IMPACT OF CONVENTIONAL AND MICROWAVE-ASSISTED PYROLYSIS ON PRODUCT QUALITY: A COMPREHENSIVE REVIEW

Abstract

In light of the diminishingof fossil fuel reservesand increasing worries about the environment, Recent years have seen a rise in the amount of research conducted on alternative energy sources.The study comparing microwave pyrolysis to traditional pyrolysis and Pre-treatmentby each method was supported in this comparative study. Both microwave and traditional pyrolysis are usedeffected on yieldcharacteristics, pyrolysis behavior, quality, and quantity. Analysis of the characteristics using proximate and elemental methods demonstrates that microwave hydrothermal pre-treatment and pyrolysis are improved than conventional hydrothermal Pre-treatment and pyrolysisregarding their calorific value and oxygen content.When char is the major product, conventional pyrolysis is the method that is employed. The typical pyrolysis process generallyproduces char and gas;it is possible to turn specific fractions of the product gas into liquid by condensing them. The term "microwave-assisted pyrolysis" refers to a novel thermochemical method that transformsbiomass into bio-oil;it is more prompt, effective, selective, controllable, and adaptable thanconventional methods as a comparative,in addition to this, the variables that illustrate howconventional pyrolysis differs from microwave pyrolysis in terms of product quality aredescribed.

Keywords: Biooil, Biomass, Microwave-assisted pyrolysis, Conventional pyrolysis,Microwave power, Pyrolysis temperature.

Authors

Husam Talib Hamzah
Department of Chemical Engineering
AU College of Engineering
Andhra University
Visakhapatnam, India.
alwatanaliraqi@gmail.com

Veluru Sridevi
Department of Chemical Engineering
AU College of Engineering
Andhra University
Visakhapatnam, India.
vellurusridevi@yahoo.co.in

Noor Abdulqader Hamdullah
Department of Electrical and Computer Engineering
Altinbas University
Turkey.
Eng.noor85.noor85.n8n8@gmail.com

Thamer Adnan Abdullah
Applied Scinces Department
University of Technology
Baghdad, Iraq.
100249@uotechnology.edu.iq

R. Srikanth
Department of Chemical Engineering
Anil Neerukonda Institute of Technology and Sciences
Sangivalasa, India.
rskanth.krmr@gmail.com

M. Tukarambai
Department of Chemical Engineering
AU College of Engineering
Andhra University
Visakhapatnam, India.
drmtukarambai@gmail.com

Venkata Rao Poiba
Department of Chemical Engineering
AU College of Engineering
Andhra University
Visakhapatnam, India.
venkataraopoiba@gmail.com

I. INTRODUCTION

It had come to everyone's attention that biomass is a significant source of renewable feedstock for both fuels and chemicals, notably when the consumption of fossil fuels was the primary cause of the severe contamination of the environment as well as an energy crisis.In recent years, there has been a lot of interest in pyrolysis as an environmentally beneficial and commercially feasible method for producing bio-oil generated from biomass. However, because of the low quality of the feedstock's biomass as a source of Energy, including its low Energy and low heating value, high proportions of oxygen and water both brought their own set of challenges with them to the finished bio-oil product, which partial the technology based on the process of pyrolysis [1]. The presence of minerals within the biomass has an additional impact on the high standard of oil produced by pyrolysis. Consequently, Pre-treatment is required before pyrolysis to recover the features of the biomass to produce high-quality bio-oil. Hydrothermal Pre-treatment, identified as wet torrefaction, is an exciting novel pre-treatment approach based on thermochemical reactions that can potentially improve biomass fuel properties and bio-oil quality[2]. The grinding ability and hydrophobicity of biomass are enhanced after Pre-treatment, which reduces the costs associated with grinding and storage during biomass usage [1]. The expense incurred by preprocessing biomass is partially recouped;it improves the commercial viability of this procedure. There have been several reports in various literature about the physicochemical properties and products that pyrolysis of biomass exhibits can be affected by wet torrefaction.Changes that occur in fuel properties of duckweed as a result of wet torrefaction, discovery that wet torrefaction led to a considerable drop in oxygen content by decarboxylation and dehydration and the rise in carbon that is fixed and has a high heating value (HHV), They have provided evidence that demonstrates that wet torrefaction is capable of producing Fuel with better properties of rice husk and the removal of minerals, serving the dual purpose of dry torrefaction and demineralization [3,53,54].In comparison to the samples that were left untreated, the bio-oil yield obtained after hydrothermal Pre-treatment was much higher, while the levels of ketones and acids were reduced. In addition, hydrothermal Pre-treatment has the potential to significantly raise the amount of levoglucosan in bio-oil andEnhance the overall excellence of bio-oil as a fuel [4]. The wet torrefaction process results in a more homogenous biomass feedstock to use the publicrestrictions for the kinetic pyrolysis model of different types of biomass. The use of formic acid in the Pre-treatment of biomass before irradiation increased the number of aromatic compounds and prevented the development of coke during the pyrolysis process [5,6].When viewed from the viewpoint of the heating method, microwave-assisted heating is quite distinct from other heating approaches compared to the fundamentals of the heating process.A microwave is a sort of electromagnetic radiation with a high frequency between 300 MHz–300 GHz withheating dipole rotation and ionic conduction [7]. Conventional hydrothermal Pre-treatment and conventional pyrolysis have received much attention, and the study on microwave hydrothermal pre-treatment and microwave-assisted pyrolysis was reported widely. A comparison of the effect of microwave and traditional hydrothermal pre-treatments and microwave and conventional pyrolysisfor feedstock,behaviors of pyrolysis, and characteristics are presented in this work for the first time.Comparison among pyrolysis behaviors from different heating techniques can help optimizethe pre-treatmentand pyrolysis process to advancethe quality of products [53,54,55].

II. RENEWABLE ENERGIES

The essential factor is Energy and the fundamental requirement of the existence of humans on this planet.It has a hand in almost all economic spheres, such as transportation, agricultural production, industrial activity, food production, and power generation[8,9]. There are three primary classes of energy resource types;Fossil fuels, nuclear resources, and renewable resources make up the three most important categories of energy resources [10].Renewable technologies are regarded to be clean sources of Energy since natural methods produce them. The best utilization of these resources helps limit adverse effects on the environment and produces the fewest possible secondary wastes; Therefore, they are non-depletable resource sources since they can meet the demands of the economy and society now and in the future [11]. The restricted availability of resources related to petroleum, global warming issues, both the production of greenhouse gases and the price of fuels derived from petroleum are expected to continue to riseand have inspired researchers to look for new sources of Energy that are less expensive and alternative [12].In the middle of the 1970s, an oil crisis led to a spike in the cost of crude oil and, as a result, a frantic search for other energy resources. Many technologies emerged involving pyrolysisthat can reach bio-oil yields of between 70 and 80 percent of biomass [13,14] or somewhere between 80 and 95 percent by weight [15]. The value that is added to bio-oil by the process of producing it from biomass offers a multitude of advantages, some of which are listed: (1) CO_2/GHG (greenhouse gas), (2) minimal or zero SOx emissions, (3) NOx Reduce Emissions, (4) biodegradable, (5) locally producible, (6) renewable, (7) sustainable. Because of this, bio-oil extracted from biomass can potentiallylessen the detrimental effects on the environment considerably.As a continuation of our research efforts, which have been focused on the valorization of biomass and waste products, we report herein that a comparison between traditional pyrolysis and Several different types of biomass feedstocks have been valorized using a process called microwave-assisted pyrolysis, including waste residues. The results of this comparison are presented herein. The results of this comparison are presented herein [16,17].

III. BIOMASS CONVERSION TECHNOLOGIES

The several methods that can turn biomass into usable Energy are grouped under the term "bioenergy conversion technologies."Most of these technological advancements can be categorized into two distinct groups: thermochemical and biochemical conversion. Throughout the thermochemical conversion processes, the creation of Energy from biomass requires the utilization of heat in addition to chemical catalysts, the biochemical conversion routes involve the utilization of biological organisms and biological catalysts in producing Energy from biomass and products with added value.With the help of these conversion technologies, biomass can be converted into a diverse range of valuable products for the energy industry, including many kinds of fuels, sources of heat, and forms of power [18,19]. The direct conversion technologies employed in the past or are now developing aim to produce secondary energy carriers as a byproduct of the development.The total amount of power and heat combined, Combustion,domestic heating, co-combustion, gasification, and pyrolysis, are considered to be the fundamental processes involved in thermochemical transformation, even though fermentation and transesterification are the two metabolic conversion pathways that occur most frequently, several other routes can be taken to produce biodiesel [20,21].

IV. GENERAL OVERVIEW OF THE PYROLYSIS PROCESS

Necessary to decide on the most suitable method for transforming prospective biomass resources into products with added value to help alleviate the effects of the energy problems and the deterioration of the environment that is brought on by these problems as a direct result.Combustion or the process of incinerating (complete oxidation) andthe process of partial oxidation (gasification), and the decomposition caused by heat in conditions devoid of oxygen (pyrolysis) are the fundamental thermochemical mechanisms in their three forms that allow heat to be generated from biomass resources, power, fuels, and chemicals, or any more products with increased value [22,23].

Pyrolyzing biomass is one of these crucial technologies that has received significant attention from researchers and has been utilized over the last few decades to add value to a diverse variety of feedstocks ranging from residues of biological materials. This technology can potentiallychange a wide variety of feedstocks into valuable products.In order to transform the initial raw material into a variety of products, including biogases, the process calls for the feedstock to be heated to temperatures that reach very high levels in a comparatively short time, the so-called oil produced by pyrolysis, which consists for the most of low volatile organic component mixed with a carbonaceous deposit, as well as water known as biochar; the oil is produced during the pyrolysis process [24,25,26].In addition to the traditional pyrolysis process, using microwaves in conjunction with rapid or flash pyrolysis is an innovative approach to processing materials.It can be a perfect option for successfully pyrolyzing waste feedstocks and biomass such as seaweed, algae [27,28,29],and other primary components, including carbohydrates. The meticulous regulation of pyrolysis's operating conditions achieved through a process called microwave-assisted pyrolysis (MAP)is anactual helpful aspect to maximize the manufacture of gas or oil, taking into consideration the fact that different operational settings can affect different chemical reactions, as a consequence of which the produced volatiles and oils have distinct chemical signatures [30].Traditional heating techniques have many limitations, including resistance to heat transfer, heat losses to the surroundings, use of a portion of the heat delivered to biomass materials, damage caused to the reactor walls due to continual electrical heating, etc. The absence of rapid heating is another disadvantage associated with this method. Due to the lack of quick heating, there is a prolonged heating period, which in turn generates an undesirable or secondary reaction;these secondary reactions are responsible for the poor quality of the product that was achieved as a result of cracking of the product further.in typical systems, the temperature along the reactor is elevated to a level that is high enough to encourage secondary reactions. Lastly, using typical hot pyrolysis methods on big biomass particles is not suggested since this might severely diminish the heating rates, production, and quality of bio-oil and biofuel [31].

The most significant advantage of the pyrolysis caused by microwaves, as was previously mentioned by Miura et al. (2004) [32],is the avoidance of an unwanted subsequent reaction that could have led to the production of contaminants in the product. That was accomplished by lowering the yield of desired compounds in the process.The volumetric heating that microwaves provide is another advantage, which, due to the high frequency, causes the molecules to rotate, producing heat, provided that the microwaves can penetrate the materials to a suitably sufficient depth. Thus, in contrast to traditional heating, in which only the surface of an object is heated, the heating mechanism utilized in microwave heating is unique. (Figure 1.) shows a diagrammatic representation of the distribution of temperatures, the transfer of heat, and the mass transfer in the microwave and conventional heating, and (Table 1.) shows a comparison between the usual electrical heating method and the microwave-assisted heating method [16,18,19]. Pre-treatment of materials with the help of microwaves or conventional ovens is an effective way to increase productivity and improve chemical and physical properties before pyrolysis [55].

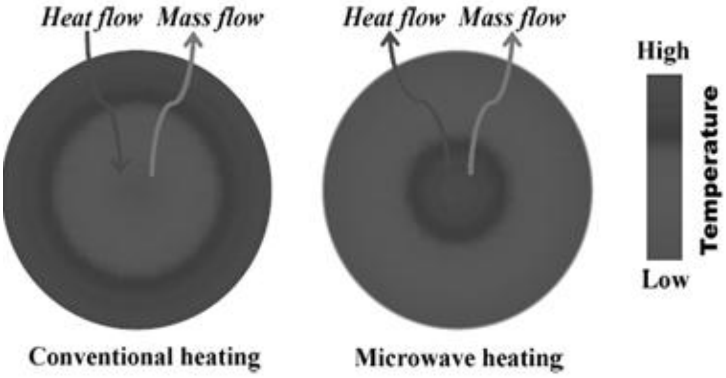

Figure 1: Diagrammatic representation of the temperature distributionand heat transfer process in traditional and microwave heating [16].

Table 1: Comparison between microwave-assisted heating and traditional methods of using electrical heat [18, 19].

Microwave-assisted heating	Conventional electrical heating
Conversion of Energy	Transfer of Energy
In-core volumetric and uniform heating at a molecularlevel	Superficial heating through conduction, convection, andradiation
Hot spot	No hot spot
Rapid and efficient	Slow, inefficient, limited
Higher electricity conversion efficiency	Lower electricity conversion efficiency
Selective	Nonselective
Dependent on the material's properties	Less dependent
Precise and controlled heating	Less controllable
Process flexible	Less flexible
Equipment Portable	Less portable
Lower contaminants	Higher contaminants
Lower thermal inertia and faster response	Higher thermal inertia and slower response

V. PHYSICAL PROPERTIES

The amount of moisture and solids contained in bio-oil, viscosity, density, and pH are the primary components that make up the physical qualities of bio-oil. The feedstock properties and the parameters of the process can have a significant impact based on the amount of moisture present in the bio-oil, which can range anywhere from 7.86 to 69.19

percent by weight.Since water is capable of mixing with lignocellulosic-derived substances,as a result of the fact that polar hydrophilic chemicals have a solubilizing action (acids, alcohols, hydroxyaldehydes, and ketones), the existence of water in the bio-oil would result in a decrease in the viscosity of the oil and an improvement in its flow properties, which contribute positively to the burning process. However, it is also possible to lower the heating values of bio-oils, resulting in an extension of the time it takes for the ignition to occur and a slowing of the Combustion rate[33]. The amount of solids that are contained in bio-oil should be kept below one percent for use in engines and boilers [34]. The amount of water in pyrolysis bio-oil can also affect its viscosity, setup, parameters of the process, characteristics of the feedstock, circumstances of storage, and lengths of time spent in storage.Companies that manufacture engines are worried about how viscosity it will become of bio-oil produced by pyrolysis;due to the extreme viscosity consistency of the bio-oil, it could result in an unnecessary fuel pressure injection once the engine is warming up.

On the other hand, when operating at low temperatures, engines would be deprived of Fuel since the Fuel would pass via either the filters or the lines very slowly because of the high viscosities present [35]. The significant concentrations of organic acids are primarily responsible for the low pH values that are found in pyrolysis bio-oils, such as(acetic acid and formic acid);because of these factors, bio-oil is corrosive to conventional materials for the construction industry, such as carbon steel and aluminum [36,37,38]. Once the bio-oil produced by pyrolysis is subjected to higher temperatures, the corrosiveness is more intense and increases water concentrations. In this case, because polyolefins are resistant to the corrosive effects of bio-oils, they are frequently utilized as a substitute for traditional building materials. (Table 2.)demonstrates the primary characteristics of the bio-oil produced using microwave-assisted pyrolysis, the bio-oil produced by traditional methods of electrically heated pyrolysis, diesel oil, and petroleum oil. The traditional electrical heating and microwave-assisted pyrolysis bio-oil produce identical physical qualities.As a result of thedetail that pyrolysis produces, bio-oils are generated primarily from the depolymerization and fragmentation of the three primary building componentsof biomass (cellulose, hemicellulose, and lignin). Although the bio-oil produced by microwave-assisted pyrolysis and the bio-oil produced by traditional electrical heating pyrolysis may share some physical features, microwave-assisted pyrolysis is currently the preferred method; the two methods of producing bio-oil may produce bio-oil with significantly different physical properties because of the many distinct mechanisms of pyrolysis as shown in (Table 2.) [36].

Table 2: Physical properties of the microwave-assisted pyrolysis bio-oil, conventional electrical heating pyrolysis bio-oil, diesel oil, and petroleum oil.

Property	**Unit**	**Pyrolysis bio-oil**		**Diesel oil[34]**	**Petroleum oil[33]**
		Microwave[35]	Conventional[36]		
Moisture	wt.%	15.2	4.5–43.0	-	0.1
Solid content	wt.%	0.22	0.1–3.0	-	0.1
Dynamic viscosity	mPa·s	60 at 50°C	40–100 at 50°C	1.6–2.3 at 50°C	180 at 40°C
Density	g/mL	1.25	0.91–1.29	0.83–0.84	0.94
pH	-	2.87	2.3–5.5	-	-

VI. ENERGY PROPERTIES

Distinguishing qualities of a wide variety of elemental compositions were observed during both the traditional electrical heating pyrolysis of bio-oil and the more modern microwave-assisted pyrolysis of bio-oil share a common characteristic in that they produce bio-oil with a higher oxygen content (29–40 percent). While it has a lower carbon content (54–60 percent) than diesel and petroleum oils(Table 3). Oxygen can be found in the majority of the compositions of oil that have been discovered in bio-oils (more than 300). The biomass properties significantly impact the distributions of these compounds (ultimate analysis and approximate analysis) and the prevailing operating conditions (residence time, pyrolysis temperature, and heating rate). Because oxygen by itself is not a flammable element, thebio-oil with high oxygen content would lead to the bio-oil having both a lower high-heat value (HHV) and a lower low-heat value (LHV) [36].

Table 3. Energy properties of the microwave-assisted pyrolysis bio-oil, conventional electrical heating pyrolysis bio-oil, diesel oil, and petroleum oil.

Property	**Unit**	**Pyrolysis bio-oil**		**Diesel oil[34]**	**Petroleum oil[33]**
		Microwave[35]	Conventional[36]		
C	wt.%	60.66	54–58	86.23– 86.31	85
H	wt.%	7.70	5.5–7.0	13. 14–13.27	11
N	wt.%	2.02	0–0.2	–	0.3
S	wt.%	0.15	–	0.034–0.039	–
O	wt.%	29.4	35–40	–	1.0
HHV	MJ/kg	17.51	14–19	42.7–43.0	40

VII. EFFECT OF PYROLYSIS TEMPERATURE

The pyrolysis of a biomass feedstock is significantly influenced by temperature. In general, the biomass feedstock goes through microwave-assisted pyrolysis,which causesdecomposition, resulting in a greater bio-oil output thanthe conventional application of pyrolysis by electrical heating [37]. The microwave-assisted pyrolysis has its own set of distinctive features at various temperatures. Table 4 The comparison between the two temperatures demonstrates quite clearly the significant variances (lower than 250−380 ^{0}C) concerning the development of biogases while undergoing the pyrolysis process.Notably, it has been discovered that Feedstocks with a temperature of decomposition that is very low, for example, macroalgae and reed canary grass, present a promising opportunity;it might be put to use in the production of a variety of products like bio-oils under relatively benign circumstances. An additional intriguing benefit of the microwave approach is the opportunity to collect organic volatiles and biogases primarily. A beneficial result at a nearly identically low temperature in contrast to the astonishingly high temperatures necessary to obtain the gas products produced from other feedstocks such as bracken and waste paper. When using microwaves to aid in the pyrolysis process, both the production of bio-oil and gas can be synchronized, which is themost significant unique benefit of the microwave [38].

Table 4. Evolution of the different bio-gaseous fractions obtained from various biomass pyrolysis at different temperatures: conventional vs. microwave-assisted pyrolysis (Peter Shuttleworth et al.) [38].

Temperature of decomposition (T/ ◦C)					
conventional			**bio-gases fraction**	**microwave-assisted pyrolysis**	
Biomass feedstock	**organic volatiles**			**organic volatiles**	**bio-gases fraction**
	Peak-1	Peak-2			
Wheat straw	283	314	428	160	160
Reed canary grass (RCG)	300	335	420	150	150
Softwood pelletized	334	373	410	175	175
Bracken pelletized	303	349	580	168	168
Waste office paper	354	−	670	185	185
Barley dust	284	310	412	135	180
Macroalgae	242	329	490	120	120

VIII. THE DIELECTRIC LOSS TANGENT (TANΔ)

The capability of a substance to transform electromagnetic radiation into usable Energy (thermal Energy)based on material dielectric characteristics, consisting of the dielectric loss tangent (tanδ). The tanδ is a measure of the proportion energy of microwave that is successfully transformed into a form that can be used as heat energy (dielectric loss factor - ε'') and the capability of the molecules of the substance to be polarized (dielectric constant - ε') [39]. Some materials do not possess the requisite dielectric characteristics to be heated in a microwave field.This type of selective heating is seen as a benefit in MWAP, as microwave energy only heats the biomass and not the chamber or the atmosphere during pyrolysis, in contrast to the traditional heating methods[40]. The vast majority of biomass does not heat up in a microwave field, and as a result, it must be combined with materials with a high tan δ;certain materials are referred to as microwave absorbers or susceptors.The role of a hot spot is played by a microwave susceptor, passing through dielectric heating and then changing this into thermal heating. A substance that possesses (tanδ> 0.2) is thought to be an effective absorber [41].The heating rate is the most important operating parameter in pyrolysis and pyrolysis temperature and residence time [42]. These operational parameters primarily depend on biomass feedstocks'microwave absorbance in the pyrolysis process that a microwave helps. The value of the biomass feedstock's tan δ represents the biomass feedstock's microwave absorbance, also known as the tan δ value.(Table 5.) shows some biomass feedstocks' (tan δ) values at room temperature and (2.45 GHz). Microwave-assisted pyrolysis typically results in higher heating rates than traditional pyrolysis, which uses electrical heating, pyrolysis temperatures, and conversion efficiencies. Because of the specific heating mechanisms, biomass feedstocks' decomposition often occurs at inferior temperatures, such as 100–150°C; In contrast, the standard electrical heating method produces less bio-oil overall, and the microwave-assisted pyrolysis method produces significantly more bio-oil. All operational parametersin microwave-assisted pyrolysis, including heating rate, pyrolysis temperature, and residence duration, depend on the amount of microwave energyabsorbed mainly by the biomass feedstocks. The value of a biomass feedstock's tan δindicates the microwave absorption of the material;it is highly impacted by the amount of moisture present in the biomass feedstock because water has a higher high tan δ value (0.12)(Table 5.) [43].

Table 5. tan *δ* values of some biomass feedstocks at room temperature and 2.45 GHz [43].

Feedstock	Tan δ	References
Aspen Bark	0.22	[37]
Pinewood	0.19	[38]
Wood	0.11	[39]
Cellulose	0.035	[40]
Polystyrene	0.0002–0.0003	[41]
Water	0.12	[42]

IX. CRITICAL LITERATURE REVIEW ON THE IMPACT OF CONVENTIONAL AND MICROWAVE ON PRODUCT QUALITY

Guangcan Su et al. [44] reported thatWhen comparing the two different ways of pyrolysis, the differences in product distribution and characteristics, as well as the economic viability of each pyrolysis mode, are given much consideration. Using microwaves in the pyrolysis process results in a different pyrolysis performance. It provides a new source of Energy, which is distinct from the traditional method due to its unique energy transmission mechanism. According to the conventional method, pyrolysis is beneficial to bio-oil production. In contrast, microwave-assisted pyrolysis can improve the surface characteristics of biochar and bio-oil composition;the benefits and drawbacks of using traditional pyrolysis versus microwave-assisted pyrolysis are the primary topics covered in this article.

(Jing Sun et al.) [45] Reported The Effects of the Pyrolysis Method, Temperature of the Catalyst Bed, and the Power of the Microwave on Both the Product Yield and An investigation was conducted into the biochemical oil's composition. The Results displayed that compared with conventional pyrolysis, The production of aromatic hydrocarbons was increased through microwave-assisted metal pyrolysis; this might be improved even further with the application of ex-situ HZSM-5 bed. The amount of product created is significantly impacted by the (temperature of the catalyst bed, the chemical profile of bio-oil, and deposits of coke on the catalyst).In addition to the temperature of the catalyst bed, increased microwave power resulted in a more significant amount of bio-oil being produced; however, Taking into consideration the remarkable results obtained in the deoxygenation of bio-oil, This body of work constitutes an essential reference for the advancement of technologies on bio-oil upgrading.

(Rozita Omar et al.) [46] Studiedthe pyrolysis of rapeseed oil as virgin oil (unused) and simulated waste oil (SWO), carried out using batch reactors employing both traditional heating methods and heating enhanced by microwaves.Temperatures of (500, 550, and 600) degrees Celsius and microwave powers ranging from (300 to 500) watts were utilized for heating via conventional methods and microwaves.Adding of catalyst 10% (w/w) HSZM-5 was also investigated.The oil and the catalyst have a low dielectric loss factor, ranging between (0.001 and 0.12), though Heating the material is achievable even without microwave absorbers.When compared with earlier investigations, this constitutes a significant breakthrough. In conventional heating, extremely high conversion rates (between 70 and 97 percent) of virgin oil and SWO into gas and liquid products were accomplished.OLP, also known as organic liquid products, and light bio-oil are preferred at an intermediate temperature of 550 degrees Celsius.The addition of a catalyst did not considerably boost the conversion rate. Still, it increased the yields of OLP and light bio-oil, although there is only a slight distinction between the investigated oils. Interestingly,the microwave pyrolysis treatment identified many aromatic compounds relative to the traditional treatment.After treatment with microwaves, aromatics were also discovered in the oil that was left over, whereas none were discovered by using a traditional method of pyrolysis.

(Victor Abdelsayed et al.) [47] According to the findings, microwave pyrolysis of Mississippi coal produced more gaseous products and a smaller amount of tars than conventional pyrolysis.During coal gasification, pyrolysis conditions significantly impact the char's structure-reactivity connection. This study aimed to evaluate the influence of temperature and microwave heating on the structural qualities of chars produced during pyrolysis, in addition to gaseous and tar products.A higher ratio of CO/CO_2 (greater than 1) was found under microwave pyrolysis in comparison to traditional pyrolysis (CO/CO_2 ratio of less than 1); it may be explained by a greater extent of gasification that occurred between the solid carbon and the CO_2 that was generated during microwave pyrolysis.Moreover, the oil tars produced using microwave pyrolysis displayed decreased amounts of polar oxygenates;wax tars, on the other hand, have larger quantities of non-polar alkanes. Finally, the char reactivity towards burning revealed that chars formed by microwaves have higher thermal stability than chars produced by other methods, likely due to lesser O/C ratios.

(Xin-hui et al.) [48] investigated the preparing activated carbon from Jatropha hull using two distinct heating methods: traditional and microwave. A 3 kW, 2.45 GHz microwave oven and to action taken in the experiments, a quartz pipe was positioned in the focal point of the microwave.The statistical response methods typical for full factorial designs (RSM) were utilized to maximize the number of successful tests. In this study, steam and CO_2 were utilized as activating agents during the pyrolysis process.Results that were found demonstrated thatthe output rate improved because of the use of microwave heating from (18.02% to 36.60%), employing carbon dioxide (CO_2) as the activating agent and that the activation temperature, activation time, and CO_2 flow rate were noticeably lower when compared to the traditional method. Because of this, the procedure became more cost-effective, although the porosity of carbon was on the same scale in terms of its magnitude.In addition, it was demonstrated that the created activated carbon had a yield that did not seem to be affected significantly by the activation of steam using microwaves or more traditional heating methods. At the same time, the pore volume and the surface area were discovered to be twice as effective when employing a heating system that included a microwave.

(Dominguez et al.) [49] Stated the impact of pyrolysis temperatures and the kinds of heating used (pyrolysis, both conventional and with the assistance of microwaves) concerning the quantity and quality of the productswere studied.The primary material consisted of the coffee hulls utilized for pyrolysis at (500 ^{0}C, 800 ^{0}C, and 1000 ^{0}C). The volume of Gas produced regarding this specific raw material was more significantthan the other solid and liquid fractions. However, it was operating at low temperatures, both types of heating systems. The use of microwaves as a heating technology could producea more significant proportion of gas and a lower proportion of oil when compared to traditional methods. The microwave heating approach resulted in the production of gas with higher H_2 content and syngas contents (H_2, CO) up to (40 vol% and 72 vol%) respectively,in contrast to the traditional procedures used up to (30 vol%) and (53 vol%). The total amount of Energy accumulated in the gas and solid fractions raised and decreased directly to the temperature, respectively, and the percentage of Energy accumulated in each fraction went down. The temperature was the cause of the increase in the amount of gas fraction yield for both procedures, although there was a drop in the overall yield of the solid fraction;in contrast to other approaches to heating, the microwave method led to higher total product yields than any of the other methods.

(Dominguez et al.) [50] reported that analyzed the differences in bio-oil composition between traditional and microwave-assisted pyrolysis. The Sewage sludge (varieties of three originate from plants water treatment, while one variety originates from a milk-derivative manufacturing facility) and the graphite between 0.5 g and 3 g were employed both in the production process and as an absorbent (to raise the temperature of the reaction) for pyrolysis of this investigation, respectively.It was determined to be beneficial to pyrolyze the sewage sludge in a (2.45 GHz)microwave oven with multiple modes that uses a quartz reactor. According to the findings, the oil producedutilizing a typical electrical furnace at extreme temperatures posed a significant threat to the environment;substances such as PAHs are included in this category. Althoughthey contained a low percentage of PAHs, they had a high calorific value when microwave pyrolysis was used to process the material.

(Fernandez and Menéndez) [51] investigated the impact of the original properties of materials used in the production of syngas from their raw state in both the microwave and the traditional heating method systemsand the connected time and energy savings that come with them.The following three types of biomass waste were subjected to the microwave-assisted pyrolysis process: (a)sewage sludge, (b)coffee hull, and (c)glycerol. It was discovered that glycerol combined with sewage sludge producedsyngas with the highest and lowermost levels and the lowest $H_2$and highest CO. In contrast, coffee hull resulted in values that are comparable to those of both of them. The method that included microwave assistance resulted in higher gas production and a higher syngas content in contrast to the method of heating that is more commonly used.During this process, the temperature of the pyrolysis step was raised due to the phenomena of hot spots that take place for each of the three distinct source materials as they are being heated in a microwave. In addition, the results demonstrated that the conventional heating method involves more time and Energy but can be accomplished in a microwave in significantly less time. The time reductions varied from 40% to 60% according to a variety of temperatures and primary materials, as well as the values for the energy usage;It was found that they had a score that was lesser than 0.004 kW h for heating by microwave and higher than 0.005 kW h in favor of the traditional approach.

(Fidalgo et al.) [52] Reported that,in addition to the effects caused by microwave irradiation, the effects of traditional heating when CH_4 is pyrolyzed over activated carbon (as a substance that is effective in absorbing microwaves and as a catalyst) were investigated. Within the scope of this study, the effect of utilizing various ratios of ($CH_{4)}$ to (N_2)to produceH_2 from methane was another source that was looked at.There was a quartz reactor in service in both an electric furnace (EF) (traditional methods of heating) and a microwave that operates in a single mode (MW)to carry out the trials at a temperature of 800 degrees Celsius for sixty-five minutes.According to the findings of this investigation, N2 significantly increased the conversion yield, even though it appeared to have various effects based on the type of heating source; Only by redistributing the methane molecules did it make the pyrolysis process more efficient within the bed of activated carbon when EF is present as a heating source, while furthermore having one more noticeable impact of energetic microplasmas generation (as a result of which there is an increase in conversions). At the same time, the MW was being utilized and dispersing the molecules of methane (CH_4)when microwaves were being used as the heating source.

(Leilei Dai et al.) [53] conducted a comparative investigation of the Pre-treatment of bamboo sawdust by traditional hydrothermal processes and microwaves was carried out in this study. Both conventional hydrothermal pre-treatment and microwave pre-treatment effectively improved the material's hydrochar characteristics and pyrolysis behaviors.The qualities of hydrochar produced by microwave hydrothermal pre-treatment are superior to those produced by traditional hydrothermal Pre-treatment, conferring proximate and elemental analysis.In terms of their oxygen content and calorific value, except for 150 degrees Celsius.Compared to hydrothermal Pre-treatment using more traditional methods, Pre-treatment through microwave hydrothermal treatment can remove a more significant number of acetyl groups from hemicellulose;there may be a connection between this and the hot spot effect. Caused by the irradiation from microwaves.The highest points on the thermogravimetric and derivative thermogravimetric curves representing pretreated samples continually shift to a place with higher temperatures.The samples prepared by traditional hydrothermal methods are more thermally stable than those heated by microwaves.In addition, the amount of glucopyranose that was present in the pyrolysis vapors of bamboo sawdust that had been pretreated with microwave hydrothermal heat at a temperature of 190 degrees Celsius was 9.82 percent higher than what was found in conventionally hydrothermally pretreated bamboo sawdust.The acids content of pretreated bamboo sawdust by microwave hydrothermal (150 degrees Celsius) was 4.12% lesser. In this aspect, microwave hydrothermal pre-treatment is superior to conventional hydrothermal Pre-treatment to improve the quality of the pyrolysis oil.

(Husam Talib Hamzah et al.) [54] This study focuses on microwave-assisted pyrolysis (MAP) of fresh waste tea powder and torrefied waste tea powder as feedstocks. Solvents, including benzene, acetone, and ethanol, were used to soak feedstocks. The feedstock torrefaction temperature (at 150 °C) and solvents soaking enhanced the yields of char (44.2–59.8 wt%) and the oil (39.8–45.3 wt%) in MAP. Co-pyrolysis synergy increased the yield of gaseous products (4.7–20.1 wt%). The average heating rate varied in the range of 5–25 °C/min. The energy consumption in MAP of torrefied feedstock (1386 KJ) significantly decreased compared to fresh (3114 KJ). The pyrolysis index dramatically varied with the solvent soaking in the following order: ethanol (26.7) > benzene (25.6) > no solvent (10) > acetone (6). It shows that solvent soaking plays an essential role in the pyrolysis process. The obtained bio-oil was composed of mono-aromatics, poly-aromatics, and oxygenated compounds.

(Husam Talib Hamzah et al.) [54] The prime objective of this work is to investigate the role of acid pre-treatment on TWP. Diluted acids (HCl, H_3PO_4, CH_3COOH, and H_2SO_4) were used to soak the TWP to understand the role of acids on bond cleavage and chemical formation. One gram of TWP was soaked in 100 mL of diluted acids for 24 h. The soaked samples were further subjected to a hot air oven (temperature: 80 °C, duration: 6 h), orbital shaking (shaking speed: 80–100 rpm, duration: 6 h), and microwave irradiation (microwave power: 100 W, duration: 10 min) to understand the synergistic effects of acids and mode of exposure. The pretreated solid and liquid samples were analyzed using FTIR to understand the presence of functional groups. The mass loss of TWP after treatment significantly varied with the type of acid and exposure mode used. In a hot air oven, high mass loss was observed [HCl (48%) > CH_3COOH (37%) > H_2SO_4 (35%) > H_3PO_4 (33%)]. The mass loss in microwave irradiation is lower (19 to 25%) with all acids. In the solid samples, O–H stretching, C–H stretching, C=O stretching, C=C stretching, –C–O–, and –C–OH– functional groups were noticed. Similarly, C=O and C=C peaks and C–O and –C–OH peaks were noticed in liquid samples. Interestingly, microwave irradiationshowed promising results in 10 min of pre-treatment; hot air oven pre-treatments require six hours to achieve the same result.

X. CONCLUSIONS AND FUTURE OUTLOOK

The traditional approach to the heating process is one of the conventional approaches to pyrolysis that have been used. However,various new and upcoming technologies, including Recent developments, have introduced microwave assistance methods. The utilization of microwave-induced heat for biomass pyrolysis is an example of a thermochemical conversion technique developed relatively recently.The oxygen content of bio-oils produced through biomass pyrolysis using microwaves is lower. At the same time, their HHV values are higher than those derived from the traditional pyrolysis of biomass. During the pyrolysis process that is helped by microwaves, the dielectric characteristics of the biomass play a significant impact because of their effect on biomass's ability to absorb microwaves.Making use of the higher microwave absorbance offered by exogenous reaction catalysts and microwave absorbents, Wecan attain high rates of heating, high temperatures during the pyrolysis process, as well as the catalytic cracking of massive molecules, the result being a larger yield and an improvement in the quality of the bio-oils produced.A temperature at which pyrolysis occurs that is too high can harm the amount of bio-oil produced by causing secondary reactions that decompose the volatiles into gases that cannot be condensed.

Nonetheless, using microwaves to assist in the pyrolysis process has a promising future as it provides many benefits compared to traditional pyrolysis procedures.Notably, using microwaves to generate heat is now a developed technology that is simple to deploy and can be precisely regulated. Future research to be conducted in the fields of screening for catalysts and application, the co-pyrolysis of different feedstocks using microwave heating characteristics that are complementary to one another, pilot study, and To manufacture of high-quality bio-oils at a price that is competitive with other options, there is a requirement for the development of new equipment and commercialize the technology.

Declaration of Competing Interest: The authors declare that they have no known competing interests for this paper.

REFERENCES

[1] Chen D, Zheng Z, Fu K, Zeng Z, Wang J, Lu M.,Torrefaction of biomass stalk andits effect on the yield and quality of pyrolysis products, Fuel.159 (2015) 27–32.
[2] Bach Q-V, Skreiberg., Upgrading biomass fuels via wet torrefaction: a review and comparison with dry torrefaction, Renew Sustain Energy Rev. 54 (2016) 665–77.
[3] Zhang S, Chen T, Li W, Dong Q, Xiong Y., Physicochemical properties and combustion behavior of duckweed during wet torrefaction,Bioresour Technol. 218 (2016) 1157–62.
[4] Chang S, Zhao Z, Zheng A, Li X, Wang X, Huang Z, et al., Effect of hydrothermal Pre-treatment on properties of bio-oil produced from fast pyrolysis of eucalyptus wood in a fluidized bed reactor,Bioresour Technol. 138 (2013) 321–8.
[5] Bach Q-V, Tran K-Q, Skreiberg, Trinh TT., Effects of wet torrefaction on pyrolysis of woody biomass fuels, Energy. 88 (2015) 443–56.
[6] [6] Feng Y, Li G, Li X, Zhu N, Xiao B, Li J, et al., Enhancement of biomass conversion in catalytic fast pyrolysis by microwave-assisted formic acid pre-treatment,Bioresour Technol. 214 (2016) 520–7.
[7] Wang Y, Dai L, Fan L, Shan S, Liu Y, Ruan R., Review of microwave-assisted lignin conversion for renewable fuels and chemicals, J Anal Appl Pyrol. 119 (2016) 104–13.
[8] Silitonga AS, Atabani AE, Mahlia TMI, Masjuki HH, Badruddin IA, Mekhilef S., A reviewonprospect of Jatropha curcas for biodiesel in Indonesia, Renewable and Sustainable EnergyReviews.15(2011) 3733–56.
[9] Enweremadu CC, Mbarawa MM., Technical aspects of production and analysis of biodieselfrom used cooking oil—a review, Renewable and Sustainable Energy Reviews. 13 (2009)2205–24.
[10] Demirbas A., Recent advances in biomass conversion technologies, Energy EducationalScience and Technology. 6 (2000) 19–40.
[11] Panwar NL, Kaushik SC, Kothari S., Role of renewable energy sources in environmentalprotection: a review, Renewable and Sustainable Energy Reviews. 15 (2011)1513–24.
[12] Motasemi F, Ani FN., Microwave irradiation biodiesel processing of waste cooking oil. In:Thefourth international meeting of advances inthermofluids (IMAT), AIP conferenceproceedings. 1440 (2012) 842–53.
[13] Bridgwater AV, Peacocke GVC., Fast pyrolysis processes for biomass, Renewable andSustainable Energy Reviews. 4 (2000) 1-73.
[14] Czernik S, Bridgwater AV., Overview of applications of biomass fast pyrolysis oil, EnergyFuel. 18 (2004) 590-598.
[15] Mohan D, Pittman CU, Steele JPH., Pyrolysis of wood/biomass for bio-oil: A criticalreview,Energy Fuel. 20 (2006) 848-889.
[16] Motasemi F, Ani FN., A review on microwave-assisted production of biodiesel,Renewableand Sustainable Energy Reviews. 16 (2012) 4719-4733.
[17] Saber M, Nakhshiniev B, Yoshikawa K., A review of production and upgrading of algalbio-oil. Renewable and Sustainable Energy Reviews, 58 (2016) 918-930.
[18] Motasemi F, Afzal MT., A review on the microwave-assisted pyrolysis technique,Renewable and Sustainable Energy Reviews. 28 (2013) 317-330.
[19] Chen P, Xie Q, Addy M, Zhou W, Liu Y, Wang Y, Cheng Y, Li K, Ruan R., Utilizationof municipal solid and liquid wastes for bioenergy and bioproducts production, BioresourceTechnology. 215 (2016) 163-172.
[20] Decker SR, Sheehan J, Dayton DC, Bozell JJ, Adney WS, Hames B, et al., Biomass conversion Kent and Riegel′s handbook of industrial chemistry andbiotechnology. US: Springer; 2007. p. 1449–548.
[21] Faaij A., Modern biomass conversion technologies, Mitigation and Adaptation Strategies forGlobal Change. 11 (2006) 335–67.
[22] Yin C., Microwave-assisted pyrolysis of biomass for liquid biofuels production, BioresourceTechnology. 120 (2012) 273–84.
[23] Yin C, Kaer SK, Rosendahl L, Hvid SL., Co-firing straw with coal in a swirl stabilized dualfeed burner: modelling and experimental validation, Bioresource Technology.101 (2010) 4169-78.
[24] Michael Jerry Antal and Morten Grønli Industrial & Engineering Chemistry Research **2003** 42 (8), 1619-1640
[25] Mohan D, Pittman C U, Steele P H, Energy Fuels. 20 (2006) 848.
[26] Bridgwater A V, Peacocke G V C., Renewable & Sustainable Energy Reviews. 4 (2000) 1.
[27] Budarin V L, Clark J H, Lanigan B A, Shuttleworth P, Breeden S W, Wilson A J,MacquarrieD J, Milkowski K, Jones J, Bridgeman T, Ross A.,Biores Technol. 100 (2009) 6064.

[28] Budarin V L, Zhao Y Z, Gronnow M J, Shuttleworth P S, Breeden S W, Macquarrie D J,Clark J H., Green Chem, 13 (2011) 2330.
[29] Dufour A, Girods P, Masson E, Rogaume Y,Zoulalian A., Int J Hydrogen Energy. 34 (2009) 1726.
[30] Richel A, Laurent P, Wathelet B, Wathelet J P, Paquot M.,ComptesRendusChim. 14 (2011)224.
[31] Bridgwater, A.V., Principles and practice of biomass fast pyrolysis processes forliquids, J. Anal. Appl. Pyrolysis. 51 (1999) 3–22.
[32] Miura, M., Kaga, H., Sakurai, A., Kakuchi, T., Takahashi, K., Rapid pyrolysis ofwoodblock by microwave heating, J. Anal. Appl. Pyrolysis. 71 (2004)187–199.
[33] Yu F, Deng S, Chen P, Liu Y, Wan Y, Olson A, Kittelson D, Ruan R., Physical andchemical properties of bio-oils from microwave pyrolysis of corn stover, Applied Biochemistryand Biotechnology. 137-140 (2007) 957-970.
[34] Oasmaa A, Czernik S., Fuel oil quality of biomass pyrolysis oils-State of the art for theend user, Energy Fuel. 13 (1999) 914-921.
[35] Tat ME, van Gerpen JH., The kinematic viscosity of biodiesel and its blends with dieselfuel,Journal of the American Oil Chemists Society. 76 (1999) 1511-1513.
[36] Czernik S, Bridgwater AV., Overview of applications of biomass fast pyrolysis oil, EnergyFuel. 18 (2004) 590-598.
[37] Tian Y, Zuo W, Ren Z, Chen D., Estimation of a novel method to produce bio-oil fromsewage sludge by microwave pyrolysis with the consideration of efficiency and safety,Bioresource Technology. 102 (2011) 2053-2061.
[38] Peter Shuttleworth, VitaliyBudarin, Mark Gronnow, James H. Clark, RafaelLuque, Low temperature microwave-assisted vs conventional pyrolysis of various biomassfeedstocks,Journal of Natural Gas Chemistry. 21(2012)270–274.
[39] J. A. Menéndez, A. Arenillas, B. Fidalgo, Y. Fernández, L. Zubizarreta, E. G. Calvo, et al.,Microwave heating processes involving carbon materials,Fuel ProcessingTechnology.91 (2010) 1-8.
[40] [40] Y. Fernández, A. Arenillas, and J. A. Menéndez, Advances in induction and microwave heating of mineral and organic materials, (2011)724-752.
[41] J. A. Menéndez, M. Inguanzo, and J. J. Pis, Microwave-induced pyrolysis of sewagesludge, Water research. 36 (2002) 3261-3264.
[42] Saber M, Nakhshiniev B, Yoshikawa K., A review of production and upgrading of algalbiooil, Renewable and Sustainable Energy Reviews. 58 (2016) 918-930.
[43] Budarin VL, Shuttleworth PS, De bruyn M, Farmer TJ, Gronnow MJ, Pfaltzgraff L,Macquarrie DJ, Clark JH., The potential of microwave technology for the recovery, synthesisandmanufacturing of chemicals from bio-wastes, Catalysis Today. 239 (2015) 80-89.
[44] GuangcanSu, ʾHwaiChyuanOngʾMei YeeCheahʾWei-HsinChenʾSuShiungLamʾYuhanHuang,Microwave-assisted pyrolysis technology for bioenergy recovery: Mechanism, performance, and prospect,Fuel. 326 (2022) 124983.
[45] JingSun, KeWang, Zhanlong Song, YutingLvShouyan Chen.,Enhancement of bio-oil quality: Metal-induced microwave-assisted pyrolysis coupled with ex-situ catalytic upgrading over HZSM-5,Journal of Analytical and Applied Pyrolysis.137(2019) 276-284.
[46] Rozita Omar, John P., Robinson. Conventional and microwave-assisted pyrolysis of rapeseed oil for bio-fuel production, Journal of Analytical and Applied Pyrolysis. 105 (2014) 131–142.
[47] Victor Abdelsayed, Dushyant Shekhawat, Mark W. Smith, Dirk Link, Albert E. Stiegman., Microwave-assisted pyrolysis of Mississippi coal: A comparative study withconventional pyrolysis, Fuel. 217 (2018) 656–667.
[48] Xin-hui D, Srinivasakannan C, Jin-hui P, Li-bo Z, Zheng-yong Z., Comparison of activatedcarbon prepared from Jatropha hull by conventional heating and microwave heating, BiomassandBioenergy. 35 (2011)3920–6.
[49] Dominguez A, Menendez JA, Fernandez Y, Pis JJ, Nabais JMV, Carrott PJM, et al., Conventional and microwave induced pyrolysis of coffee hulls for the production of a hydrogenrich fuel gas, Journal of Analytical and Applied Pyrolysis. 79 (2007)128–35.
[50] Dominguez A, Menéndez JA, Inguanzo M, et al.,gas chromatographic–mass spectrometricstudy of the oil fractions produced by microwave-assisted pyrolysis of different sewage sludges,Journal of Chromatography A. 1012 (2003)193–206.
[51] Fernandez Y, Menéndez JA., Influence of feed characteristics on the microwave-assistedpyrolysis used to produce syngas from biomass wastes, Journal of Analytical and AppliedPyrolysis. 91 (2011) 316–22.

[52] Fidalgo B, Fernandez Y, Domínguez A, Pis JJ, Menéndez JA.,Microwaveassisted pyrolysisof CH 4 /N 2 mixtures over activated carbon, Journal of Analytical and Applied Pyrolysis.82 (2008) 158–62.

[53] Leilei Dai, Chao He, Yunpu Wang, Yuhuan Liu, Zhenting Yu, Yue Zhou, Liangliang Fan,DengleDuan, Roger Ruan., Comparative study on microwave and conventional hydrothermal pre-treatment of bamboo sawdust: Hydrochar properties and its pyrolysis behaviors, Energy Conversion and Management. 146 (2017) 1–7.

[54] Talib Hamzah, H., Sridevi, V., Seereddi, M., Suriapparao, D. V., Ramesh, P., Sankar Rao, C., Gautam, R., Kaka, F., & Pritam, K. (2022). The role of solvent soaking and pre-treatment temperature in microwave-assisted pyrolysis of waste tea powder: Analysis of products, synergy, pyrolysis index, and reaction mechanism. *Bioresource Technology*, *363*, 127913. https://doi.org/10.1016/j.biortech.2022.127913

[55] Hamzah, H.T., Sridevi, V., Surya, D.V. *et al.* Conventional and microwave-assisted acid pre-treatment of tea waste powder: analysis of functional groups using FTIR. *Environ Sci Pollut Res* (2023). https://doi.org/10.1007/s11356-023-28272-8