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Enabling Plastic-to-Oil Conversion and Circular Economy Transition: An Framework for Converting Waste Plastic-Derived Oil into Fuels

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***Abstract*— The exponential increase in global plastic waste necessitates urgent, scalable interventions that bridge the gap between waste management and sustainable energy production. Transitioning from a linear extraction-disposal model to a circular economy relies heavily on robust waste-to-energy (WtE) conversion pathways, particularly the thermochemical transformation of end-of-life plastics into viable transportation fuels. This paper proposes a comprehensive, digitally integrated framework for the conversion of waste plastic-derived oil into transportation-grade fuel, positioning this chemical process within the broader context of industrial ecology and supply chain sustainability. By synthesizing advanced catalytic upgrading methodologies with digital circular economy tools—such as blockchain for material traceability and semantic ontologies for data interoperability—this research offers a multi-disciplinary approach to resource recovery. Although empirical implementations of the proposed thermochemical facility are currently in the design phase, we present a detailed hypothetical laboratory evaluation plan, complete with projected experimental data and systems modeling, to demonstrate the viability of the approach. Ultimately, this work illustrates how integrating advanced material processing with modern data infrastructure can catalyze the transition toward a truly circular and energy-efficient economy. Within this transformative paradigm, waste-to-energy (WtE) technologies hold substantial promise for mitigating environmental impacts by valorizing plastic waste streams into reusable resources and closing material loops in accordance with circular economy principles (Liaskos et al., 2019).these technologies not only recover energy but also facilitate the recirculation of materials, aligning waste management practices with the foundational goals of the circular economy (Liaskos et al., 2019).**

***Keywords*— Waste-to-Oil, Sustainability, Pre-treatment technologies, Impurity removal, Oil upgrading, Oil recovery.**

I. INTRODUCTION

The contemporary global economy is grappling with the severe environmental repercussions of widespread plastic consumption and the subsequent accumulation of non-biodegradable waste.

Traditional linear economic models, which follow a "take-make-dispose" paradigm, have proven fundamentally unsustainable, leading to the depletion of finite petrochemical resources and the saturation of terrestrial and marine ecosystems with polymer debris. In response, the circular economy has emerged as a critical systemic shift aimed at closing material loops, extending product lifecycles, and minimizing environmental footprints through the strategic reuse, recycling, and recovery of resources. Within this transformative paradigm, waste-to-energy (WtE) technologies hold substantial promise, particularly the conversion of waste plastics into synthetic crude oil via pyrolysis, and its subsequent upgrading into high-value transportation fuels. This conversion process not only diverts hazardous waste from landfills but also provides a localized, alternative energy source that can offset conventional fossil fuel demands. Organizational and network management strategies that integrate circular economy principles across the entire value chain (Liaskos et al., 2019).

Despite the conceptual appeal of converting plastic waste into fuel, the realization of this technology at an industrial scale remains hindered by multifaceted technical, logistical, and informational challenges. The raw oil derived from plastic pyrolysis is often highly unstable, contaminated with heteroatoms (such as chlorine and nitrogen), and possesses a broad molecular weight distribution, making it unsuitable for direct use in standard internal combustion engines. Furthermore, the broader ecosystem required to support this physical conversion—spanning waste collection, sorting, processing, and distribution—suffers from profound inefficiencies and a lack of systemic integration. Enabling a seamless circular economy transition requires not only chemical innovations but also rigorous frameworks for tracking material flows, verifying environmental compliance, and ensuring economic viability across the entire supply chain.

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These systemic deficiencies underscore the urgent need for integrated frameworks that combine advanced monitoring, automation, and transparent digital infrastructure to facilitate accurate tracking and optimization across the plastic-to-fuel lifecycle (Zocco et al., 2024).

Existing approaches to plastic-to-fuel conversion and circular supply chain management are insufficient for several critical reasons. First, traditional linear process models frequently fail to incorporate advanced thermodynamic monitoring and robotic manipulation, resulting in suboptimal resource efficiency and high operational uncertainties during waste handling (Zocco et al., 2024). Second, there is a pronounced lack of semantic interoperability and transparent data documentation across different industrial sectors, making it exceedingly difficult to trace the origin of waste materials, track the precise composition of plastic-derived oils, and verify the carbon emission reductions of the finalized fuel products (Li et al., 2026). Without robust data architecture and physical systems integration, current WtE initiatives operate in isolated silos rather than functioning as cohesive components of a closed-loop industrial ecology.Integrating blockchain technology offers enhanced supply chain transparency and traceability within circular economy models, though scalability and interoperability challenges remain (Abid et al., 2024).

To address these systemic deficiencies, this paper proposes an integrated approach that harmonizes chemical processing with digital circular economy enablers. The core contributions of this research are as follows:

- We introduce a comprehensive, multi-layered framework that integrates the catalytic upgrading of plastic-derived oil with blockchain and ontology-based tracking systems to ensure chemical quality and supply chain transparency. This framework leverages blockchain's decentralized, tamper-resistant capabilities to improve transparency and traceability of chemical flows throughout the supply chain, while acknowledging that scalability and interoperability concerns persist (Abid et al., 2024).
- We outline a rigorous, hypothetical experimental methodology and evaluation plan to assess fuel conversion yields, incorporating projected laboratory results, gas chromatography-mass spectrometry (GC-MS) data graphs, and circularity infographics.

Blockchain technology has emerged as a critical enabler for circular economy transitions by facilitating transparent and secure supply chain management, although achieving its full potential requires addressing challenges like scalability and interoperability (Abid et al., 2024).

II. Related Work

A. Circular Economy Frameworks and Industrial Ecology

The conceptual foundations of the circular economy are deeply intertwined with the principles of industrial ecology, which examines material and energy flows through industrial systems to optimize resource utilization and minimize environmental impact (Saidani et al., 2020). Previous research has demonstrated that transitioning from linear to closed-loop supply chains can yield substantial economic and environmental benefits, provided that the network is designed to balance multiple sustainability objectives (Shah et al., 2025). For instance, mathematical optimization models, such as multi-objective mixed-integer linear programming, have been successfully applied to healthcare supply chains to facilitate the disinfection and reprocessing of materials, thereby reducing carbon emissions and enhancing profitability (Shah et al., 2025). While these studies provide excellent frameworks for discrete product recovery, their application to continuous chemical processes—such as the conversion of mixed plastic waste into fuel—requires adaptation. Our work extends these industrial ecology principles by applying them directly to the continuous thermodynamic flow of plastic-to-fuel WtE systems, ensuring that both the physical chemical conversion and the macroscopic supply chain operate within a synergistic closed loop. we systematically review recent literature to identify the technical, regulatory, and operational factors influencing successful blockchain adoption in circular economy applications 5.

B. Digital Tracking, Blockchain, and the 4R Framework

The integration of blockchain technology has been widely recognized as a pivotal enabler for transitioning to a circular economy, specifically by supporting the 4R framework of reducing, reusing, recycling, and recovering (Abid et al., 2024). Blockchain's decentralized and tamper-resistant architecture allows for the creation of highly transparent supply chains, which is essential for maintaining product accountability from the point of waste collection to the final energy output (Abid et al., 2024).

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However, integrating blockchain into circular systems is not without challenges; expert consensus highlights that while some blockchain applications are likely to succeed, others may fail if specific technical and contextual conditions are not rigorously met (Caldarelli, 2023). In this paper, we leverage the strengths of distributed ledger technology to propose a tracking module that specifically authenticates the chemical composition and source origin of waste plastics. Compared to existing literature that broadly discusses blockchain in waste management, our approach directly links cryptographic verification to continuous chemical sensor data, mitigating the risks of greenwashing in fuel production.By employing standardized ontologies like CEON, organizations can achieve greater semantic interoperability, facilitating more effective collaboration and information exchange throughout product lifecycles (Li et al., 2026).

C. *Semantic Ontologies and AI in Sustainable Manufacturing*

Information sharing across diverse industry sectors is a fundamental prerequisite for a functioning circular economy, yet defining cross-sectorial concepts and maintaining semantics-aware data documentation remains a significant challenge (Li et al., 2026). Recent advancements have introduced systems like the Circular Economy Ontology Network (CEON), which aims to bridge these gaps by providing standardized infrastructural communication along the product lifecycle (Li et al., 2026). Furthermore, the deployment of Large Language Models (LLMs) augmented with domain-specific knowledge graphs has shown immense potential in enhancing decision-making for sustainable manufacturing, overcoming issues like AI hallucination regarding industrial codes and emission factors (Zhao et al., 2025). In contrast to standalone LLM applications that struggle with multi-hop reasoning in industrial contexts, frameworks utilizing Retrieval-Augmented Generation (RAG) provide verified, structured data crucial for regulatory compliance (Zhao et al., 2025). Our proposed methodology builds upon these semantic and AI advancements by utilizing ontological networks to document the lifecycle of the plastic-derived fuel, ensuring that emission factors and chemical conversion metrics are accurately represented and universally understood across the energy sector.By integrating these two modules, the P2F-CF ensures an end-to-end, scientifically grounded system that harmonizes physical processing with transparent digital records for real-time monitoring and regulatory compliance(Zocco et al., 2024).

III. METHOD/APPROACH

The Plastic-to-Fuel Circularity Framework (P2F-CF)

To effectively convert waste plastic-derived oil into high-grade fuel while adhering to circular economy principles, we propose the Plastic-to-Fuel Circularity Framework (P2F-CF). This framework is structurally divided into two primary domains: the Physical-Chemical Conversion Module and the Digital Traceability Module. The Physical-Chemical Conversion Module governs the actual thermodynamic and catalytic processes required to upgrade raw pyrolysis oil into stable, combustible hydrocarbons. We base this design on a unified approach that respects the physical foundations of compartmental dynamical thermodynamics, ensuring maximum energy recovery and process repeatability (Zocco et al., 2024). The Digital Traceability Module runs in parallel, utilizing semantic ontologies to define material states and blockchain ledgers to record process variables securely. This dual-module architecture ensures that every liter of fuel produced is not only chemically viable but also digitally certified for its circular origin and low-carbon footprint.This integrated sorting and characterization workflow exemplifies how advanced autonomous systems support efficient resource management inherent to circular economy frameworks (Zocco et al., 2024).

Step-by-Step System Pipeline

The operational execution of the P2F-CF follows a structured, numbered pipeline to guarantee that both the physical transformation and the data documentation occur synchronously. This integration of deep-learning vision and robotic manipulation into material sorting optimizes circularity, reduces contamination risks, and aligns with circular economy principles (Zocco et al., 2024).

1. *Waste Feedstock Characterization:* Incoming mixed plastic waste is autonomously sorted using robotic manipulation systems guided by deep-learning vision, minimizing contamination risks and human labor (Zocco et al., 2024). The sorted feedstock's polymer composition is logged into the block chain via smart contracts. This autonomous and data-driven sorting process exemplifies the benefits of integrating advanced robotics and deep-learning vision to enhance both circularity and operational efficiency in waste management systems (Zocco et al., 2024).
2. *Pyrolysis and Primary Condensation:* The plastics undergo thermal degradation in an oxygen-free reactor at temperatures ranging from 400°C to 550°C.

The resulting volatile compounds are condensed into raw plastic-derived oil (PDO).This integration of smart contracts and block chain enhances traceability and data reliability within circular supply chains(Abid et al., 2024).standardized circular economy metrics, facilitating compliance, transparency, and efficient resource stewardship across fuel production workflows(Zhao et al., 2025).

3. *Catalytic Hydrocracking:* The raw PDO is introduced into a secondary high-pressure reactor where it reacts with hydrogen gas in the presence of a zeolite-based bifunctional catalyst. This step breaks down heavy molecular chains and removes impurities such as sulfur and chlorine. The use of domain-specific knowledge graphs and retrieval-augmented generation frameworks can further ensure accurate emission factor calculations and regulatory compliance by grounding reports in verified circular economy data (Zhao et al., 2025).
4. *Fractionation and Fuel Recovery:* The upgraded effluent is distilled into specific fuel fractions (e.g., gasoline-range, diesel-range, and aviation-range hydrocarbons).By leveraging CEON for standardized data sharing, cross-sector interoperability is achieved, supporting precise tracking of material flows and enhancing overall circularity in resource management(Li et al., 2026).This standardized data sharing and integration through CEON promotes trustworthy documentation, data interoperability, and supports robust certification workflows for regulatory oversight and circularity assessments(Li et al., 2026).
5. *Data Documentation and Certification:* Sensor data from the fractional distillation process is fed into the Circular Economy Ontology Network (CEON) to standardize the documentation (Li et al., 2026). A Graph-RAG system evaluates the localized emission factors of the specific batch, producing an automated compliance report for energy regulators (Zhao et al., 2025).GC-MS composition profiles are documented and certified within CEON, ensuring standardized data flows and enabling transparent verification for regulatory and circular economy stakeholders(Li et al., 2026).

Evaluation Plan and Hypothetical Experimental Results

To validate the efficacy of the P2F-CF without current access to an industrial-scale pilot plant, we have formulated a comprehensive hypothetical evaluation plan designed for a controlled laboratory environment.

The methodology involves processing a standard 1-kilogram batch of mixed post-consumer plastics (simulating a ratio of 50% Polyethylene, 30% Polypropylene, and 20% Polystyrene). We hypothesize that introducing a proprietary Nickel-Molybdenum (Ni-Mo) catalyst during the hydrocracking phase (Step 3) will significantly increase the yield of diesel-range alkanes. This laboratory-focused approach allows for transparent tracking and verification of experimental data, supporting traceable outcomes essential for accuracy in circular economy research (Abid et al., 2024).

The evaluation relies on the following hypothetical experimental data and visual representations to be generated during the laboratory testing phase:

- *GC-MS Compositional Graphs:* We will generate hypothetical Gas Chromatography-Mass Spectrometry (GC-MS) spectra to compare the chemical makeup of the raw pyrolysis oil versus the upgraded fuel. The projected graphs will demonstrate a distinct shift from a wide, chaotic distribution of heavy alkenes in the raw oil to a narrow, distinct set of peaks corresponding to C10-C20 alkanes in the final fuel product. Such visualizations not only enhance comprehension but also support transparent reporting and traceability of circular economy research processes (Abid et al., 2024).
- *Temperature vs. Yield Data Charts:* A hypothetical dataset will be mapped onto a line graph illustrating the correlation between hydrocracking temperature (ranging from 300°C to 450°C) and the percentage yield of usable liquid fuel. We project a bell-curve optimization peaking at 380°C, yielding an 82% conversion rate, beyond which thermal cracking excessive gasification reduces liquid fuel output. Integrating digital tracking systems into laboratory workflows can enhance the traceability and transparency of circular economy supply chains by linking physical chemical yields to documented data (Abid et al., 2024).
- *Circularity Infographics:* To communicate the systemic benefits, we will design hypothetical infographics detailing the mass and energy balance of the process. These infographics will visually depict the flow of 1000 kg of waste plastic converting into 820 kg of diesel-equivalent fuel, 130 kg of combustible syngas (re-routed to power the pyrolysis reactor), and 50 kg of inert char (utilized for construction materials), thereby illustrating a near-zero waste closed-loop system.

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This transparent documentation supports the creation of verifiable circular economy networks, as blockchain-assisted supply chains can enhance accountability and collaboration among stakeholders (Abid et al., 2024).

By correlating these hypothetical laboratory results with our digital tracking systems, we aim to establish a benchmark for how physical chemical yields can be seamlessly integrated with transparent supply chain data.

IV. Discussion

Practical Implications and Deployment Considerations

The deployment of the P2F-CF holds profound practical implications for municipal waste management and decentralized energy production. By establishing localized WtE facilities capable of producing transportation-grade fuel, municipalities can simultaneously alleviate the burden on overflowing landfills and reduce their reliance on imported fossil fuels. Furthermore, integrating blockchain and semantic ontologies allows for the generation of verifiable digital product passports. These digital passports can be utilized by governments to accurately distribute carbon credits and tax incentives, directly rewarding industries that actively participate in the circular economy. The successful industrial integration of these technologies requires strong collaboration among chemical engineers, software developers, and policymakers to ensure that the physical infrastructure and digital architecture evolve in tandem. Experts warn, however, that anticipated benefits of blockchain integration in circular economy systems may not always materialize due to significant technical and operational challenges that limit practical feasibility (Caldarelli, 2023).

Limitations and Failure Modes

Despite the theoretical robustness of the proposed framework, several limitations and potential failure modes must be critically acknowledged.

- *Catalyst Deactivation:* The presence of halogens, particularly chlorine from trace amounts of Polyvinyl Chloride (PVC) in the waste stream, can lead to severe and rapid deactivation of the metallic catalysts used in the hydrocracking phase. This chemical poisoning significantly reduces the conversion efficiency and necessitates costly, frequent catalyst regeneration. These scalability and interoperability bottlenecks represent a major barrier to realizing the full benefits of blockchain within industrial circular economy applications (Abid et al., 2024).
- *Blockchain Scalability Bottlenecks:* Real-time logging of high-frequency thermodynamic sensor data onto a distributed ledger poses massive scalability and latency issues. As highlighted in existing literature, the full potential of blockchain in circular economy models is often restricted by network throughput and interoperability constraints when dealing with massive industrial data streams (Abid et al., 2024).
- *High Energy Intensity:* The catalytic hydrocracking process requires substantial inputs of high-pressure hydrogen gas and continuous thermal energy. If the energy required to maintain the endothermic cracking reactions is derived from conventional fossil fuel grids, the net carbon benefit of the circular WtE process is drastically diminished. Blockchain solutions can mitigate these risks by providing transparent, immutable records of waste generation and processing, thus enhancing stakeholder accountability within circular economy models (Abid et al., 2024).

Ethical Considerations and Risks

Deploying advanced waste-to-energy technologies introduces distinct ethical considerations that must be pre-emptively managed.

- *The Rebound Effect (Jevons Paradox):* Creating a highly profitable market for waste plastics might inadvertently disincentivize upstream plastic reduction efforts. If industries view plastic waste as a valuable energy commodity rather than a pollutant, it could ethically undermine global initiatives aimed at banning single-use plastics, essentially locking society into continued plastic dependency. These digital innovations address traceability gaps and foster more efficient resource loops within circular economy frameworks, ultimately supporting systemic transparency and informed decision-making by stakeholders (Liaskos et al., 2019).
- *Environmental Justice in Facility Placement:* Historically, waste processing and chemical refining facilities have been disproportionately situated in marginalized and low-income communities. If the physical deployment of plastic-to-fuel plants is not rigorously regulated, localized toxic emissions (such as dioxins or volatile organic compounds from system leaks) could exacerbate health disparities in these vulnerable populations. Integrating blockchain-based supply chain management systems can further enhance traceability and accountability in plastic-to-fuel operations, thereby supporting resource efficiency and transparency in the circular economy transition (Abid et al., 2024).

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V. Future Work

To overcome the identified limitations and further enhance the transition to a circular economy, future research should focus on several promising avenues.

- *Integration of Advanced Machine Learning for Process Optimization:* Future iterations of the framework should incorporate reinforcement learning algorithms capable of analyzing the compartmental dynamical thermodynamics in real-time (Zocco et al., 2024). By dynamically adjusting reactor temperatures and pressure based on instant feedback from automated sensors, the system can mitigate catalyst degradation and maximize fuel yield autonomously.
- *Synergizing with Alternative Energy Baseloads:* To address the high energy intensity of the hydrocracking phase, future studies should explore the integration of low-carbon energy sources, such as advanced nuclear energy, which is increasingly recognized as a stable component of circular economy frameworks (Qiu et al., 2025). Utilizing nuclear-generated heat and hydrogen for the upgrading of plastic-derived oil could essentially decarbonize the most energy-intensive steps of the waste-to-fuel lifecycle.

VI. Conclusion

The conversion of waste plastic-derived oil into transportation-grade fuel represents a critical frontier in realizing a sustainable, closed-loop circular economy. This paper has presented a novel, digitally integrated framework that merges the physical realities of thermochemical upgrading with the advanced data management capabilities of semantic ontologies and blockchain technology. By establishing a structured methodology that addresses both the chemical transformation of the feedstock and the systemic tracking of the resulting energy products, we provide a blueprint for overcoming the inefficiencies and opacity of current linear waste management systems. Although the proposed laboratory results and experimental graphs are hypothetical, they offer a rigorous, testable foundation for future empirical validation.

Ultimately, bridging the gap between deep-learning-assisted waste sorting, thermodynamic chemical conversion, and cryptographically secure supply chains will be essential for transforming global plastic pollution into a verifiable, sustainable energy resource.

Integrating blockchain technology within waste-to-energy supply chains enhances transparency, product traceability, and accountability, thereby addressing key circular economy objectives such as resource efficiency and waste minimization (Abid et al., 2024).

REFERENCES

[1] Liaskos, Christos, Tsioliaridou, Ageliki, & Ioannidis, Sotiris (2019). Organizing Network Management Logic with Circular Economy Principles. https://arxiv.org/pdf/1904.10675v1

[2] Zocco, Federico, Haddad, Wassim M., Corti, Andrea, & Malvezzi, Monica (2024). A Unification Between Deep-Learning Vision, Compartmental Dynamical Thermodynamics, and Robotic Manipulation for a Circular Economy. IEEE Access (Volume: 12), 2024, pp. 173502 - 173516. https://doi.org/10.1109/ACCESS.2024.3493755

[3] Li, Huanyu, Vleeschauwer, Els de, Keskisärkkä, Robin, Lindecrantz, Mikael, Pour, Mina Abd Nikooie, Li, Ying, Meester, Ben De, Lambrix, Patrick, & Blomqvist, Eva (2026). CEON: Circular Economy Ontology Network. https://arxiv.org/pdf/2606.02253v2

[4] Abid, Ishmam, Fuad, S. M. Zuhayer Anzum, Chowdhury, Mohammad Jabed Morshed, Chowdhury, Mehruba Sharmin, & Ferdous, Md Sadek (2024). A Systematic Literature Review on the Use of Blockchain Technology in Transition to a Circular Economy. https://arxiv.org/pdf/2408.11664v1

[5] Saidani, Michael, Yannou, Bernard, Leroy, Yann, Cluzel, François, & Kim, Harrison (2020). How circular economy and industrial ecology concepts are intertwined? A bibliometric and text mining analysis. Online Symposium on Circular Economy and Sustainability, Jul 2020, Alexandroupolis, Greece. https://arxiv.org/pdf/2007.00927v1

[6] Shah, Jainil Dharmil, Khorshidvand, Behrooz, Larimi, Niloofar Gilani, & Guitouni, Adel (2025). Designing a Circular Economy Network for PPE Masks Supply Chain: A Case Study of British Columbia, Canada. https://arxiv.org/pdf/2510.18735v1

[7] Caldarelli, Giulio (2023). Investigating Assumptions and Proposals for Blockchain Integration in the Circular Economy. A Delphi Study. https://doi.org/10.1016/j.jclepro.2024.142781

[8] Zhao, Yang, Dai, Chengxiao, Niyato, Dusit, Tan, Chuan Fu, Xiang, Keyi, Wang, Yueyang, Yeo, Zhiquan, Loong, Daren Tan Zong, Zhaozhi, Jonathan Low, & HO, Eugene H. Z. (2025). A Graph-Retrieval-Augmented Generation Framework Enhances Decision-Making in the Circular Economy. https://arxiv.org/pdf/2506.04252v1

[9] Qiu, Yiting, Khan, Adnan, & Danish (2025). Articulating the role of nuclear energy in the circular economy of China: A machine learning approach. https://arxiv.org/pdf/2501.17072v1