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Optimization of Pyrolysis Process Parameters: A Comprehensive Review

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ABSTRACT

This comprehensive review analyzes the optimization of critical pyrolysis process parameters—including reaction temperature, heating rate, vapor residence time, and catalyst loading—to maximize the yield and quality of bio-oil, bio char, and syngas. Operating within an optimal 450°C–550°C range balances devolatilization against secondary cracking, which directly controls liquid output. Incorporating acidic catalysts (like ZSM-5) lowers activation energy, yielding stable, deoxygenated bio-crude. Advanced statistical methods like Response Surface Methodology (RSM) and predictive Machine Learning models are vital for mapping multi-objective outcomes. Furthermore, innovative configurations like catalytic co-pyrolysis exploit synergistic effects between biomass and plastics to eliminate sorting costs and improve fuel properties. However, real-world scaling faces significant hurdles, including high computational costs, rapid catalyst coking, heat transfer resistance, and feedstock variability. Resolving these engineering trade-offs is essential for transforming bench-scale pyrolysis into a profitable, commercial-scale circular economy system.

1. INTRODUCTION

The increasing demand for energy, coupled with the rapid depletion of fossil fuel reserves and rising environmental concerns, has driven the need for sustainable and renewable energy sources. Biomass, which includes organic materials such as agricultural residues, forest waste, dry leaves, and even wet organic matter, is one of the most promising alternatives for energy generation. Among the various biomass conversion technologies, pyrolysis has gained significant attention due to its ability to convert solid biomass into valuable products such as biochar, bio-oil, and syngas. Pyrolysis is a thermochemical decomposition process that occurs in the absence or near absence of oxygen. During this process, biomass is subjected to high temperatures (typically between 300°C and 700°C), resulting in the breakdown of complex organic compounds into simpler substances. The products obtained from pyrolysis depend on factors such as temperature, heating rate, type of biomass, and reactor design. Solid biomass such as coal, dry leaves, and wet leaves exhibits different thermal behaviours, making it essential to design a reactor capable of handling varied feedstock efficiently.

The development of a small-scale pyrolysis reactor is particularly important for decentralized and rural applications, where biomass waste is readily available but often underutilized. Such a system can help in converting waste into useful energy and carbon-rich materials, thereby reducing environmental pollution and supporting sustainable waste management practices. A small-scale reactor is also cost-effective, portable, and suitable for experimental studies, making it ideal for academic and research purposes. Pyrolysis reactor is designed and developed to perform the thermal decomposition of different types of biomass, including coal, dry leaves, and wet leaves. The reactor is engineered to ensure controlled heating, minimal oxygen entry, and efficient collection of pyrolysis products. Special consideration is given to the challenges associated with processing wet biomass, such as higher moisture content and energy requirements for drying. The study focuses on understanding the operational parameters of the reactor, such as temperature control, residence time, and feedstock characteristics, and their influence on the yield and quality of pyrolysis products. By comparing the performance of the reactor with different biomass inputs, the project aims to evaluate its efficiency, versatility, and practical applicability. Overall, this project contributes to the development of an eco-friendly and sustainable technology for biomass utilization. It highlights the potential of small-scale pyrolysis systems in energy recovery, waste reduction, and environmental protection, while also providing a foundation for further advancements in biomass conversion technologies.

2. LITERATURE REVIEW

A. Awad, M. I., Makkawi, Y., & Hassan, N. M. (2024).

Yield and Energy Modeling for Biochar and Bio-Oil Using Pyrolysis Temperature and Biomass Constituents. *ACS Omega*, *9*(16), 18654-18667. Cited by: 44 Pyrolysis offers a sustainable and efficient approach to resource utilization and waste management, transforming organic materials into valuable products. The quality and distribution of the pyrolysis products highly depend on the constituents' properties and set process parameters. This research aims to investigate and model this dependency, offering decision-makers a tool to guide them when designing the process for a particular application. Experimental data on the pyrolysis of various types of feedstock processed at a wide range of pyrolysis temperatures (350–650 °C) are utilized to develop the prediction models. Four variables are modelled: the yield and energy content for both the bio char and bio-oil as a function of the pyrolysis temperature and feedstock characteristics. The models developed had very good prediction power with the coefficient of determination above 90%. The results highlight the advantages of food waste (leftover) as a suitable feedstock to produce biochar at the pyrolysis temperature within the range of 450–550 °C. Furthermore, the biofuels produced from food waste are found to be of good quality, with the bio-oil exceptionally high in energy content (HHV = 34.6 MJ/kg), which is almost 80% of that of diesel. The developed models provide a tool for predicting the biofuel yield and quality based on the feedstock selection and process temperature.

B. Charis, G., Danha, G., Muzenda, E., & Nhubu, T. (2021).

Modeling a Sustainable, Self-Energized Pine Dust Pyrolysis System with Staged Condensation for v Optimal Recovery of Bio-Oil. *Frontiers in Energy Research*, *8*. Cited by: 5

There has been a drive toward higher value conversion alternatives for biomass wastes such as sawmill waste. Waste lignocellulosic biomass has become an attractive source of renewable solid, liquid and gaseous fuels for heating, power and transportation. Although thermochemical technologies for biomass to biofuel conversions such as gasification and methanol synthesis and lignocellulosic ethanol production are at the brink of commercialization, they are characteristically large investment projects requiring high technical expertise and could take another decade to fully reach developing countries. Pyrolysis has been identified as a low investment technology that is less technically complex than other thermochemical methods and could be a short to medium-term answer to the energy poverty in developing regions like Southern Africa. It also has advantages of high efficiency and effective utilization of feedstock over biological conversion methods, with high yields of a liquid fuel or intermediate referred to as "bio-oil". The target for this particular study is lower value applications of bio-oil. One of the appealing avenues is the substitution of heavy fuel oil (HFO) in the power generation and marine industries, since pyrolysis oil has compatible properties with the HFO. Characterization and blending tests with HFO showed the bio-oil to be miscible with HFO, improving overall efficiency and reducing energy requirements for heating and pumping HFO in a flowable state. The motivation for this study is therefore to provide an alternative power generation source, especially for remote areas detached from the grid, where timber sawmills are mostly located.

C. Design of an Energy-Efficient Pilot-Scale Pyrolysis Reactor Using Low-Cost Insulating Materials. (2025). MDPI.

A pilot-scale reactor prototype was designed to produce hydrocarbons through the catalytic pyrolysis process of low-density polyethylene, thereby extending its life cycle and contributing to energy efficiency and sustainability. The reactor consists of a stainless-steel tank encased in a ceramic jacket with refractory cement and clay bricks. The tank, made of 304 stainless steel, ensures mechanical strength and efficient heat transfer to the reactor core. A spiral condenser was incorporated into a water tank to cool the vapors and recover the liquid oil. The insulating materials, ceramic, refractory cement and clay brick, demonstrated a high combined thermal resistance of 0.159 $m^2 \cdot K/W$. Simulations and energy flow calculations demonstrated that heat is efficiently directed to the reactor core, reaching 350 °C with only 3000–3800 W, while the outside of the jacket remained close to 32 °C. These results confirm that the proposed design improves thermal efficiency and optimizes energy use for catalytic pyrolysis. The novelty of this design lies in its energy-efficient configuration, which can be replicated in rural regions worldwide due to the accessibility of its construction materials. This reactor was developed based on a smaller-scale model that previously yielded excellent results.

D. Devi, M., Rawat, S., & Sharma, S. (2020).

A comprehensive review of the pyrolysis process: from carbon nanomaterial synthesis to waste treatment. *Oxford Open Materials Science*, *1*(1). Cited by: 174
Thermally induced chemical decomposition of organic materials in the absence of oxygen is defined as pyrolysis. This process has four major application areas: (i) production of carbon materials, (ii) fabrication of pre-patterned micro and nano carbon-based structures, (iii) fragmentation of complex organic molecules for analytical purposes and (iv) waste treatment. While the underlying process principles remain the same in all cases, the target products differ owing to the phase and composition of the organic precursor, heat-treatment temperature, influence of catalysts and the presence of post-pyrolysis steps during heat-treatment. Due to its fundamental nature, pyrolysis is often studied in the context of one particular application rather than as an independent operation. In this review article, an effort is made to understand each aspect of pyrolysis in a comprehensive fashion, ensuring that all state-of-the-art applications are approached from the core process parameters that influence the ensuing product. Representative publications from recent years for each application are reviewed and analyzed. Some classical scientific findings that laid the foundation of the modern-day carbon material production methods are also revisited. In addition, classification of pyrolysis, its history and nomenclature and the plausible integration of different application areas are discussed.

E. Hylton, J., Hugen, A., Rowland, S. M., Griffin, M., & Tunstall, L. E. (2024).

Relevant biochar characteristics influencing compressive strength of biochar-cement mortars. *Biochar*, *6*. Cited by: 29
To counteract the contribution of CO_2 emissions by cement production and utilization, biochar is being harnessed as a carbon-negative additive in concrete. Increasing the cement replacement and biochar dosage will increase the carbon offset, but there is large variability in methods being used and many researchers report strength decreases at cement replacements beyond 5%. This work presents a reliable method to replace 10% of the cement mass with a vast selection of biochar's without decreasing ultimate compressive strength, and in many cases significantly improving it. By carefully quantifying the physical and chemical properties of each biochar used, machine learning algorithms were used to elucidate the three most influential biochar characteristics that control mortar strength: initial saturation percentage, oxygen-to-carbon ratio, and soluble silicon. These results provide additional research avenues for utilizing several potential biomass waste streams to increase the biochar dosage in cement mixes without decreasing mechanical properties.

F. Selective Product Enhancement in an Auger Reactor: Pyrolysis of Pine Bark through In Situ ... (2025). PMC
In biomass pyrolysis, final product selectivity is governed not only by major reaction conditions like temperature and heating rate but also by complex vapor–solid interactions and secondary reactions. Yet, the influence of internal flow configuration on pyrolysis vapor remains poorly understood in continuous pyrolysis systems. This study aims to evaluate how controlled vapor–solid interactions via changes in the vapor outlet port location affect the distribution and transformation of pyrolysis products. Experiments were performed in a continuous laboratory-scale auger reactor, processing pine bark at highest treatment temperatures (HTT) of 600, 700, and 800 °C. The reactor featured five independently heated zones and six selectable vapor outlet ports, enabling three vapor flow modes: parallel flow (PF, conventional concurrent flow operation) and two counterflow (CF

configurations to systematically manipulate vapor–solid contact. Results showed that one of the CF configurations, where vapors passed through the coldest (the incoming) biomass zone before exiting, enhanced vapor condensation on incoming biomass and promoted secondary reactions, leading to up to a 15.5% relative increase in biochar yield compared to PF. The increase in biochar yield was accompanied by an increase in fixed carbon yield, and H_2 and CH_4 yields, indicating intensified thermal cracking and polymerization of pyrolysis vapors. In contrast, the CF configuration involving vapor recirculation without interaction with the coldest zone favored external condensation and achieved the highest bio-oil recovery. The PF configuration exhibited the lowest char yield and the highest unaccounted carbon fraction due to poor vapor condensation at elevated outlet temperatures. These findings demonstrate that the manipulation of vapor–solid interactions serves as a critical parameter for steering pyrolysis pathways toward targeted product enhancement, offering a scalable approach for optimizing biochar, gas, and bio-oil yields through in situ vapor recirculation.

G. S. Yorgun, D. Yıldız, Slow pyrolysis of paulownia wood: effects of pyrolysis parameters on product yields and bio-oil characterization, J. Anal. Appl. Pyrolysis. 114 (2015) 68–78.

The study by S. Yorgun and D. Yıldız (2015) investigates the slow pyrolysis of *paulownia wood* to understand how different pyrolysis parameters affect product yields and the characteristics of bio-oil. In this research, the biomass was subjected to controlled heating under oxygen-limited conditions, and the effects of temperature on the formation of biochar, bio-oil, and gases were analyzed. The results showed that increasing the pyrolysis temperature led to a decrease in biochar yield while enhancing gas production due to thermal cracking of volatile compounds. The yield of bio-oil increased up to an optimum temperature (around 500°C) and then decreased at higher temperatures. The produced bio-oil was further analyzed using techniques such as GC-MS, revealing the presence of various organic compounds including phenols, acids, and hydrocarbons. The study concluded that pyrolysis temperature is a critical parameter influencing product distribution and that paulownia wood is a suitable biomass for biofuel production. These findings are important for optimizing pyrolysis conditions and are highly relevant for small-scale reactor design and biomass conversion studies.

H. J.A. Okolie, A. Mukherjee, S. Nanda, A.K. Dalai, J.A. Kozinski, Next-generation biofuels and platform biochemicals from lignocellulosic biomass, Int. J. Energy Res. 45 (10) (2021) 14145–14169.

The paper by J. A. Okolie, A. Mukherjee, S. Nanda, A. K. Dalai, and J. A. Kozinski (2021) provides a comprehensive review of the production of next-generation biofuels and platform biochemicals from lignocellulosic biomass. The study focuses on the conversion of biomass materials such as agricultural residues, wood, and plant waste into valuable energy products using thermochemical and biochemical processes, including pyrolysis, gasification, and fermentation. It highlights the importance of lignocellulosic biomass, which is mainly composed of cellulose, hemicellulose, and lignin, as a sustainable and abundant resource for renewable energy production. The authors discuss various advanced technologies for improving fuel quality and yield, such as catalytic upgrading and process optimization. The paper also emphasizes the challenges associated with biomass conversion, including high oxygen content in bio-oil, process inefficiencies, and economic constraints. Overall, the study concludes that with proper technological advancements and process improvements, lignocellulosic biomass has strong potential to replace fossil fuels and contribute to sustainable energy development, making it highly relevant for biomass pyrolysis reactor research and applications.

I. N.C. Kokkinos, E. Emmanouilidou, Waste-to-Energy: Applications and Perspectives on Sustainable Aviation Fuel production, Renewable Fuels for Sustainable Mobility, Springer, 2023, pp. 265–286.

The work by N. C. Kokkinos and E. Emmanouilidou (2023) discusses the role of waste-to-energy technologies in the production of sustainable aviation fuel (SAF) and their contribution to sustainable mobility. The study highlights how various waste materials, including municipal solid waste, agricultural residues, and biomass, can be converted into valuable fuels through thermochemical processes such as pyrolysis, gasification, and hydrothermal liquefaction. It emphasizes that converting waste into fuel not only helps in reducing environmental pollution and landfill usage but also supports the transition toward low-carbon aviation fuels. The authors examine different conversion pathways and upgrading techniques required to produce high-quality aviation fuels that meet industry standards. The paper also addresses key challenges such as process efficiency, feedstock variability, and economic feasibility. Overall, the study concludes that waste-to-energy technologies have significant potential for sustainable aviation fuel production, making them an important area of research for future energy systems and highly relevant to biomass pyrolysis and waste conversion projects.

J. A. Pattiya, Catalytic pyrolysis, Direct Thermochem Liquefact. Energy Appl. (2018) 29–64.

The chapter by A. Pattiya (2018) focuses on the concept and application of catalytic pyrolysis as an advanced thermochemical conversion process for producing high-quality fuels from biomass. Unlike conventional pyrolysis, catalytic pyrolysis involves the use of catalysts to improve the composition and properties of the resulting bio-oil by reducing oxygen content and increasing the formation of valuable hydrocarbons. The study explains how different types of catalysts, such as zeolites and metal-based catalysts, influence reaction pathways, promote cracking, deoxygenation, and aromatization reactions, and enhance fuel quality. It also discusses the effects of operating conditions like temperature and catalyst-to-biomass ratio on product yield and composition. The paper highlights that catalytic pyrolysis can significantly upgrade bio-oil into more stable and energy-dense fuels suitable for practical applications. However, it also points out challenges such as catalyst deactivation, coke formation, and higher operational costs. Overall, the study demonstrates that catalytic pyrolysis is a promising approach for improving biomass conversion efficiency and fuel quality, making it highly relevant for advanced pyrolysis reactor development.

K. M.A. Mehmood, G. Ye, H. Luo, C. Liu, S. Malik, I. Afzal, J. Xu, M.S. Ahmad, Pyrolysis and kinetic analyses of Camel grass (Cymbopogon schoenanthus) for bioenergy, Bioresource. Technol. 228 (2017) 18–24.

They study by M. A. Mehmood, G. Ye, H. Luo, C. Liu, S. Malik, I. Afzal, J. Xu, and M. S. Ahmad (2017) investigates the pyrolysis behaviour and kinetic analysis of *Camel grass (Cymbopogon schoenanthus)* as a potential biomass source for bioenergy production. The research primarily uses thermogravimetric analysis (TGA) to study the thermal decomposition characteristics of the biomass under different heating rates. The results show that the decomposition of camel grass occurs in multiple stages, mainly corresponding to the breakdown of hemicellulose, cellulose, and lignin. The study also evaluates important kinetic parameters such as activation energy, which helps in understanding the reaction rate and energy requirement of the pyrolysis process. It was observed that increasing the heating rate shifts the decomposition to higher temperatures and affects the yield distribution. The findings suggest that camel grass is a suitable feedstock for bioenergy production due to its favourable thermal properties. This study is useful for optimizing pyrolysis conditions and provides valuable insights for the design and operation of biomass pyrolysis reactors.

L. B. Zhao, X. Xu, H. Li, X. Chen, F. Zeng, Kinetics evaluation and thermal decomposition characteristics of co-pyrolysis of municipal sewage sludge and hazelnut shell, Bioresource. Technol. 247 (2018) 21–29.

The study by B. Zhao, X. Xu, H. Li, X. Chen, and F. Zeng (2018) investigates the thermal decomposition behavior and kinetic characteristics of the co-pyrolysis of municipal sewage sludge and hazelnut shell. The research focuses on understanding how combining these two different feedstocks affects the overall pyrolysis process and product formation. Using thermogravimetric analysis (TGA), the authors examined decomposition patterns at various heating rates and evaluated key kinetic parameters such as activation energy. The results showed that co-pyrolysis leads to synergistic effects, improving the thermal degradation behavior compared to individual materials. The interaction between sewage sludge and biomass enhances volatile release and can lead to better product yield and quality. The study also found that blending ratios significantly influence the decomposition stages and reaction kinetics. Overall, the research concludes that co-pyrolysis is an effective approach for waste management and energy recovery, offering improved efficiency and potential for producing valuable fuels, making it highly relevant for advanced biomass pyrolysis systems.

M. J.E. White, W.J. Catallo, B.L. Legendre, Biomass pyrolysis kinetics: a comparative critical review with relevant agricultural residue case studies, J. Anal. Appl. Pyrolysis. 91 (1) (2011) 1–33.

The paper by J. E. White, W. J. Catallo, and B. L. Legendre (2011) presents a comprehensive and critical review of biomass pyrolysis kinetics, with a focus on agricultural residues as feedstock. The study analyses various kinetic models and experimental methods used to understand the thermal decomposition behaviour of biomass components such as cellulose, hemicellulose, and lignin. It highlights that pyrolysis is a complex, multi-stage process influenced by factors like temperature, heating rate, particle size, and biomass composition. The authors compare different kinetic approaches, including single-step and multi-step reaction models, and discuss their limitations in accurately predicting real pyrolysis behaviour. The review also includes case studies on agricultural residues, emphasizing their potential for bioenergy production. Overall, the paper concludes that a deeper understanding of reaction kinetics is essential for improving reactor design, optimizing operating conditions, and enhancing product yield, making it highly relevant for biomass pyrolysis research and small-scale reactor development.

N. J. Nascimento, E. Camelo, M. Carvalho, C. Virgens, Kinetic evaluation of Pachira aquatica Aubl biomass slow pyrolysis towards to biochar production, Biofuels. 15 (6) (2024) 615–625.

The study by J. Nascimento, E. Camelo, M. Carvalho, and C. Virgens (2024) focuses on the kinetic evaluation of the slow pyrolysis of *Pachira aquatica Aubl* biomass with the aim of maximizing biochar production. The research investigates the thermal decomposition behaviour of the biomass using techniques such as thermogravimetric analysis (TGA) under controlled heating conditions. The results show that the decomposition occurs in multiple stages corresponding to the breakdown of hemicellulose, cellulose, and lignin. The study also determines important kinetic parameters, including activation energy, which helps in understanding the energy requirement and reaction rate of the pyrolysis process. It was observed that slow pyrolysis conditions Favor higher biochar yield due to longer residence time and controlled heating rates. The authors conclude that *Pachira aquatica* biomass is a promising feedstock for biochar production, and the findings provide useful insights for optimizing process parameters and improving the design and operation of pyrolysis reactors for efficient biomass conversion.

O. T.G. Ambaye, M. Vaccari, A. Bonilla-Petriciolet, S. Prasad, E.D. van Hullebusch, S. Rtimi, Emerging technologies for biofuel production: a critical review on recent progress, challenges and perspectives, J. Environ. Manage 290 (2021) 112627.

The paper by T. G. Ambaye, M. Vaccari, A. Bonilla-Petriciolet, S. Prasad, E. D. van Hullebusch, and S. Rtimi (2021) presents a critical review of emerging technologies for biofuel production, focusing on recent advancements, challenges, and future perspectives. The study highlights various conversion methods such as thermochemical processes (pyrolysis, gasification), biochemical routes (fermentation, anaerobic digestion), and hybrid technologies for producing biofuels from biomass and waste materials. It emphasizes the importance of utilizing lignocellulosic biomass as a sustainable and abundant resource for renewable energy generation. The authors discuss technological improvements like catalytic upgrading, process integration, and advanced reactor designs to enhance efficiency and product quality. The paper also identifies key challenges, including high production costs, feedstock variability, and scalability issues. Overall, the study concludes that while significant progress has been made, further research and innovation are required to make biofuel production technologies economically viable and environmentally sustainable, making it highly relevant for biomass pyrolysis and small-scale reactor development projects.

P. R.K. Mishra, M. Misra, A.K. Mohanty, Value-added biocarbon production through slow pyrolysis of mixed bio-oil wastes: studies on their physicochemical characteristics and structure–property–processing co-relation, Biomass Convers. Biorefined. 14 (6) (2024) 7887–7901.

This paper titled "Value-added biocarbon production through slow pyrolysis of mixed bio-oil wastes: studies on their physicochemical characteristics and structure–property–processing co-relation" (Mishra, Misra & Mohanty, 2024, *Biomass Conversion and Biorefinery*) focuses on converting mixed bio-oil waste into useful biocarbon using a slow pyrolysis process. The study investigates how different pyrolysis temperatures (mainly around 600 °C and 900 °C) influence the yield, structure, and properties of the resulting biocarbon. It shows that higher temperatures significantly improve key properties such as carbon content, thermal stability, graphitic structure, and electrical/thermal conductivity, due to enhanced carbonization and removal of oxygen and hydrogen components. Advanced characterization techniques like SEM, Raman spectroscopy, elemental analysis, and surface studies were used to understand the morphology and microstructure of the biocarbon. The results establish a clear structure–property–processing relationship, meaning that processing conditions (temperature and heating behaviour) directly control the final material properties. Overall, the study highlights that waste bio-oil can be effectively upgraded into high-value carbon materials suitable for applications in energy storage, composites, and advanced carbon-based materials.

Q. N. Schmitt, A. Apfelbacher, N. J¨ager, R. Daschner, F. Stenzel, A. Hornung, Thermo- chemical conversion of biomass and upgrading to biofuel: the Thermo-Catalytic Reforming process–a review, Biofuel. Bioproduct. Biorefining 13 (3) (2019) 822–837.

The paper "Thermo-chemical conversion of biomass and upgrading to biofuel: The Thermo-Catalytic Reforming process – a review" (Schmitt et al., 2019) published in *Biofuels, Bioproducts and Biorefining* provides a detailed overview of the Thermo-Catalytic Reforming (TCR®) technology for converting biomass into advanced biofuels. The authors explain that TCR is a two-stage thermochemical process combining intermediate pyrolysis followed by catalytic reforming. This integrated approach converts various biological wastes and residue biomass into valuable energy products such as hydrogen-rich syngas, high-quality liquid bio-oil, and solid char. A key focus of the review is the improvement in fuel quality achieved through TCR, where the produced bio-oil has low water and oxygen content, high carbon content, and higher heating value, making it more suitable for direct energy use or further upgrading. The paper also discusses downstream upgrading routes, especially hydrotreatment (hydrodeoxygenation/hydrogenation), which further refines TCR bio-oil into transportation-grade fuels like gasoline and diesel that can meet standards such as EN 228 and EN 590. It highlights catalyst systems (e.g., $NiMo/Al_2O_3$, $CoMo/Al_2O_3$, Ru/C) and operating conditions used in fuel upgrading. Overall, the review emphasizes TCR as a promising and scalable pathway for waste biomass valorisation, supporting sustainable production of biofuels, reduction of waste streams, and integration into existing fuel infrastructure

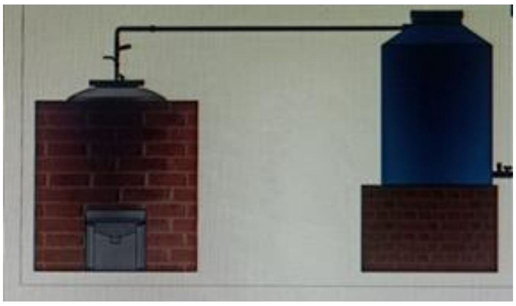

FIGURE 1: Prototype

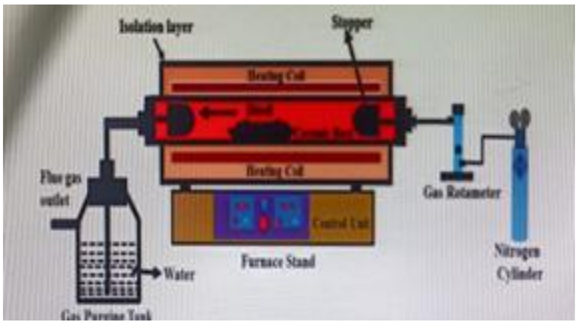

FIGURE 2: Pyrolysis experiment set up

CONCLUSION

This comprehensive review has systematically analyzed the multi-dimensional landscape of pyrolysis process parameter optimization, reconciling experimental behaviors with underlying transport phenomena, kinetic pathways, and advanced computational modeling. The structural distribution and compositional quality of bio-oil, bio-char, and pyrolytic gas are governed by a delicate, highly non-linear interplay of operational variables. Reaction temperature remains the primary thermodynamic driver, dictating the initial volatilization regimes and secondary cracking pathways. However, its influence is profoundly modified by the heating rate and intra-particle thermal gradients, where fast pyrolysis regimes (micro-scale particle sizes) maximize condensable bio-oil yields, while slow pyrolysis configurations favor high-fixed-carbon bio-chars. A critical synthesis of recent optimization methodologies reveals a definitive paradigm shift away from empirical, One-Factor-at-a-Time (OFAT) experimental approaches toward multi-variable mathematical frameworks. Response Surface Methodology (RSM), predominantly utilizing Box–Behnken and Central Composite Designs, has proven highly effective at quantifying the synergistic interactions between parameters—such as the coupled effects of temperature and residence time on polycyclic aromatic hydrocarbon (PAH) formation. Concurrently, data-driven modeling utilizing Machine Learning (ML), Artificial Neural Networks (ANN), and Genetic Algorithms has unlocked unprecedented predictive capabilities, allowing for the accurate forecasting of product yields across highly heterogeneous feedstocks without requiring computationally prohibitive, first-principles CFD (Computational Fluid Dynamics) simulations.However, a persistent disconnects remains between laboratory-scale optimization models and industrial realities. Most optimization models rely on idealized, tightly controlled bench-scale reactors. When scaled up to fluidized-bed or auger systems, these models often encounter unpredictable deviations due to non-isothermal zones, mass transfer limitations, and auto-catalytic interactions triggered by fluctuating feedstock mineral contents.

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