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Importance and Application of Pyrolysis of Organic Waste in Chemical Processing Industry: A Review

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ABSTRACT: Pyrolysis is a vital thermochemical process extensively employed in thechemical industry. It involves the irreversible thermal decomposition of organic and inorganic waste in to valuable products such as bio-oil, syngas, and char. This review highlights the importance and broad industrial applications of pyrolysis, especially under varying process conditions like temperature, moisture content, and residence time.

Keywords: Pyrolysis, application, chemical, temperature, food processing and industry.

I. INTRODUCTION

1.1Background of Study

Bio-waste poses serious environmental concerns to both our health and economic development of a country if not critically addressed. According to World bank, over 2 billion tonnes of municipal solid waste (MSW) is generated globallyand about53% of this waste is not managed in an environmental friendly manner. While Nigeria generates about 32 million metric tonnes of waste annually. With a yearly

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Incremental rate of 2.4%, waste generation in Nigeria will increase exponentially in subsequent years to come (Fumilayo, 2023). Biomass waste provides a form of renewable and clean energy feedstock that can be harnessed into improving and increasing our energy supply, environment sanitary and economic development. If regulated and utilized properly and efficiently, these wastes can generate huge gross domestic income (GDI) for a country (Vigouroux, 2001).

Some reasons and importance of utilizing biomass waste for energy and chemical production are:

i. Locally outsourced: Biomass waste can be gotten locally either through agricultural, kitchen or industrial waste and they are not sensitive to world market cost or price fluctuations. It can be easily acquired.
ii. Security: Biomass waste can significantly contribute to a country's energy supply needs, thereby reducing the over independency on fossil fuel and external resources.
iii. Environmental implication: Biomass waste is widely available and eco- friendly when harnessed properly and converted into useful product has Great potential of reducing the sulfur- dioxide and carbon-dioxide in the environment.

Organic and inorganic waste can be treated and converted into useful chemical products and energy using various thermo-chemical processes. Chemical engineering processes such as gasification, pyrolysis, hydrothermal carbonization, torrefaction, hydrothermal liquefaction and combustion are subjected to various thermal and chemical processes to produce different chemical products such as bio-oil, char, syngas and other combustible gases which are used for the generation of heat and electricity, biodiesel and other important chemical solvents.(Gao et al., 2016; Wijekoon et al., 2021).

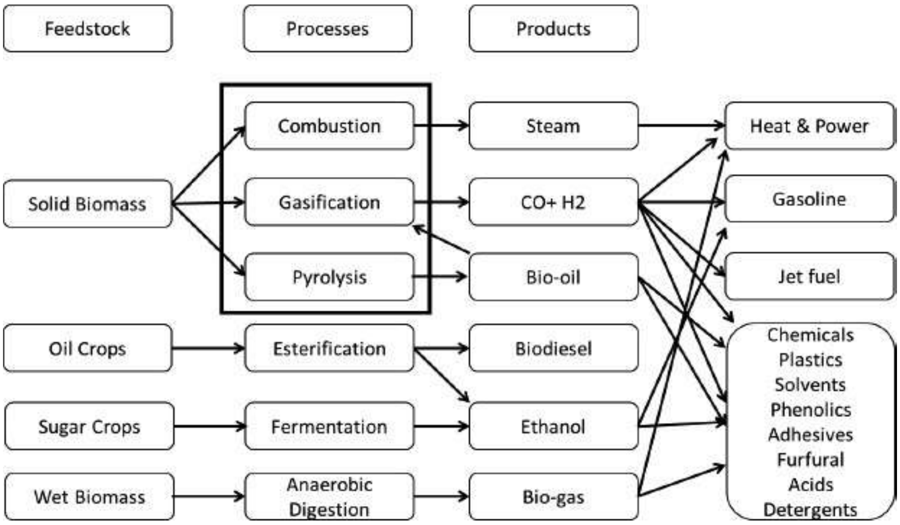

Figure1.1:Conversion of biomass

Source:(Chu,2014)

Figure 1.1 shows the various organic feedstock, thermo-chemical conversion method of converting these feedstock into products such as bio-oil, biogas and ethanol.

Biomass contains a complex mixture of many organic polymers and complex compounds. They are classified into cellulose, hemicellulose and lignin as their major constituents in various ratios and properties depending on the type of biomass. The composition of various organic compoundsis shown in Table 1.1.

Table1.1:Composition of Various Biomass Type (wt% on drymass) (Prakashetal.,2008)

Type	Cellulose	Lignin	Hemicellulose	Ash	Others
Soft wood	41	28	24	0.4	2
Hardwood	39	20	35	0.3	3
Rice husks	30	12	25	16	18
Pine bark	34	34	16	2	14
Peat	10	44	32	6	11

The chemical industry is an industry that is known for the processing and production of a wide range of chemicals and products from textile, oil and gas, plastics, to ceramics and many other endless lists of products that requires and generates either organic or inorganic feedstock or waste. These feedstock or waste most times are treated and converted into semi-finished products with the aid of pyrolysis process. This paper reviews the importance and application of pyrolysis process in chemical Industries in producing useful economical important products.

II. PYROLYSIS

Pyrolysis is essentially the thermochemical conversion of biomass (organicmatter),It is aprocesswhere,thermaldegradationof organic matter in the absence of oxygen happens. The destructive part composes of high thermal energy, heating content and numerous biomass matters, which gives the chances of extraction of heat energy and chemicals from the organicmatter. Pyrolysis generates three different products in different quantities: char, oils and gases (Prakash, 2008).

There are two kinds of pyrolysis process, the fast or flash, and the slow pyrolysis process. (Bridgwater,2003).Organic matter is mostly composed of cellulose, hemi-cellulose and lignin in various proportions. Using of any of the types of pyrolysis process (fast or slow) the pyrolysis of this

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material involves many chemical complex reactions leading into various intermediary or finished products as shown is table 2.1.

Table2.1:CharacterizationandProductsofPyrolysisof Biomass(Demirbas,2001)

Type	FeatureandProcess	ProductsandtheirCharacterization
Pyrolysisofholocellulose	Generaleffects: Colour changes from brown to black,flexibilityandmechanical strength are lost, size reduced, weight reduced Processes: Dehydration – also known as charformingreactionsproduces volatile products and char. Depolymerization–producestar Effect of temperature: Atlowtemperaturesdehydration predominates, at 630K depolymerization with production of levoglucosan dominates. Between 550 and 675K products formed are	Volatileproducts: independent of temperature Readilyescapeduringpyrolysis process, 59 compounds are produced out of which 37 have beenidentifiedCO,CO2,H2O, acetal, furfural, aldehydes, ketones. Tar: Levoglucosanisprincipal component Char: As heating continues there is 80% loss of weight and remaining cellulose is converted to char, prolonged heating or exposure to higher temperature (900K)reducescharformationto 9 %.
	Conventional(Carbonization): At 375-450 K endothermic reaction From675Kexothermicreaction Maximum rate occurring between 625and 725 K FastandFlashpyrolysis: Hightemperatureof750K,rapid heating rate, finelygroundmaterial,lessthan 10% moisture content,rapidcoolingand condensation of gases, yieldsin80%range,charand gas used for fuel	Char: approximately 55%Distillates:20%,methanol,methoxyl groups, acetone, acetic acid Tar:15%,phenoliccompoundsand carboxylic acid Gases:CO,methane,CO2,ethane Bio-oil: will not mix with hydrocarbon liquids,cannotbedistilled,substitutefor fuel oil and diesel in boilers, furnaces, engines, turbines, etc. Phenols: utilizes a solvent extraction processtorecoverphenolicsandneutrals, 18-20% of wood weight,secondaryprocessingofphenol pharmaldehyde resins,adhesives,injectionmolded plastics. Otherchemicals,extractionprocess: chemical for stabilizing the brightness regression of thermochemicalpulp(TMP) whenexposedtolight,foodflavorings, resins, fertilizers,etc.

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Table2.2:TypesofReactorsUsedinPyrolysisProcess Type of Reactor Pyrolysis Process

Type of Reactor	Pyrolysis Process
Fluidized bed reactor	Pyrolysiswoodfeedstocksandricestraw Pyrolysis of rice straw Pyrolysisofmunicipalsolidwaste
Dual fluidized bed reactor	Pyrolysis of municipal solid was
Fluidizedsandbedreactor	Pyrolysisofdifferentbiomasstoobtain Olefin
	Pyrolysisofwheatstrawandaspen-poplarwood Pyrolysis of almond shells at low and high temperatures Pyrolysisofpolyethylene Pyrolysisofvarioustypesofplasticsandsewage sludge Pyrolysis of plastics PyrolysisofNapierGrass
Fixed bed reactor	Pyrolysisofricestraw,sugarcanebagasseand coconut shell Pyrolysisofshaleoil Pyrolysis of lignin
Two-stagereactor	Pyrolysisofwoodtars
Rotary bed horizontal batch reactor	pyrolysisofscraptrucktires
Fixed-bedtubular reactor	pyrolysisofrice straw

2.2ImportanceofPyrolysis

Pyrolysis has emerged as a cornerstone process in the chemical industry due to its role in converting waste materials into v

aluable energy carriers and industrial chemicals. One of its primary advantages is in waste valorization, where organic and inorganic wastes such as biomass, plastics, and rubber are transformed into fuels and feedstocks. This not only reduces environmental pollution and landfill use but also supports cleaner production strategies (Demirbas, 2001). Pyrolysis is widely acknowledgedforitscapabilitytogeneratea range of products including bio-oil, syngas, and char. These outputs serve as renewable alternatives to fossil fuels in power generation,boilers,andengines(Bridgwater, 2003; Ma and Hanna, 1999).

In addition to energy generation, pyrolysis produces high-value chemicals such as phenols,furans,andaceticacid,whichcanbe extracted and utilized in the manufacture of adhesives, resins, and solvents. This significantlycontributestoresourcerecovery and industrial input efficiency (Fukuda, Kondo and Noda, 2001). For instance, phenolic compounds derived from the pyrolysis of lignin-rich biomass can substitute petroleum-based inputs in phenol-formaldehyde resins (Prakash and Karunanithi, 2008).

Furthermore,the process playsacriticalrole in carbon sequestration through biochar, a solid residue that can be applied as a soil amendment to improve fertility and retain carbonoverlongperiods(Yacob,Donaldand Manny, 2018). The application of pyrolysis inthetreatmentofmunicipalsolidwasteand plastics also facilitates the recovery of monomers and reduction in waste volume, which aligns with circular economy principles (Kiran, Mustafa and Ahmed, 2000).

The adaptability of pyrolysis systems across scalesfromsmallruralsetupstolarge industrial operations enhances its practical importance. Additionally, the process contributes to energy security by producing fuels locally and reducing dependency on volatile fossil fuel markets (Al-Haj Ibrahim, 2020). The thermal decomposition of triglycerides during pyrolysis, for example, produces hydrocarbons comparable to diesel fuels,althoughcaremustbetakentoaddress challenges related to fuel properties such as pour point and carbon residue (Schwab, Bagby and Freedman,

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1988).

Altogether, the widespread applicability of pyrolysisinwastetreatment,fuelgeneration, chemical synthesis, and environmental managementunderscoresitsvitalimportance in modern chemical engineering and industrial sustainability efforts (Vigouroux, 2001; Ma and Hanna, 1999).

2.3By-ProductofPyrolysis

Themajorby-productofthisprocessischar and gas. The proportion of the by-product depends on temperature, heating rate, pressure and residence time.

A. Char

Charisablackcolorsubstanceformedatthe bottom of the reactor drum; the char formation depends upon the temperature.

The main components of the char arevolatile matter and fixed carbon while moistureandashareminorcomponents.Itis used as a road surfacing, building materialas a feedstock in the production of activated carbon and as a solid fuel in boilers for power generation (Jency, 2019).

B. Gas

The gas produced depends upon the type of the plastic used in the process. The main components present in the gases are hydrogen,methane,ethane,ethane,propane, butane, butene. The gases are used in gas turbinesfortheproductionofelectricityand a direct firing in boilers in power plants (Jency, 2019)

Figure2.1PyrolysisandTemperatureReading

III. APPLICATION OF PYROLYSIS IN CHEMICAL INDUSTRY

Pyrolysis is a proven and energetically-efficient chemical technology that is used heavilyin the chemical industry. There are a great many pyrolysis processes used in the production of fuels and chemicals. Such processesdifferinthetypeofprocess,theuse of catalysts, the substances treated and the end products. Pyrolysis processes include catalyticandnon-catalyticpyrolysis,hydrous pyrolysis, vacuum pyrolysis, slow pyrolysis, torrefaction, fast pyrolysis, fluidized bed pyrolysis, flash pyrolysis, microwave- induced pyrolysis, plasma pyrolysis, empty tube pyrolysis, on-line pyrolysis and ultrasonic spray pyrolysis (USP). Other pyrolysis processes include also thermal decomposition, destructive and dry distillation, charring, tyre recycling and pyrolysis, liquefaction, high- and low- temperature carbonisation, coking and thermal and catalytic cracking (Al-Haj Ibrahim, 2020).

Pyrolysis has been used for pretreatment of lignocellulosic materials for thermal conversion of cellulose and hemicellulose into fermentable sugars (Tomas-Pejo et al., 2008).Whenthematerialsaretreatedat temperatures greater than 300°C, cellulose rapidly decomposes to produce gaseous productsandresidualchar(Kilzer&Broido, 1965; Shafizadeh & Bradbury, 1979). The decomposition is much slower and less volatile products are formed at lower temperatures. When zinc chloride or sodium carbonate is added as a catalyst, the decompositionofpurecellulosecanoccur at a lower temperature (Sun & Cheng, 2002; Shafizadeh & Z Lai, 1975).

Pyrolysis pretreatment prior to enzymatic hydrolysisofthreewastecellulosicmaterials (officepaper,newspaperandcardboard)was examined byLeustean where the conversion of cellulose to glucose yield from enzymatic hydrolysis was markedly improved (Leustean, 2009).

Apre-treatmentprocesstoremovepotassium and chlorine from straws may be based on pyrolysis followed by char leaching (Ayhan Demirbas, 2003; Jensen et al., 2001). The straw is pyrolysed at moderate temperatures atwhichthepotassiumisretainedinthechar. Potassium and residual chlorine are then extractedfromtheresidualcharbywater.To evaluate this pretreatment process, wheat strawcharswereexperimentallyinvestigated inthelaboratory.Thelaboratoryexperiments showed that three fractions of potassium in the straw reacted differently: 35–58% of the char potassium was dissolved very fast, followed by a secondary slow potassium release that was strongly influenced by particle sizes, water temperature, char type and water KCl content. The residual 5–10% ofthecharpotassiumremainsinthecharand could not be removed with pure water.

Radiation pretreatment of agricultural cellulosic wastes may accelerate the subsequent enzymic hydrolysis of rice straw and rice hull bycellulase. In a studybyDela Rosa et al., gamma irradiation significantly increased the acid hydrolysis of rice straw, rice hull and corn husk (Deal Rosa et al., 1983).Irradiationbyanelectron-beam acceleratorwas foundto beveryeffective as a form of pretreatment for enzymatic hydrolysis of cellulosic materials (Kojima et al., 1983).

Pyrolysis is used in several types of thermal cleaning systems in order to remove organic substances such as polymers, plastics and coatings from different parts or production components. The removed organic substancesareconvertedintovolatileorganic compounds, hydrocarbons and carbonised gas. Synthetic hormones and other organic contaminants, for example, maybe removed from sewage sludge by pyrolysis and heavy metals remainingin the sludgemaybemade inert thereby allowing the sludge to be used safelyasfertilizer.Thecleaningsystemsused include molten salt baths, fluidised bed systems, vacuum and burn-off ovens, also knownasheat-cleaningovens.(Kojimaetal., 1983).

Green petroleum coke is normally calcined before being used in the manufacture of carbon electrodes.The calcinationof cokeis a high-temperature (> 1000ºC) pyrolysis treatment of green coke in which moisture and volatile matter (hydrogen, methane and tar)areremovedinordertopreventcracking dueto shrinkageinthesubsequent bakingof the electrodes. During calcination the carbonisation and aromatization processes which began in the coker are completed, dehydrogenation and dealkylation reactions continue, and large aromatic structures fuse into highly organised shapes with definite crystalline characteristics (Hassan Al-Haj, 2023).

Pyrolysis of waste plastics may also be used to reduce the volume of the wastes and regenerate the monomers (precursors) to the polymersthataretreated.Inonestudy,alow heating rate (5°C/min) was used to pyrolyze waste polyethylene and polystyrene, which wereheatedtoatemperatureof600°C.Inthis study, polystyrene yielded higher liquid and polyethyleneyieldedhighergaseous products. The weight percentage of mono- aromatics was about 63% of the total oil products. The dominant product of polystyrenewasstyrene,with37%,followed by toluene, naphthalene and xylene. For polyethylene, on the other hand, the dominant product was prophenyl benzene followed by butenyl benzene (Kiran et al., 2000).

Co-pyrolysis of waste printed circuit boards and some compound additives (Fe_3O_4 and Si-Al zeolite) was investigated by Ziwei Ye et al. (Ziwei Ye et al., 2018). The pyrolysis oilproducedhasacalorificvalueof33MJ/kg and improved combustion properties.

Pyrolysis of plant oils gives in general products that are chemically similar to petroleumderiveddieselfuel,althoughsome ofthepropertiesofthesecompoundsmaynot be acceptable such as pour point, carbon residue and ash contents. In addition, the removalofoxygenduringthermalprocessing eliminates the environmental benefits of using an oxygenated fuel (Ma & Hanna, 1999; Fukuda et al., 2001).

Thepyrolysisoftriglycerideswiththeaimof obtainingproductssuitablefordieselengines was investigated by a number of workers. Thermal decomposition of triglycerides produces compounds of several classes including alkanes, alkenes, alkadienes, aromatics and carboxylic acids. The nature and relative amounts of such compounds depend largely on the type of vegetable oil used, as different vegetable oils give on pyrolysis widely different compounds. Pyrolysis of soybean oil for instance gives a lowerviscosityandhighercetanenumberoil containing 79% carbon and 12% hydrogen (Fukuda et al., 2001; Schwab et al., 1988).

In a study by Prathmesh and Paresh (Prathmesh & Paresh, 2012), pyrolysis of scrap truck tyres was carried out in a rotary bedhorizontalbatchreactoratatemperature of 430°C. The pyrolysis oil produced was foundtohavepropertiessimilartothe properties of diesel fuel in terms of its calorific value and carbon and hydrogen contents but with higher viscosity. Comparison of the performance characteristics of diesel fuel and different blends oftyrepyrolysis oil and diesel fuel in a four-stroke single-cylinder diesel engine wasinvestigatedbyYounusetal.(Younuset al.,2013).Itwasfoundthatthebrakethermal efficiency increased with all blends when comparedtotheconventionaldieselfuel,fuel consumption decreased and there was a significant decrease of CO, CO_2 and HC emissions (Younus et

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al., 2013).

Inordertoimprovetarrecovery,co-pyrolysis of tyres was carried out with other materials including coal, coal tar, pine nut shells and pistachio seeds (Sun & Cheng, 2002). Pre-treatment of scrap tyres by immersion in wastecoaltarpriortopyrolysiswasfoundto improve the pyrolysis efficiency and the quality of the produced tar which contained more light fractions. Other pre-treatment methods include soaking of scrap tyres in organicsolventswhichwillcausescraptyres to swell and reduce their tensile strength (Ouyang et al., 2018).

Slow pyrolysis experiments at 1–10 °C/min. heatingrateswereconductedbyYacobetal. on human feces and the char and gas yields werequantified.Usefultechnicalinformation was provided that can guide the design of a pyrolysis system to treat fecal waste, although social acceptance and scale-up issues need to be addressed through further research. Pyrolysis of human feces renders thewastefreeofpathogensandisapotential method of treating fecal sludge waste collected from non-sewered systems (Yacob et al., 2018).

IV. CONCLUSION

Pyrolysis is an important process in the chemicalengineeringindustry,itisalsoused heavily in the chemical industry to produce many forms of carbon and other chemicals frompetroleum,coal,wood,oilshale, biomass or organic waste materials, and it is the basis of several methods for producing fuel from biomass. The end products of pyrolysis include solid residual co-products and ash, non-condensable gases and condensable liquids. These products can be controlled by optimizing pyrolysis parameters such as temperature and residence.

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