Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 12, No.1, December : 2024

CATALYTIC PYROLYSIS OF WOOD BIOMASS

Dr Tanushree Bhattacharjee Assistant Professor, Department of Chemical Engineering, Vishwakarma Institute of Technology, Pune – 411057
Subhadeep Chakrabarti Department of Chemical Engineering, Vishwakarma Institute of Technology, Pune – 4110
Sumitkumar Prasad Department of Chemical Engineering, Vishwakarma Institute of Technology, Pune – 4110
Harsh Mule Department of Chemical Engineering, Vishwakarma Institute of Technology, Pune – 4110
Mayuresh Naikwade Department of Chemical Engineering, Vishwakarma Institute of Technology, Pune – 4110
Shreyash Koyale Department of Chemical Engineering, Vishwakarma Institute of Technology, Pune – 4110

ABSTRACT:

Biomass pyrolysis is a significant research area as it can produce a range of products such as char, bio-oil, and syngas, which can be used as fuels or green chemicals. During biomass pyrolysis, lignocellulosic materials thermally degrade in the absence of oxygen at atmospheric pressure over a specific residence time, forming solid char, bio-oil, and syngas. For bio-oil to be used as a fuel source or processed into chemicals, it must be upgraded. Catalytic pyrolysis is a highly effective method for enhancing the quality of bio-oil. This study provides a comprehensive review of the latest advancements in the catalytic pyrolysis of biomass, focusing on improvements in catalysts and the catalytic pyrolysis process. Firstly, kinetic analysis of our wood biomass was carried out using isoconversional models and graph plotting. Then a simulation was run on Aspen Plus by designing a fluidized bed reactor for the pyrolytic process. The concept of Machine Learning was applied by taking into consideration the synergistic effects of combining different pyrolytic biomass, which we have taken as wood and algae. Finally, a comprehensive market survey was performed on biochar to assess the commodities and factors affecting the need and production of biochar globally.

Index –
Biomass, Kinetics, Fluidisation, Pyrolysis, Synergy

I. INTRODUCTION

Biomass pyrolysis has emerged as a significant research focus due to its versatility in generating various products such as char, bio-oil, and syngas. This process is particularly important as it offers multiple options for producing renewable fuels and green chemicals. During biomass pyrolysis, lignocellulosic materials undergo thermal degradation in an oxygen-free environment at atmospheric pressure over a specific residence time, resulting in the production of solid char, bio-oil, and syngas. If bio-oil is intended for use as a fuel source or for chemical production, it requires upgrading to enhance its quality. Catalytic pyrolysis has been identified as the most promising method for this purpose, as it significantly improves the quality of bio-oil. This study provides an improved review of the catalytic pyrolysis of biomass, emphasizing recent advancements in catalysts and the catalytic pyrolysis process.

In our research, we first conducted a kinetic analysis of wood biomass using isoconversional models and graphical plotting techniques to understand the thermal degradation behaviour. Subsequently, we performed a simulation using Aspen Plus by designing a fluidized bed reactor tailored for the pyrolytic process. To further optimize the process, we applied machine learning concepts, taking into account the synergistic effects of combining different types of pyrolytic biomass, specifically wood and algae. This innovative approach aimed to enhance the efficiency and yield of the pyrolysis process. Lastly, we conducted a comprehensive market survey on biochar to evaluate global production trends, demand, and the various factors influencing the market. This survey provided valuable insights into the economic aspects and potential growth opportunities in the biochar industry. By integrating advanced analytical techniques, simulation, and market analysis, our study aims to contribute to the development of more efficient and economically viable biomass pyrolysis technologies.

1.1 NEED OF PYROLYSIS :

Pyrolysis offers numerous benefits over conventional methods of waste management and energy production, making it a superior alternative in several ways. Unlike traditional incineration, which burns organic material in the presence of oxygen, pyrolysis operates in an oxygen-free environment, reducing the emission of harmful pollutants such as dioxins and furans. This results in a cleaner process with a significantly lower environmental impact. Pyrolysis also offers advantages over traditional fossil fuel extraction and use. It provides a renewable source of energy and chemicals from biomass, reducing dependence on finite fossil resources and contributing to energy security. Furthermore, the bio-oil produced through pyrolysis can be upgraded to high-quality fuels, presenting a sustainable alternative to conventional petroleum-based fuels.

In terms of efficiency, pyrolysis processes can be optimized with catalysts and advanced reactor designs, achieving higher conversion rates and better control over product composition. This flexibility and efficiency make pyrolysis a promising and sustainable technology for waste management and renewable energy production.

1.2 SOURCES OF PYROLYSIS :

Biomass, which includes wood, agricultural residues, algae, and energy crops, is a primary source of pyrolysis. Wood, including sawdust and forestry residues, is a traditional feedstock due to its availability and renewable nature. Agricultural residues such as straw, husks, and stalks are by-products of crop harvesting that can be effectively utilized in pyrolysis. Algae, both microalgae and macroalgae, are promising due to their high productivity and potential for biofuel production. Energy crops like switchgrass and miscanthus are specifically grown for bioenergy and provide a sustainable feedstock for pyrolysis.

Municipal solid waste, particularly its organic fraction, is another significant source of pyrolysis. This includes food scraps, yard waste, and paper. Non-recyclable and mixed plastics within MSW can also undergo pyrolysis to produce valuable fuels and chemicals.

Animal manure and crop residues from agricultural activities are suitable for pyrolysis. Animal manure, a significant by-product of livestock farming, can be converted into biochar and syngas, deriving an efficient solution for nutrient management and renewable energy production.

Forestry residues, such as logging residues, branches, bark, and tops leftover from timber harvesting, are excellent feedstocks for pyrolysis. Forest thinnings, including small-diameter trees and understory vegetation removed during forest management, also provide material for pyrolysis. These residues can be converted into biochar and bio-oil, supporting sustainable forest management and utilization practices.

1.3 PROCESS OF PYROLYSIS :

Pyrolysis is a thermodynamically chemical process that decomposes organic materials without the presence of oxygen, transforming biomass into char, bio-oil, and syngas. The process begins with feedstock preparation, involving drying and grinding the biomass. The feedstock is then heated in reactors such as fixed-bed, fluidized-bed, rotary kiln, or ablative reactors. As the temperature rises, typically between 300°C and 1000°C, the biomass undergoes thermal decomposition, producing char, volatile compounds, and gases. These products are subsequently separated, with char collected at the reactor's bottom, bio-oil condensed from vapours, and syngas captured for fuel or chemical use. Catalytic upgrading can enhance bio-oil quality, reducing oxygen content and increasing stability. Key factors influencing pyrolysis include temperature, heating rate, residence time, and feedstock properties.

1.3.1 *Operating Parameters :*

Temperature is a critical parameter in pyrolysis, significantly influencing the distribution of products. At low temperatures (300°C - 500°C), the process favours the production of char, with relatively limited amounts of bio-oil and syngas. Intermediate temperatures (500°C - 700°C) provide a balanced yield of char, bio-oil, and syngas, making this range optimal for diverse applications. At high temperatures (700°C - 1000°C), the process maximizes syngas production, while reducing the yields of char and bio-oil. Precise control of temperature allows for targeting specific product outputs based on the desired application.

The heating rate plays a crucial role in determining the efficiency and product distribution in pyrolysis. Slow pyrolysis is characterized by lesser heating rates (0.1°C to 1°C per second)and is optimal for maximizing char production. Fast pyrolysis, with heating rates fluctuating from 10°C to 200°C per second, is designed to maximize bio-oil yield. Flash pyrolysis involves extremely high heating rates (>1000°C per second) and is used to optimize syngas yield. Adjusting the heating rate can thus tailor the process towards specific product outputs, enhancing overall process efficiency.

Residence time, or the duration the biomass remains in the reactor, also significantly affects product distribution. Short residence times are preferred in fast and flash pyrolysis processes to maximize the yield of bio-oil and syngas, as they limit the extent of secondary reactions that can degrade these products. Conversely, longer residence times increase char production and allow more secondary reactions to occur, which can affect the quality and composition of bio-oil and syngas. Balancing residence time with other parameters is essential for optimizing pyrolysis outcomes.

The properties of the biomass feedstock, including moisture content, particle size, and composition, are crucial for the efficiency of pyrolysis. Lower moisture content (typically lessthan 10%) is preferred to reduce energy consumption for drying and improve overall process efficiency. Smaller particle sizes

Ensure more uniform heating and faster reaction rates, leading to more consistent product yields. The composition of thefeedstock, such as its lignin, cellulose, and hemicellulose content, also affects the types and quantities of products generated. Different biomass sources, such as wood, agricultural residues, and algae, will thus yield different outcomes based on their inherent properties.

1.3.2 *Products of Pyrolysis*

Char is one of the primary products of pyrolysis and consistsof the solid residue left after the thermal decomposition of biomass. It is rich in carbon and has a porous structure, making it useful for a variety of applications. In agriculture, char, often referred to as biochar, is used as a beneficiary for soil to enhance soil fertility, water retention, and sequestration of carbon. It enhances microbial activity and nutrient availability in the soil, leading to better crop yields. Additionally, char can be used in water and air filtration systems due to its high adsorption capacity. Its stability and long-term persistence in soil make it a valuable tool for mitigating climate change by sequestering carbon that would otherwise be released as CO_2.

Bio-oil is a complex mixture of water, organics, and oxygenated compounds produced from the volatile components released during pyrolysis. This dark, viscous liquid can be used as a renewable fuel or as a feedstock for producing various chemicals. The high oxygen content in bio-oil, however, poses challenges for its direct use as a fuel, necessitating further upgrading processes such as hydrodeoxygenation, catalytic cracking, or emulsification to improve its stability and calorific value. Upgraded bio-oil can be refined into transportation fuels like gasoline and diesel or used as a substitute for heating oil in industrial applications. Its versatility and potential to replace fossil-derived products make bio-oil a key focus in the development of sustainable energy solutions.

Syngas, or synthetic gas, is a mixture of gases predominantly composed of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and methane (CH_4). It is produced from the non-condensable gases released during pyrolysis. Syngas is highly valuable due to its versatility as an energy carrier and chemical feedstock. It can be directly combusted to generate heat and electricity or processed through the Fischer-Tropsch synthesis to produce liquid fuels such as synthetic diesel and methanol. Syngas are also used to produce hydrogen, which is essential for various industrial processes and as a clean fuel in fuel cells. The composition of syngas can be adjusted by modifying the pyrolysis conditions, making it a flexible and strategic product in the pursuit of renewable energy and chemical production

CATALYTIC V/S NON CATALYTIC PYROLYSIS

Catalytic and non-catalytic pyrolysis are two approaches to transforming biomass into valuable products such as bio-oil, syngas, and char. While both processes involve the thermal decomposition of organic materials in the absence of oxygen, the presence of catalysts in catalytic pyrolysis significantly influences the yield and quality of the products.

Non-catalytic pyrolysis relies solely on heat to break down the biomass. The process operates at temperatures typically between 300°C and 700°C. The main advantage of non-catalytic pyrolysis is its simplicity and lower operational costs, as it does not require the addition or regeneration of catalysts. However, the bio-oil produced through non-catalytic pyrolysis tends to have a high oxygen content, resulting in lower stability and energy density. This bio-oil often requires further upgrading to be used as a fuel or chemical feedstock. Additionally, the distribution of products can be less controlled, leading to variability in yield and quality.

Catalytic pyrolysis, on the other hand, incorporates catalysts such as zeolites, metal oxides, and mesoporous materials into the process. These catalysts facilitate secondary reactions that decrease the bio-oil's oxygen content, enhancing its stability and calorific value. Catalysts also influence the cracking of larger molecules, resulting in a more uniform and higher-quality bio-oil. The presence of catalysts can also increase the yield of desired products such as light hydrocarbons and aromatics, making the process more efficient and economically viable. However, catalytic pyrolysis involves higher operational costs due to the need for catalyst preparation, addition, and potential regeneration or replacement.

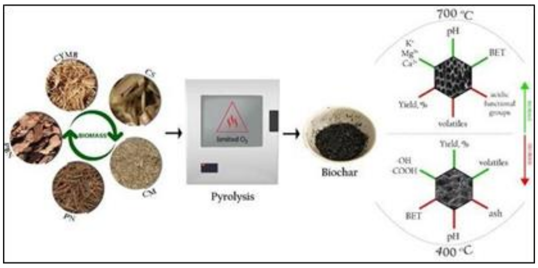


Fig 1. Wood Sawdust to Biochar. [18]

1.4 FLUIDIZED BED REACTOR

A fluidized bed reactor (FBR) is a popular reactor used in various chemical processes, including pyrolysis, combustion, gasification, and catalytic reactions. It consists of a cylindrical vessel filled with solid particles (typically sand, silica, or alumina) that are fluidized by an upward flow of gas. The fluidization process creates a bed of particles with properties resembling a fluid, providing excellent mass transfer and heat transfer characteristics.

In a fluidized bed reactor, the fluidizing gas (usually air, nitrogen, or steam) enters from the bottom of the reactor and flows upward through a distributor plate. As the gas velocity increases, it lifts the solid particles, causing them to behave like a fluid. The upward flow of gas carries the particles, creating a suspended or fluidized bed. The bed expands and exhibits fluid-like properties, such as uniform temperature and composition throughout the reactor volume.

One of the main advantages of FBRs is their enhanced heat transfer capability due to the intimate contact between the fluidizing gas and the solid particles. Additionally, the continuous movement of particles promotes high mixing and turbulence, leading to efficient mass transfer and reaction kinetics. FBRs offer flexibility in accommodating a wide range of feedstock sizes and shapes, making them suitable for processing diverse materials.

They find applications in industries such as petroleum refining, chemical synthesis, environmental remediation, energy generation, and carbon capture and storage. Despite their advantages, FBRs face challenges such as particle attrition, bed agglomeration, and the selection of appropriate bed materials. Overall, fluidized bed reactors play a crucial role in modern industrial processes, offering compact designs, high efficiency, and versatility for a wide range of applications.

2. LITERATURE REVIEW

The field of catalytic pyrolysis of biomass has garnered significant attention due to its potential to produce biochar, a valuable product for soil amendment and carbon sequestration. This literature review explores the various processes and methodologies employed in the catalytic pyrolysis of wood biomass, focusing on advancements in analytical techniques, reactor simulations, machine learning applications, and market analysis.

Thermogravimetric Analysis (TGA) is a fundamental technique used to study the thermal decomposition behaviour of biomass. By applying kinetic models such as Flynn-Wall-Ozawa (FWO) and Kissinger-Akahira-Sunose (KAS), researchers can determine the activation energy required for pyrolysis [1][3]. These models provide insights into the thermal stability and reaction kinetics of the biomass, which are crucial for optimizing the pyrolysis process. For instance, the activation energy obtained from these models helps in predicting the energy input required, thus aiding in the design of more efficient pyrolysis reactors [5][7].

Simulation of Fluidized Bed Reactors (FBR) is another critical aspect in optimizing biochar production. FBR simulations allow for the examination of various operational parameters, such as temperature, pressure, and catalyst type, on the yield and quality of biochar [2][6]. Studies have shown that using catalysts like zeolites can significantly enhance the yield of biochar and improve its physicochemical properties [4][9]. The simulation results are used to fine-tune the reactor conditions, ensuring maximum efficiency and yield.

Machine learning (ML) models have emerged as powerful tools in predicting biochar yield from catalytic pyrolysis. By correlating extensive experimental data with operational parameters, ML models can provide accurate predictions, thus facilitating the optimization of the pyrolysis process [8][11]. These models can handle the complex interactions within the pyrolysis system, offering a predictive edge that traditional methods lack. The integration of ML models into pyrolysis research represents a significant advancement, enabling researchers to explore a wider range of conditions and parameters efficiently [10][12].

A comprehensive market survey is essential to understand the economic feasibility of biochar production. This involves analyzing the cost factors at each stage, from raw material collection to final product distribution [1][4]. The cost of raw materials, transportation, pyrolysis, and pelletizing, along with the inclusion of catalysts, significantly impacts the overall production cost. [2][5]. Market demand for biochar in agriculture, industry, and environmental management further influences the economic viability [7][9].

3. MATERIALS AND METHODS

3.1 Thermogravimetric Analysis

Thermogravimetric analysis (TGA) is an essential analytical technique utilized to measure changes in the mass of a sample as its temperatures are changed or kept constant under a controlled atmosphere. This method is particularly valuable for studying the thermal stability, composition, and decomposition patterns of various materials. The core of TGA involves a sensitive balance that continuously records the mass of a sample as the temperature changes. This sample is placed in a furnace where it is subjected to a predefined temperature program, and the surrounding atmosphere can be adjusted to be inert, oxidative, or reducing, depending on the requirements of the analysis.

Kinetic analysis in TGA aims to determine the rate of a thermal decomposition reaction and the associated kinetic parameters, such as the activation energy (Ea), pre-exponential factor (A), and reaction order (n). The general rate equation is: $d\alpha dt=k(T)f(\alpha)$ where α is the degree of conversion (fractional mass loss), it is time, k(T) is the temperature-dependent rate constant, and f(α is the reaction model.

The rate constant k(T) typically follows the Arrhenius equation: $k(T)=A\exp(-Ea/RT)$ where A is the exponential factor, Ea is the activation energy, R is the universal gas constant, and T is defined as the absolute temperature in Kelvin.

Isoconversional methods analyze the rate of reaction at different degrees of conversion without assuming a specific reaction model. The activation energy is determined as a function of conversion. Common isoconversional methods include:

3.1.1 FWO Kinetic Model

The Flynn-Wall-Ozawa method is based on the integral isoconversional principle. It uses multiple heating rates to determine the activation energy (Ea) of a thermal process without knowing the reaction model.

The FWO method is described by the equation:

$$\log(\beta)=\log(AEa/Rg(\alpha))-2.315-0.4567Ea/RT$$

Where β is the heating rate, T is the temperature in absolute conditions and finally G(α) is the integral form of the function we have to convert.

By plotting log(β) versus 1/T at constant α (degree of conversion), the activation energy Ea can be determined from the slope of the straight line.

3.1.2. KAS Model

The Kissinger-Akahira-Sunose method is another isoconversional method used to calculate the activation energy. It also utilizes multiple heating rates to determine the kinetic parameters.

The KAS method can be expressed as:

$$\ln(\beta/T^2)=\ln(AR/EaG(\alpha))-Ea/RT$$

By plotting $\ln(\beta/T^2)$ versus 1/T at constant α, the activation energy Ea can be obtained from the slope of the straight line.

Both methods are typically applied to data obtained from thermogravimetric analysis (TGA) or differential scanning calorimetry (DSC), where the sample is subjected to different heating rates, and the degree of conversion (αα) is measured as a function of temperature.

Table 1: Parameters for Kinetic analysis using (a) FWO and

Ln (β)	**1/T(K)**
1.6094379	0.0017452
1.6094379	0.0014859
1.6094379	0.0012937
1.6094379	0.0011455
1.6094379	0.0010277
2.3025851	0.0016722
2.3025851	0.0014327
2.3025851	0.0012531
2.3025851	0.0011136

2.3025851	0.001002
2.7080502	0.0016051

(b) KAS equations

Ln(β/T^2)	**1/T(K)2**
9.79813	0.001745
10.3735	0.001486
10.8198	0.001294
11.1844	0.001145
11.4927	0.001028
9.26507	0.001672
9.80159	0.001433
10.2242	0.001253
10.5729	0.001114
10.8698	0.001002
9.00782	0.001605
9.51044	0.001383
9.91179	0.001215
10.2459	0.001083
10.5321	0.000978

3.2Chemical Analysis

Chemical analysis of catalytic wood pyrolysis involves the study of the decomposition of wood into various chemical compounds under the influence of a catalyst. Pyrolysis is a thermochemical process where organic materials, such as wood, are heated in the absence of oxygen to break down into smaller molecules. Catalytic pyrolysis involves the use of a catalyst to enhance the pyrolysis process, leading to higher yields of desired products and potentially altering the composition of the resulting bio-oil or biochar.

One aspect of chemical analysis in catalytic wood pyrolysis is the determination of the product distribution. This includes analyzing the types and quantities of gases, liquids (bio-oil), and solids (biochar) produced during the pyrolysis process. Gas chromatography-mass spectrometry (GC-MS) and other analytical techniques are commonly used to identify and quantify the various chemical compounds present in the pyrolysis products.

3.2.1 Proximate Analysis

Proximate analysis determines the major components of a material, typically focusing on organic matter, and is commonly used in industries such as coal mining, food processing, and biomass utilization. It involves the determination of several key parameters.

The proximate analysis breaks down the material into four key components: moisture, which affects handling and energy content . Volatile matter, indicating the fraction that vaporizes upon heating; fixed carbon, the solid residue that provides an energy measure; and ash, the non-combustible mineral residue. These components help assess the material's properties for various industrial applications.

3.2.2 Ultimate Analysis

The ultimate analysis provides a more detailed characterization of the elemental composition of a material, focusing on the precise proportions of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). This analysis is essential for understanding the chemical structure and energy content of organic compounds and is widely used in fields such as fuel chemistry, environmental science, and organic chemistry.

3.2.3 *Synergistic Effect in Chemical Analysisn*

Synergistic effects in the chemical analysis of wood pyrolysis refer to the interactions between different components or additives during the pyrolysis process that result in enhanced or altered outcomes compared to what would be expected if the components acted independently. Understanding these synergistic effects is crucial for optimizing pyrolysis conditions and improving the efficiency and quality of the products obtained.

Several research papers have shown bamboo wood biomass to show an excellent synergistic effect with algal biomass. Although a specific type of algae cannot be singled out because of their abundant variation in properties, we haveconsidered the properties of spirogyra for our research analysis. Show below is the dataset for the proximate andultimate analysis of bamboo biomass when blended with algal type.

Table 2: *Ultimate analysis of wood algae* biomass blend

C % content	**H** % content	**N %** content	**O %** content
50.75	6.85	1.325	40.575
52.5	6.31	1.3112	39.4
54.11	5.97	1.3	37.88
56.69	5.58	1.288	34.36
59.37	5.24	1.266	32.56
69.66	4.44	1.225	24.33
71.22	2.88	1.059	23.56
73.18	2.25	0.998	22.24
74.06	1.88	0.994	21.08
39.06	4.8	0.82	53.09
41.66	4.56	0.82	51.9
43.77	4.23	0.8	48.67
48.21	4.06	0.799	44.66
55.42	3.7	0.775	38.06
59.6	3.5	0.72	36.23
63.34	2.66	0.686	30.77

Table 3: *Proximate analysis of wood algae* biomass blend

VM content	**FC content**	**Ash content**
83.3	10.4	6.3
81.4	12.3	6.3
78.66	12.66	8.66
74.5	15.375	9.05
72.39	14.88	13.87
69.99	16.25	14.56
56.25	29.15	14.99
48.32	37.25	15.15
42.16	40.44	17.24
66.43	6.8	26.77
65.44	7	27.24
63.66	7.16	28.82
61.28	7.34	31.35
60.59	7.84	32.44
57.25	8.98	34.07

3.1 Aspen Simulation of Fluidized Bed Reactor

The simulation of this process using Aspen Plus involves modelling the complex reactions and interactions that occur during pyrolysis, allowing for the optimization and scale-up of theprocess. By defining the components, reaction kinetics, and operating conditions, and selecting appropriate reactor models,Aspen Plus enables detailed analysis and prediction of yields and product distributions, facilitating the development of efficient and sustainable biomass conversion technologies.

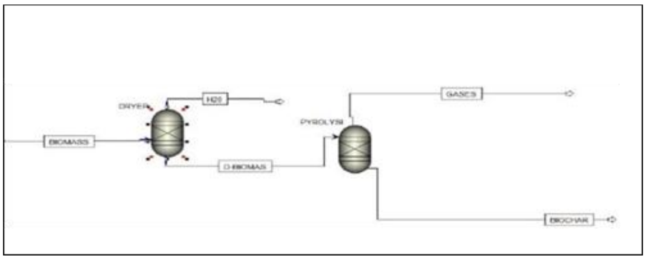


Fig. 2 Design of FBR Reactor

Define the operating conditions for the reactor, including thepyrolysis temperature, pressure, and residence time, to simulate The thermal decomposition accurately. Input the yield distributions for the pyrolysis products based on experimental data or literature, specifying the fractions of biochar, gases,and liquids produced. Simulate to execute the process model, ensuring all streams and unit operations are properly connected and the model converges without errors.

The RYield reactor in Aspen Plus is a model used to represent a reactor where the yield of each product is specified directly, rather than being calculated based on reaction kinetics or equilibrium. The RYield reactor can be used to model theoverall product distribution in a fluidized bed reactor, especially for complex processes like the pyrolysis of biomass. While the RYield reactor does not capture the detailed hydrodynamics of a fluidized bed, it is useful for cases where you need to specify the yield of products directly.

Define the operating conditions for the reactor, including thepyrolysis temperature, pressure, and residence time, to simulate The thermal decomposition accurately. Input the yield distributions for the pyrolysis products based on experimental data or literature, specifying the fractions of biochar, gases,and liquids produced. Simulate to execute the process model, ensuring all streams and unit operations are properly connected and the model converges without errors.

The RYield reactor in Aspen Plus is a model used to represent a reactor where the yield of each product is specified directly, rather than being calculated based on reaction kinetics or equilibrium. The RYield reactor can be used to model theoverall product distribution in a fluidized bed reactor, especially for complex processes like the pyrolysis of biomass. While the RYield reactor does not capture the detailed hydrodynamics of a fluidized bed, it is useful for cases where you need to specify the yield of products directly.

4. RESULTS AND DISCUSSIONS :

From the slopes of the plots, the activation energy was determined using the respective equations. This process will give us the activation energy as a function of the degree of conversion, providing insights into the kinetics of catalytic pyrolysis of wood biomass.

Case-1: FWO Plot

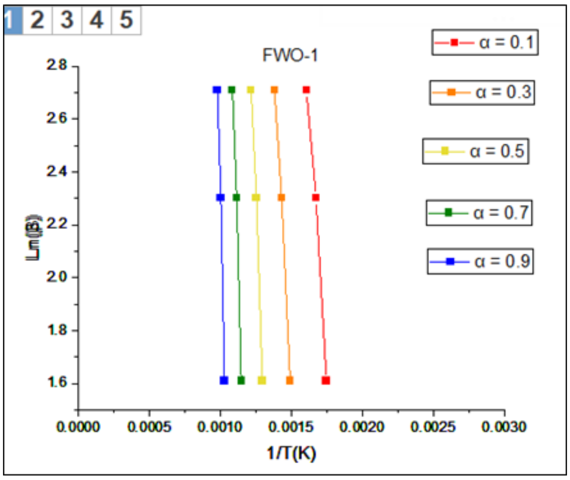


Fig 3. Plot for FWO plot

A steeper slope indicates a higher activation energy, suggesting that more energy is required for the decomposition reaction to proceed. Conversely, a shallower slope corresponds to a lower activation energy, implying that the reaction requires less energy to occur. By analyzing the slopes at different conversion levels, one can determine how the activation energy changes throughout the decomposition process, providing insights into the kinetic behaviour and mechanism of the reaction.

Case-2: KAS Plot

The slope of the Kissinger-Akahira-Sunose (KAS) plot, which is obtained by plotting ln(β/T2) versus 1/T for a specific degree of conversion (α), is directly related to the activation energy (Ea) of the thermal decomposition process. The slope of this plot is proportional to −Ea/R, where R is the universal gas constant (8.314 J/mol·K).

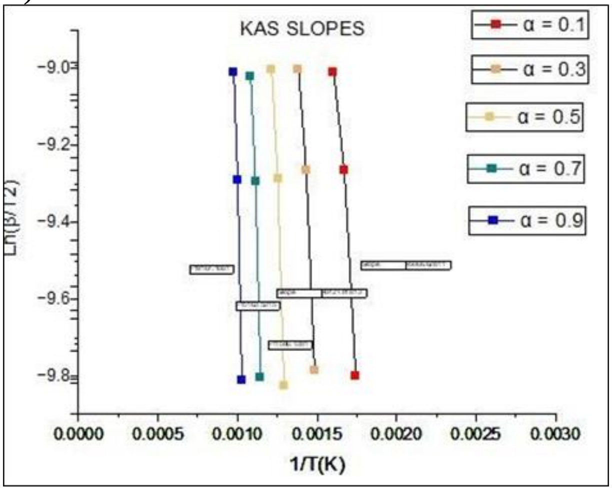


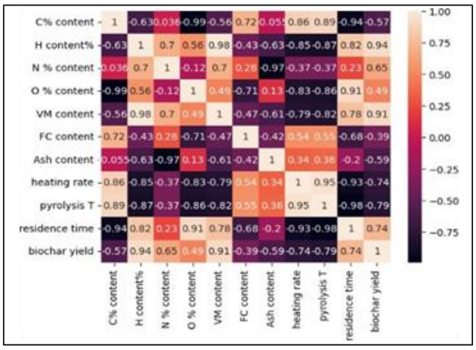
Fig.4 KAS model graph

A steeper slope in the KAS plot indicates a higher activation energy, meaning that the decomposition reaction requires more energy to proceed. A less steep slope suggests a lower activation energy, indicating that the reaction proceeds more easily with less energy input.

a. Synergistic Effect Correlation

After generating the heatmap to identify correlations for predicting biochar yield, it was found that the hydrogen content (H%) had the strongest correlation, followed by the volatile matter content and the residence time. Additionally, a significant correlation between pyrolysis temperature and heating rate was noted. Therefore, two datasets were analyzed for this phase: one including heating rate as a parameter and one excluding it.

From the diagram, it is evident that support vector regression achieved the highest accuracy, scoring 0.972. Additionally, all models, except for ridge regression, demonstrated highly favourable outcomes with accuracy scores exceeding 90%. This aligns with the inclusion of only highly correlated factors in the model implementations



	C% content	H content%	N % content	O % content	VM content	FC content	Ash content	heating rate	pyrolysis T	residence time	biochar yield
C% content	1	-0.63	0.036	-0.99	-0.56	0.72	0.055	0.86	0.89	-0.94	-0.57
H content%	-0.63	1	0.7	0.56	0.98	-0.43	-0.63	-0.85	-0.87	0.82	0.94
N % content	0.036	0.7	1	-0.12	0.7	0.28	-0.97	-0.37	-0.37	0.23	0.65
O % content	-0.99	0.56	-0.12	1	0.49	-0.71	0.13	-0.83	-0.86	0.91	0.49
VM content	-0.56	0.98	0.7	0.49	1	-0.47	-0.61	-0.79	-0.82	0.78	0.91
FC content	0.72	-0.43	0.28	-0.71	-0.47	1	-0.42	0.54	0.55	-0.68	-0.39
Ash content	0.055	-0.63	-0.97	0.13	-0.61	-0.42	1	0.34	0.36	-0.2	-0.59
heating rate	0.86	-0.85	-0.37	-0.83	-0.79	0.54	0.34	1	0.95	-0.93	-0.74
pyrolysis T	0.89	-0.87	-0.37	-0.86	-0.82	0.55	0.36	0.95	1	-0.98	-0.79
residence time	-0.94	0.82	0.23	0.91	0.78	-0.68	-0.2	-0.93	-0.98	1	0.74
biochar yield	-0.57	0.94	0.65	0.49	0.91	-0.39	-0.59	-0.74	-0.79	0.74	1

Fig.5 Heatmap for biochar correlation

5. CONCLUSIONS

The catalytic pyrolysis of biomass, particularly wood, offers a promising approach to biochar production, leveraging advanced techniques and models to optimise yield and efficiency. This comprehensive study begins with the analysis of the biomass using Thermogravimetric Analysis (TGA), applying the Flynn-Wall-Ozawa (FWO) and Kissinger- Akahira-Sunose (KAS) kinetic models to determine the activation energy required for the pyrolysis process. These models are crucial for understanding the thermal decomposition behaviour of biomass and for designing efficient pyrolysis processes. A fluidised Bed Reactor (FBR) is simulated to predict the yield of biochar and other pyrolysis products based on the proximate and ultimate composition of the biomass. The simulation of the FBR allows for a detailed examination of the influence of various operational parameters, such as temperature and catalyst type, on the pyrolysis outcome.

To further refine the process, machine learning (ML) models are employed to predict biochar yield. By correlating experimental data with various input parameters, these ML models can provide accurate predictions and insights, enabling the fine-tuning of the pyrolysis process. The market analysis highlights the growing demand for biochar in various sectors, particularly in agriculture for soil amendment and in industries for environmental management. The increasing awareness of biochar's benefits, such as improving soil health, enhancing crop yields, and sequestering carbon, drives this demand. Market.

6. REFERENCES

[1] Azuara, M., Kersten, S.R.A., Kootstra, A.M.J., 2013. Transport limitations in biomass pyrolysis. Energy & Fuels 27(11), 6678-6684.

[2] Bridgwater, A.V., 2012. Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy 38, 68-94.

[3] Bridgwater, A.V., 2013. Principles and practice of biomass fast pyrolysis processes for liquids. Journal of Analytical and Applied Pyrolysis 51(1-2), 3-22.

[4] Bu, Q., Lei, H., Wang, L., Wei, Y., Zhu, L., Liu, Y., Liang, J., Tang, J., 2012. Bio-based phenols and fuel production from catalytic microwave pyrolysis of lignin by activated carbons. Bioresource Technology 108, 274-279.

[5] Czernik, S., Bridgwater, A.V., 2004. Overview of applications of biomass fast pyrolysis oil. Energy & Fuels 18(2), 590-598.

[6] Demirbas, A., 2009. Pyrolysis mechanisms of biomass materials. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 31(13), 1186-1193.

[7] Fushimi, C., Araki, K., Yamaguchi, Y., Tsutsumi, A., 2003. Effect of heating rate on steam gasification of biomass. 1. Reactivity of char. Industrial & Engineering Chemistry Research 42(17), 3922-3928.

[8] Gouws, S.M., Carrier, M., Bunt, J.R., Neomagus, H.W.J.P., 2021. Co-pyrolysis of coal and raw/torrefied biomass: A review on chemistry, kinetics and implementation. Renewable and

Sustainable Energy Reviews 135, 110189.
[9] Kim, S.S., Kim, J., 2010. Pyrolysis characteristics of torrefied biomass in a lab-scale fluidized bed reactor. Bioresource Technology
[10] Mohan, D., Pittman Jr, C.U., Steele, P.H., 2006. Pyrolysis of wood/biomass for bio-oil: a critical review. Energy & Fuels 20(3),848-101(4), 1464-1470