstock variability, the scalability of microbial processes, and the high upfront capital costs associated with retrofitting or replacing conventional refinery equipment. Additionally, the economic competitiveness of bio-based products in markets dominated by low-cost fossil fuels remains a significant hurdle. Addressing these challenges requires a holistic approach that integrates technological innovation with robust policy frameworks, financial incentives, and international cooperation.

In this paper, we explore the technological pathways for converting oil refineries into bio-based refineries, with a particular focus on microbial and enzymatic processes. We propose a scalable framework that leverages life-cycle assessments and economic analyses to ensure the long-term viability and sustainability of bio-refinery projects. Through case studies and empirical data, we demonstrate how existing refineries can be reimagined as hubs for renewable energy and circular economy practices, contributing to a cleaner and more resilient future.



METHODOLOGY

The transition to bio-based refineries involves several interconnected steps, each supported by cutting-edge research and technological advancements. This section outlines the essential components and methodologies involved in retrofitting existing oil refineries or designing new facilities to operate as bio-refineries.

1. **Feedstock Selection and Pretreatment**
Feedstock selection is a critical aspect of bio-refinery development. Lignocellulosic biomass, agricultural residues, municipal solid waste, and algae represent promising feedstocks due to their availability and renewability. Each feedstock presents unique challenges, particularly in terms of structure and composition. Pretreatment is essential to enhance the digestibility of biomass and increase yield during microbial or enzymatic conversion. Methods such as steam explosion, acid hydrolysis, ammonia fiber expansion, and ionic liquid pretreatment help break down lignin barriers, exposing cellulose and hemicellulose for subsequent enzymatic hydrolysis. Studies by Takkellapati et al. (2018)

and Ibrahim et al. (2019) emphasize that optimizing pretreatment conditions can significantly impact process efficiency and cost-effectiveness.

2. **Microbial and Enzymatic Conversion**
   The core of the bio-refinery lies in microbial and enzymatic processes that convert pretreated biomass into valuable products. Engineered microbial strains such as *Saccharomyces cerevisiae*, *Escherichia coli*, and *Clostridium* species are employed to ferment sugars derived from biomass into biofuels (e.g., ethanol, butanol), organic acids, and bio-based chemicals. Metabolic engineering plays a critical role in enhancing microbial performance, improving yield, and expanding product diversity. For instance, Chou and Keasling (2013) demonstrated that adaptive control strategies in metabolic pathways could significantly increase biofuel production. Additionally, hydrocarbonoclastic bacteria, such as *Azospirillum oleiclasticum*, have been shown to degrade heavy oil fractions, contributing to waste valorization and refinery sustainability (Wu et al., 2021).

3. **Product Recovery and Refining**
   Once microbial or enzymatic conversion is complete, downstream processing and product recovery steps are crucial to isolate and purify biofuels and chemicals. Techniques such as distillation, liquid-liquid extraction, membrane filtration, and chromatographic separation are employed to ensure high-purity end products. These processes are often energy-intensive, necessitating integration with heat recovery systems and advanced separation technologies to enhance efficiency. Moreno and da Silva (2016) highlight that incorporating closed-loop recycling systems in product recovery can further improve economic and environmental performance.

4. **Economic and Life-Cycle Analysis**
   Economic feasibility and sustainability are paramount in determining the viability of bio-refineries. Techno-economic analysis (TEA) evaluates capital investment, operating costs, and market potential, providing insight into the profitability of bio-refinery projects. Concurrently, life-cycle assessment (LCA) measures the environmental impact of the entire production chain, from feedstock harvesting to final product utilization. Koutinas et al. (2015) and Wang (2016) emphasize the importance of integrating LCA with TEA to identify cost drivers and environmental hotspots, facilitating informed decision-making and continuous process improvement.

Case Studies

To illustrate the practical applications and scalability of biotechnological pathways in transitioning oil refineries to bio-based refineries, the following case studies provide insights into real-world implementations and innovations. These examples highlight the potential of microbial and enzymatic processes in producing biofuels and bio-based chemicals, demonstrating both economic feasibility and environmental benefits.

1. **Licella's Hydrothermal Liquefaction (HTL) Technology**
   Licella, an Australian-based company, has pioneered hydrothermal liquefaction (HTL) technology that converts biomass and non-recyclable plastics into a biocrude that can be refined into renewable fuels. This process mimics the natural geological processes that create crude oil but operates at much faster rates and under moderate conditions. Licella's technology accepts a wide variety of feedstocks, including agricultural residues, forestry byproducts, and municipal solid waste, making it highly adaptable to existing refinery infrastructures. The produced biocrude can replace fossil fuels in the production of aviation fuel, diesel, and other bio-based chemicals.

Key Innovations:

- The HTL process achieves high conversion efficiencies with minimal carbon emissions compared to traditional refining processes.
- Licella's partnership with global energy firms demonstrates the commercial scalability of HTL technology for retrofitting existing refineries.
- This case highlights the potential of enzymatic and microbial pathways to valorize low-value waste streams, contributing to circular economy goals (Takkellapati et al., 2018).

2. **BioTork's Microbial Fermentation Technologies**
   BioTork, a US-based biotechnology company, specializes in developing robust microbial fermentation processes that convert low-value feedstocks into high-value biofuels and biochemicals. Through adaptive evolution and metabolic engineering, BioTork has optimized microbial strains that efficiently ferment agricultural waste, food processing byproducts, and even crude glycerol into bioethanol and bio-based lubricants. Their technology reduces the need for costly enzymes and accelerates conversion rates, addressing key economic bottlenecks in bio-refinery operations.

Key Innovations:

- BioTork's fermentation processes are highly resilient to impurities in feedstocks, allowing for the use of diverse, non-food biomass.
- The company's commercial partnerships with refineries and agricultural producers underscore the potential for large-scale deployment of microbial-based fermentation systems.
- BioTork's approach aligns with circular economy principles by repurposing industrial waste into valuable energy products (Moreno and da Silva, 2016).

3. **Clariant's Sunliquid® Technology**
   Clariant, a Swiss specialty chemicals company, developed the Sunliquid® technology,

which uses enzymatic hydrolysis to convert agricultural residues (such as wheat straw and corn stover) into cellulosic ethanol. This technology integrates pretreatment, enzymatic hydrolysis, and fermentation into a seamless process, maximizing yield and reducing energy consumption. The cellulosic ethanol produced is a drop-in fuel compatible with existing fuel distribution infrastructure, reducing the carbon intensity of transportation fuels.

Key Innovations:

- The Sunliquid® process generates its own enzymes on-site, lowering production costs and enhancing process efficiency.
- Clariant's commercial-scale bio-refinery in Romania serves as a model for future bio-refineries, demonstrating economic viability and scalability.
- By utilizing agricultural residues, Sunliquid® minimizes land-use competition and promotes sustainable feedstock utilization (Ibrahim et al., 2019).

4. **POET-DSM Advanced Biofuels**
   POET-DSM, a joint venture between POET and DSM, has successfully commercialized cellulosic ethanol production at its Project LIBERTY plant in Iowa, USA. The facility converts corn cobs, leaves, and husks into bioethanol, displacing fossil fuels and reducing greenhouse gas emissions. This project is one of the largest commercial cellulosic ethanol plants globally and serves as a blueprint for future bio-refinery projects.

Key Innovations:

- Project LIBERTY has achieved significant reductions in carbon intensity compared to conventional ethanol production.
- The integration of renewable energy sources into the plant's operation further enhances environmental performance.
- POET-DSM's collaboration with local farmers creates a sustainable supply chain for feedstock, promoting rural economic development (Wang, 2016).

5. **Neste's Renewable Diesel Refinery**
   Neste, a Finnish company, operates one of the world's largest renewable diesel refineries. By leveraging microbial hydrogenation and enzymatic processes, Neste converts waste oils, fats, and non-food vegetable oils into high-quality renewable diesel. This product can directly replace fossil diesel without modifications to existing engines, significantly reducing greenhouse gas emissions.

Key Innovations:

- Neste's renewable diesel is chemically indistinguishable from petroleum diesel, ensuring seamless integration into existing fuel markets.
- The refinery's flexible feedstock approach allows for continuous operation even when specific raw materials are scarce.

- Neste's investment in expanding production capacity underscores the growing market demand for renewable fuels (de Jong & Jungmeier, 2015).

DISCUSSION

The transition from traditional oil refineries to bio-based refineries represents a transformative shift in the energy and chemical industries. This shift is driven by the urgent need to mitigate climate change, reduce dependency on finite fossil fuel resources, and align industrial practices with the principles of a circular economy. While the technological pathways to bio-based refinery development are promising, several critical challenges must be addressed to ensure widespread adoption and long-term sustainability.

Technological Barriers and Advancements

One of the primary challenges facing bio-refineries is the variability and complexity of feedstocks. Unlike petroleum, biomass is heterogeneous, and its composition can vary based on the source, season, and geographical location. This variability complicates pretreatment and microbial conversion processes, affecting yields and process efficiency. Advancements in pretreatment technologies, such as steam explosion and acid hydrolysis, have significantly improved the digestibility of lignocellulosic biomass. However, continued innovation is required to make these processes more energy-efficient and cost-effective.

Microbial engineering and synthetic biology have emerged as powerful tools to address some of these challenges. Engineered strains of *Saccharomyces cerevisiae*, *Escherichia coli*, and other microorganisms have demonstrated enhanced capabilities in fermenting diverse sugars and producing hydrocarbons analogous to those found in fossil fuels. Chou and Keasling (2013) showed that programming adaptive control mechanisms in microbial pathways could increase yield and robustness, paving the way for scalable and reliable bio-refinery operations. Additionally, hydrocarbonoclastic bacteria, such as *Azospirillum oleiclasticum*, play a crucial role in breaking down heavy oil residues, contributing to refinery waste management (Wu et al., 2021).

Economic Feasibility and Competitiveness

Despite significant technological progress, bio-refineries face economic challenges, particularly in regions where fossil fuels remain inexpensive. The high capital costs associated with building new bio-refinery facilities or retrofitting existing refineries pose financial risks. Techno-economic analyses (TEA) conducted by Koutinas et al. (2015) highlight that while bio-refineries can achieve profitability over the long term, initial investments and operational costs are substantial. Government incentives, subsidies, and carbon pricing mechanisms are essential to bridge the economic gap and stimulate private sector investments. Moreover, life-cycle assessments (LCA) reveal that bio-refineries can achieve significant reductions in greenhouse gas emissions compared to fossil fuel refineries. Wang (2016) emphasized that the environmental benefits of bio-refineries often offset the initial economic costs, providing a compelling case for policy support. By integrating LCA with TEA, decision-makers can identify key cost drivers, assess environmental impacts, and prioritize technologies that offer the highest return on investment and sustainability.

Policy and Regulatory Landscape

The success of bio-refineries is closely tied to the policy and regulatory environment. Governments worldwide are increasingly recognizing the potential of bio-based industries to drive economic growth and environmental sustainability. Policies that mandate blending biofuels with conventional fuels, set renewable energy targets, and impose carbon taxes create favorable market conditions for bio-refinery projects. For example, the European Union's Renewable Energy Directive (RED II) and the U.S. Renewable Fuel Standard (RFS) have played pivotal roles in accelerating the deployment of biofuels.However, inconsistent regulations, fluctuating biofuel mandates, and limited access to financing can hinder progress. Collaborative efforts between policymakers, industry leaders, and research institutions are crucial to developing standardized frameworks that promote bio-refinery investments and reduce market volatility.

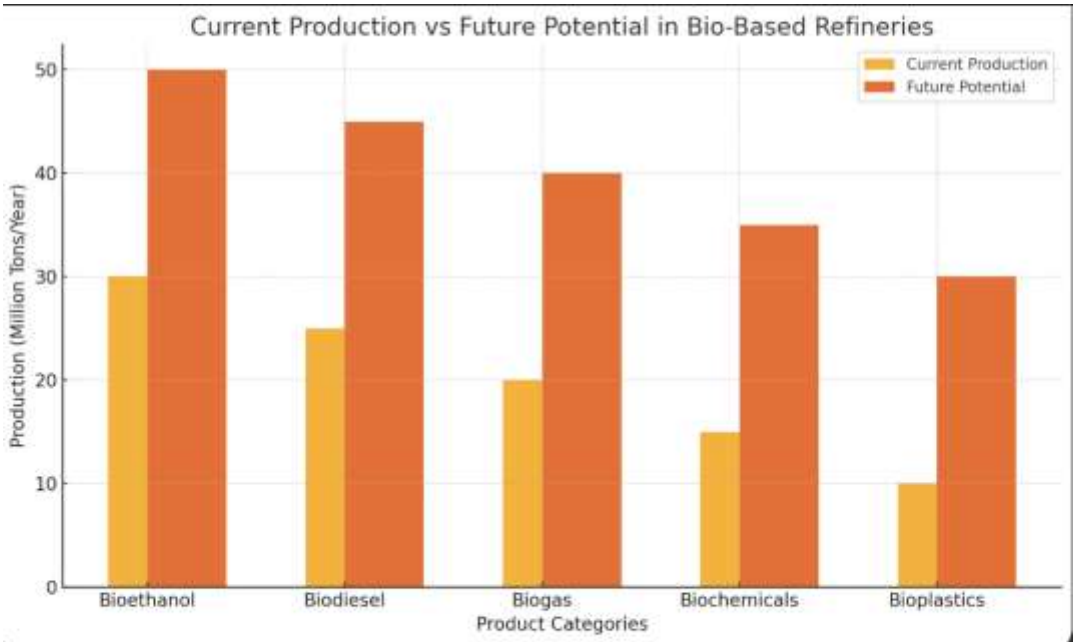
Scalability and Market Integration

Scalability remains a significant concern for bio-refineries, particularly as demand for renewable fuels and chemicals continues to rise. Case studies such as Licella's HTL technology and Clariant's Sunliquid® process demonstrate that commercial-scale bio-refineries are feasible, but scaling up from pilot to full-scale operations presents engineering and logistical challenges. The ability to integrate bio-based production within existing refinery infrastructures can accelerate this transition, leveraging existing assets and reducing capital expenditure. Neste's renewable diesel refinery exemplifies how flexible feedstock approaches and modular refinery designs can enhance scalability. By expanding capacity incrementally and diversifying feedstock sources, bio-refineries can mitigate supply chain risks and respond to market fluctuations more effectively (de Jong & Jungmeier, 2015).

Circular Economy and Waste Valorization

A critical advantage of bio-refineries is their alignment with circular economy principles. Unlike fossil fuel refineries, bio-refineries can utilize waste streams as feedstocks, converting agricultural residues, forestry byproducts, and municipal solid waste into valuable products. This not only reduces environmental pollution but also creates new revenue streams and promotes resource efficiency. Technologies developed by BioTork and POET-DSM demonstrate how waste valorization can enhance the economic and environmental performance of bio-refineries (Moreno and da Silva, 2016).

Furthermore, by integrating bio-refineries with local agricultural and industrial ecosystems, regional bio-economies can emerge, fostering job creation and promoting rural development. This localized approach reduces transportation costs, minimizes supply chain disruptions, and supports resilient, decentralized energy systems.



Future Outlook and Recommendations

The future of bio-refineries hinges on continued technological innovation, supportive policy frameworks, and collaborative industry efforts. Key recommendations include:

1. **Investment in R&D** – Increase funding for research in microbial engineering, enzymatic processes, and advanced pretreatment technologies to improve efficiency and reduce costs.
2. **Policy Incentives** – Implement long-term policy incentives, carbon pricing, and renewable fuel mandates to drive market demand and attract private investments.
3. **Infrastructure Integration** – Leverage existing refinery infrastructure to facilitate the transition to bio-based production, reducing capital expenditure and accelerating deployment.
4. **Public-Private Partnerships** – Foster collaborations between governments, private companies, and academic institutions to develop scalable bio-refinery models and ensure knowledge transfer.
5. **Education and Workforce Development** – Develop specialized training programs to equip the workforce with skills necessary for operating and maintaining bio-refineries.

By addressing these challenges and leveraging the opportunities presented by bio-based technologies, the industry can transition toward a more sustainable and resilient energy future.

CONCLUSION

The transition from conventional oil refineries to bio-based refineries represents a transformative and necessary step towards a sustainable energy future. As global economies strive to decarbonize and adopt circular economy principles, bio-refineries emerge as a key solution, capable of producing renewable fuels, bio-based chemicals, and other valuable products from organic feedstocks. This shift not only addresses the pressing challenges of climate change and fossil fuel depletion but also paves the way for new economic opportunities, job creation, and technological innovation.

Microbial and enzymatic processes form the cornerstone of this transformation, offering highly adaptable and scalable pathways for converting biomass, agricultural residues, and waste materials into energy-rich products. Case studies such as Licella's HTL technology, BioTork's microbial fermentation, and Clariant's Sunliquid® process demonstrate the feasibility and commercial potential of bio-refineries. These examples highlight the ability of bio-based processes to integrate into existing refinery infrastructure, reducing the need for greenfield investments while maximizing the utilization of current assets.

However, realizing the full potential of bio-refineries requires addressing several critical challenges. The economic viability of bio-refineries depends heavily on optimizing feedstock pretreatment, improving microbial conversion efficiencies, and reducing capital costs associated with scaling up operations. Techno-economic analyses (TEA) and life-cycle assessments (LCA) have proven invaluable in identifying cost drivers and highlighting areas for improvement. As demonstrated by Wang (2016) and Koutinas et al. (2015), these analytical tools ensure that bio-refineries achieve not only financial profitability but also significant environmental benefits by lowering carbon emissions and minimizing waste.

Policy support will play an instrumental role in accelerating the development and deployment of bio-refineries. Consistent and long-term regulatory frameworks, such as renewable fuel mandates, carbon pricing, and subsidies for bio-based products, are essential to creating market stability and attracting investment. International cooperation and public-private partnerships can further drive innovation and facilitate the scaling of technologies across different regions and industries, in particular amassing usable feedstock while minimizing waste.

Furthermore, the success of bio-refineries is intrinsically linked to advancements in synthetic biology, metabolic engineering, and industrial biotechnology. Continued investment in research and development will unlock new microbial strains, enzymatic pathways, and process efficiencies, expanding the range of products that bio-refineries can generate. This not only diversifies revenue streams but also enhances the resilience of supply chains by reducing dependency on single feedstocks or technologies.

The societal and environmental benefits of bio-refineries extend beyond carbon reduction and energy diversification. By valorizing agricultural waste, forestry byproducts, and municipal solid waste, bio-refineries contribute to waste management solutions and promote resource efficiency.

This aligns with the principles of the circular economy, where waste is transformed into valuable commodities, closing the loop on resource use and minimizing environmental degradation.

In conclusion, bio-refineries represent a forward-looking and holistic approach to industrial transformation, bridging the gap between current fossil fuel-based infrastructure and a sustainable, low-carbon future. By harnessing the power of biotechnology, fostering supportive policy environments, and investing in scalable innovations, the global community can accelerate the transition towards bio-based refineries. This shift will not only reduce greenhouse gas emissions but also drive economic resilience, energy security, and environmental stewardship for generations to come.

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