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MORALITY BEFORE KNOWLEDGE

Innovation of a modular microwave-assisted pyrolysis (MAP) reactor based on coconut shell biochar with IoT monitoring system integration for the conversion of non-B3 plastic into alternative bio-fuels

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ABSTRACT

Background: Indonesia produces more than 12.3 million tons of plastic waste each year, but only a mere 14% is recycled, leading to serious environmental concerns. On a global scale, solid waste totals 2.3 billion tons annually, with merely 61% being properly managed. This situation underscores the pressing demand for sustainable and effective technologies for handling plastic waste. Traditional pyrolysis is widely utilized but struggles with high energy requirements, needing temperatures between 700-900 °C, inconsistent heat distribution, and overall low efficiency in the process. **Methods:** This research introduces a Microwave-Assisted Pyrolysis (MAP) reactor that utilizes KOH-activated coconut shell biochar as a microwave absorber. It achieves a surface area greater than 800 m^2/g, enabling effective absorption of 2.45 GHz microwaves. Non-toxic plastics like HDPE and PP are subjected to pre-treatment before undergoing MAP processing at temperatures of 450-600 °C for a duration of 10 minutes. An Internet of Things (IoT) system facilitates real-time monitoring of temperature, pressure, and flow rate to maintain precise control throughout the process. **Findings:** Results from experiments and a review of existing literature indicate that MAP is capable of transforming plastics into 70% bio-oil, 10% syngas, and 20% biochar, with energy consumption only at 0.8-1.2 kWh/kg—30-40% less than what traditional pyrolysis requires. The activation energy for coconut shell biochar drops significantly to 24.5 kJ/mol, compared to 84.2 kJ/mol found in conventional systems, showing better efficiency in volumetric heating. MAP has the potential to cut down plastic pollution by as much as 65% while generating bio-oil as an alternative fuel source, aiding the implementation of a circular economy and supporting Sustainable Development Goals 9, 12, and 13. **Conclusion:** MAP demonstrates a highly energy-efficient and scalable alternative for plastic waste valorization, reducing environmental pollution while generating useful byproducts and supporting sustainable development objectives. **Novelty/Originality of this article:** The research stands out by integrating KOH-activated coconut shell biochar with IoT-enabled real-time monitoring and an energy-efficient MAP method, providing a sustainable approach for recovering value from plastic waste beyond traditional pyrolysis.

KEYWORDS: IoT system; microwave-assisted pyrolysis; non-hazardous plastic waste.

1. Introduction

The increasing amount of plastic waste in the world poses a major challenge for the environment and society, estimates suggest that since the 1950s, over 8.3 billion tonnes of plastic have been produced globally, with only about 9% being recycled. The vast majority has been either disposed of in landfills, burned, or has polluted natural ecosystems (Geyer

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et al., 2017). In Indonesia, a densely populated country experiencing rapid urban development reports on municipal solid waste reveal that millions of tonnes are generated every year, with a significant portion made up of plastics. The recycling rates remain minimal, leading to much of the used plastic waste being poorly managed or contaminating rivers and coastal waters (Ismawati et al., 2024). The long-lasting nature of plastics and their breakdown into microplastics pose serious risks to both natural habitats and human health, while conventional recycling struggles to handle mixed or contaminated plastics that have lost quality. Thus, investigating alternative recycling techniques that add value is essential to meet circular economy goals and reclaim resources from various sources of plastic waste.

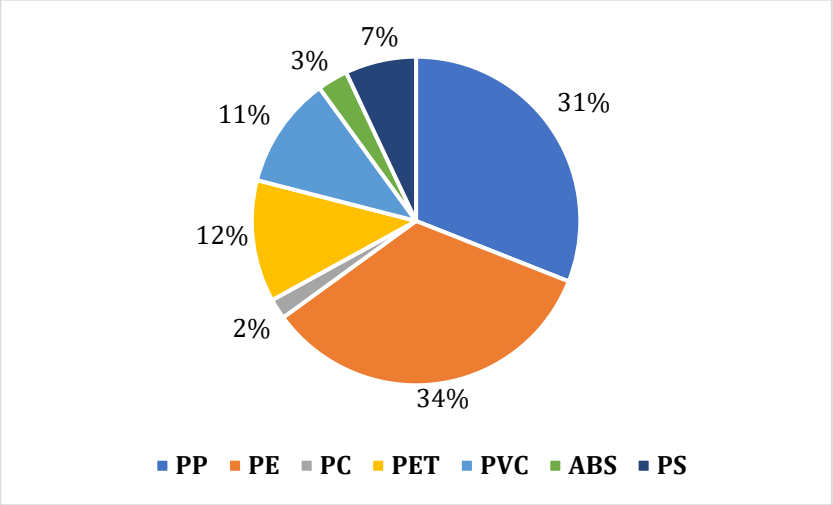

Fig. 1. Type of plastic produce and utilization in various sector

Thermochemical methods, especially pyrolysis, have been widely studied for converting mixed plastic waste into liquids, syngas, and char. A particular technique, Microwave-Assisted Pyrolysis (MAP), utilizes microwave energy that directly interacts with the materials or with added microwave susceptors resulting in uniform heat distribution throughout the material instead of heating from the outside in. This method allows for faster heating, shorter processing durations, and potentially improved selectivity and energy efficiency compared to traditional pyrolysis that depends on external heating. The basic contrasts in heating and mass movement provide a solid theoretical basis for preferring MAP in processes that convert plastics into fuels or chemical products (Yang et al., 2023).

Research on MAP using widely utilized polymers such as polypropylene, polyethylene, and polystyrene indicates strong yields and high-quality liquid outcomes when conditions are optimized. For example, the microwave-assisted pyrolysis of polypropylene has reached oil yields of about 79 wt.% under optimal temperature and power conditions (Cui et al., 2023), producing oils primarily consisting of C8-C15 hydrocarbons, which shows strong potential for fuel. Similarly, investigations into low-density polyethylene (LDPE) have shown varied yield ranges 32-75 wt. % in recent studies, highlighting how the type and proportions of microwave susceptors like silicon carbide significantly affect both the oil yield and its characteristics (Yang et al., 2023). These results emphasize MAP's ability to fine-tune product outcomes through reactor configuration, selection of susceptors, the amount of energy input, and the use of catalysts.

A key operational need for MAP is to have appropriate microwave absorbers susceptors) that can efficiently transfer microwave energy to low-loss polymer substances. Recent experimental findings of high quality indicate that carbon-based materials such as biochar and engineered porous carbons serve as cost-effective and efficient microwave susceptors while also functioning as supports for catalysts. Research shows that using biochar as a susceptor can enhance heating rates, allowing MAP to achieve desired temperatures quickly; in addition, activated biochar improved with functional oxides has

shown potential to direct product outcomes towards hydrogen-rich gases or increase gas yields through catalytic mechanisms biochar-assisted MAP studies. As a result, biochar fulfills a dual function, microwave coupling and catalyst support making it a compelling choice for eco-friendly and economical MAP systems that convert plastic waste and biomass residues into valuable products.

Though there is substantial laboratory evidence supporting the technical feasibility of MAP, there are considerable challenges that prevent its implementation at decentralized or practical levels. Many investigations into MAP are still at the bench or pilot scale, relying on batch reactors where monitoring and process control tend to be manually executed which continuous or semi-continuous reactor designs that guarantee consistent product quality are uncommon. Difficulties in scaling up include managing temperature variations, ensuring uniform product quality, addressing safety issues such as pressure and off-gas toxicity, and incorporating product separation and post-treatment for community-based applications.

Simultaneously, the fast advancement of the Internet of Things (IoT) has equipped us with tools for decentralized sensing, real-time tracking, remote operation, and data logging widely used in waste management (smart bins, route optimization, fill-level monitoring) and in monitoring industrial processes. However, there is a notable lack of explicit peer-reviewed research connecting IoT with microwave-assisted pyrolysis, real-time digital monitoring and control of MAP reactors in academic literature which creates a translational gap that MAP technologies in need of improved process management, and IoT technologies that are well-developed for monitoring, yet there is hardly any research merging the two for the thermochemical conversion of plastic waste.

Combining MAP with IoT and sustainable susceptor methods provides various benefits, real-time monitoring and closed-loop control of reactor temperature, microwave input power, feed rate, and off-gas composition could decrease variability in yield and product quality, data logging allows for model-based optimization, enhances safety in operations, and promotes reproducibility; remote dashboards and notifications lessen the need for human oversight; and utilizing locally sourced biochar susceptors contributes to a circular economy by transforming both plastic waste and agricultural or biomass byproducts. The innovation of a combined Microwave-Assisted Pyrolysis (MAP)-IoT system that uses biochar from biomass as a microwave absorber aims to facilitate effective, safe, and decentralized conversion of waste into resources, especially in areas with significant plastic waste, like Indonesia. Considering the theoretical benefits of volumetric microwave heating and the catalytic-absorptive characteristics of biochar indicated in earlier research, a one-tailed hypothesis is put forward. It suggests that the IoT-integrated MAP system, which employs biochar as a microwave susceptor, will produce greater and more consistent liquid or specific hydrocarbon yields, along with enhanced process stability, in comparison to a similar MAP reactor functioning under traditional manual supervision. This enhancement is anticipated to arise from real-time measurement and closed-loop management, which keep essential reaction factors like temperature and microwave energy within their ideal operating levels, thus minimizing process variation and improving conversion efficiency.

Microwave-Assisted Pyrolysis (MAP) is a sophisticated thermal conversion technique that creates heat internally by using microwave electromagnetic radiation, usually at a frequency of 2.45 GHz, interacting with microwave-responsive materials within the reactor. This process achieves fast volumetric heating, as opposed to the traditional method of heating from the surface to the core (Motasemi & Afzal, 2013; Yang et al., 2023). As demonstrated by the mechanism of electromagnetic waves, microwave radiation consists of alternating electric (E) and magnetic (H) fields that move perpendicular to one another. In this process, the changing electric field mainly causes dipolar polarization and ionic conduction, which transform electromagnetic energy directly into heat (Salema & Ani, 2012).

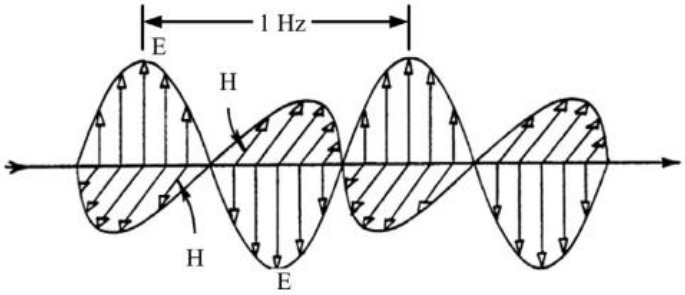

Fig. 2. Components of electric (E) and magnetic (H) fields in microwaves (Motasemi & Afzal, 2013)

When polar molecules or conductive carbon-based materials encounter this fluctuating electric field, ongoing dipole rotation and charge movement take place, resulting in internal friction and resistive losses that create consistent heating across the material's entire volume (Motasemi & Afzal, 2013). As a result of the fact that many plastic polymers, including polyethylene (PE) and polypropylene (PP), demonstrate minimal dielectric loss and are nearly transparent to microwaves, it becomes necessary to include microwave susceptors such as silicon carbide (SiC), activated carbon, or biochar derived from biomass to effectively promote microwave absorption and induce thermal runaway behavior. After the susceptor attains high temperatures, thermal energy is conveyed to adjacent polymers, initiating random homolytic cleavage of C–C and C–H bonds, succeeded by β-scission and reactions involving radical recombination. These processes yield condensable hydrocarbons (bio-oil), stable gases (H_2, CO, CO_2, CH_4), and solid carbon-rich char (Undri et al., 2014). The spread of these products is very affected by microwave power, maximum temperature, the time the vapor stays, and the physical and chemical properties of the susceptor (Yang et al., 2023; Cui et al., 2023). It was shown that raising the MAP temperature from 400 °C to 600 °C greatly improved both the gas yield and the proportion of combustible gas. Additionally, the specific surface area of char increased from 0.89 to 9.81 m^2/g^{-1}, while the pore size decreased from 282.16 to 46.64 nm. This suggests that devolatilization and carbon restructuring were enhanced (Zhao et al., 2014).

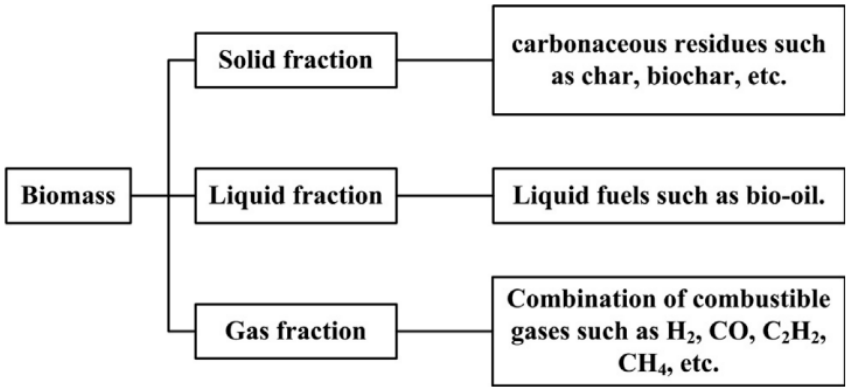

Fig. 3. Products of pyrolysis (Motasemi & Afzal, 2013)

Furthermore, it was demonstrated that both temperature and reaction time have significant statistical impacts on the yields of volatile substances and bio-oil, with the best liquid yields achieved at moderate temperatures prior to the occurrence of excessive secondary cracking (Ren et al., 2012). Besides their thermal function, carbon-based susceptors and inorganic additives also show catalytic properties by facilitating dehydrogenation, reforming, and oxygen-removal reactions. The addition of alkaline sodium substances greatly enhanced hydrogen production while reducing the presence of oxygenated compounds in the liquid product during microwave-assisted pyrolysis of pine wood sawdust (Chen et al., 2008). In contrast to traditional externally heated pyrolysis, the

unique heat-generation characteristics of Microwave-Assisted Pyrolysis (MAP) known for its internal energy delivery, rapid heating rates, lower thermal disparities, and better energy efficiency facilitate shorter processing times, greater control over reaction pathways, and adjustable product selectivity. Conventional pyrolysis is a thermochemical method where organic substances are broken down through heat at temperatures generally ranging from 350 to 700 °C in an oxygen-free or inert environment. This process generates solid char, liquid bio-oil, and gases (Bridgwater, 2012).

In traditional pyrolysis, heat moves mainly by conduction, convection, and radiation from the walls of the reactor to the inside of the feedstock particles. This can lead to notable temperature differences and slower heating inside the material (Di Blasi, 2008). Conventional pyrolysis can be divided into slow, fast, and flash types depending on the rate of heating and how long the vapor stays in the reactor. Slow pyrolysis, which has heating rates under 1 K s^{-1} and long residence times of several minutes, mainly yields biochar. In contrast, both fast and flash pyrolysis work at heating rates exceeding 10 K s^{-1} and have vapor residence durations shorter than 2 seconds, aiming to enhance the production of bio-oil (Mohan et al., 2006).

The thermal breakdown process in conventional pyrolysis occurs in two main phases which primary and secondary pyrolysis (Antal & Grønli, 2003). Primary pyrolysis includes devolatilization reactions like dehydration, depolymerization, decarboxylation, and dehydrogenation affecting key biopolymers such as cellulose, hemicellulose, and lignin (Di Blasi, 2008). The secondary pyrolysis phase happens when the produced vapors and forming char go through further reactions like cracking, reforming, and recombining, resulting in lighter hydrocarbons and permanent gases like H_2, CO, CO_2, and CH_4 (Dworzanski et al., 2005). Raising the reaction temperature significantly increases gas production by promoting bond breaking and secondary cracking, while also reducing char output. Longer vapor residence times encourage additional cracking and gasification, which leads to more gas production and less liquid yield overall (Scott & Plskorz Of Biomass, 1984).

Heating rates play a crucial role in determining the results of conventional pyrolysis; lower rates tend to support char formation due to extended solid-phase reactions, whereas higher rates promote the fast release of volatiles, leading to higher liquid and gas yields (Ronsse et al., 2013). It has been widely noted that fast pyrolysis can produce liquid yields of 60-75 wt% when conditions are optimized, typically using fluidized-bed or circulating-bed reactors (Mohan et al., 2006; Bridgwater, 2012). Nonetheless, bio-oil resulting from pyrolysis generally has high levels of oxygen, organic acids, and unstable compounds, which hinder its use as a fuel for transportation unless it undergoes upgrading processes like hydrotreating or catalytic cracking.

Table 1. Pyrolysis classification

Pyrolysis technology	Residence time (s)	Heating rate (K/s)	Temperature (K)
Slow	450-550	0.1-1	550-950
Fast	0.5-10	10-200	850-1250
Flash	<0.5	>1000	1050-1300

(Motasemi & Afzal, 2013)

From a technological standpoint, conventional pyrolysis is now well-developed, featuring several reactor types such as fixed-bed, rotary kiln, auger, and fluidized-bed setups used for converting biomass and plastics (Venderbosch & Prins, 2010). However, despite this progress, conventional pyrolysis still faces challenges like low thermal efficiency, extended start-up periods, and significant heat loss due to its reliance on external heat and slow heat transfer rates. These inherent drawbacks have prompted the exploration of alternative heating methods, such as microwave-assisted pyrolysis, which allows for rapid internal heating and energy distribution (Motasemi & Afzal, 2013).

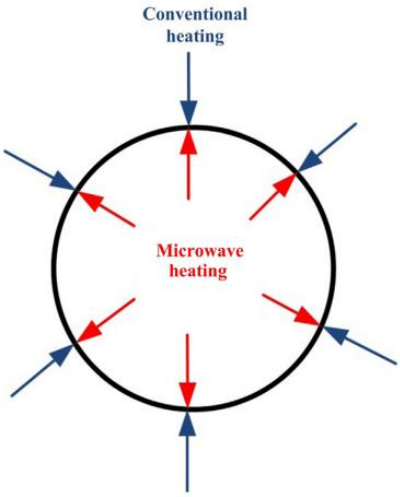

Fig. 4. Comparison between MAP and conventional pyrolysis (Motasemi & Afzal, 2013)

Traditional pyrolysis functions through external thermal heating, where heat is produced outside the material using a furnace, oil bath, or heating mantle. This heat is then conveyed into the feedstock via conduction, convection, and radiation, creating a temperature gradient that moves from the outer surface to the inner core of the particles. Consequently, the efficiency of heat transfer is significantly influenced by factors such as thermal conductivity, particle size, and the patterns of convective flow within the reactor. This often results in slow heating rates and an uneven temperature distribution internally, especially in materials with low conductivity, such as biomass and plastics (Motasemi & Afzal, 2013).

In comparison, microwave-assisted pyrolysis (MAP) utilizes dielectric heating, wherein electromagnetic microwave radiation enters the material and transforms electromagnetic energy into thermal energy at the molecular level. This occurs through dipole rotation and ionic conduction mechanisms, which enable heat to be generated throughout the entire particle (core volumetric heating), rather than transferring from the outside to the inside. This process eliminates the thermal lag that is common in traditional systems and facilitates much quicker and more uniform heating profiles (Al-Qahtani, 2023; Ke et al., 2024). This key difference in the way heat is generated significantly influences reaction rates. This is because MAP can quickly achieve elevated temperatures in just a few seconds, which speeds up bond-breaking reactions and reduces the perceived activation energy in comparison to traditional pyrolysis, especially for polar and semi-conductive substances like biomass, biochar, and carbon-rich plastics (Domínguez et al., 2007).

As a direct result of this increased heating activity, MAP generally promotes secondary cracking reactions of condensable vapors within the elevated reaction area. This alteration changes the product distribution to favor higher gas outputs and lower liquid bio-oil outputs when compared to traditional fast pyrolysis, where external heating typically maintains a greater quantity of condensable oxygenated compounds in the liquid state. Research consistently indicates that MAP generates gas rich in syngas with higher levels of H_2 and CO due to the increased reforming and cracking reactions occurring in specific high-temperature microwave zones. In contrast, CP gas tends to have greater concentrations of CO_2, CH_4, and heavier hydrocarbons, which are produced through slower heating and diffusion-limited reaction mechanisms (Ibraeva et al., 2023; Zhang et al., 2016).

The solid byproduct biochar produced from MAP has a unique structure, showing a more advanced network of pores, an increased surface area, and less tar obstruction due to in-situ vapor breakdown on the hot carbon surface. In contrast, traditional pyrolysis char typically has trapped tar and unevenly collapsed pores caused by extended heating of the surface (Qiu et al., 2023). From an energy standpoint, MAP provides quicker startup, accurate power management, and possible energy savings because it directly converts

electromagnetic energy to thermal energy without needing to heat the reactor walls. However, its effectiveness largely relies on the dielectric characteristics of the feedstock. Many types of raw biomass and plastics have low microwave absorption, necessitating the inclusion of microwave absorbers such as activated carbon, silicon carbide, or metal oxides to begin and maintain the heating process. Furthermore, the distribution of the electromagnetic field within microwave reactors is frequently uneven, which can lead to localized thermal runaway (hot spots) and inconsistent conversion, unless the reactor design, distribution of absorbers, and power coupling are effectively optimized. In contrast, conventional pyrolysis provides more consistent temperature control on a larger scale, although this comes with the disadvantages of slower heat transfer and increased thermal losses (Menéndez et al., 2010). These various differences show that MAP is not just a change in the heat source but a completely distinct thermochemical conversion method in which volumetric electromagnetic heating alters reaction rates, interactions between vapor and solid, product preferences, and energy efficiency compared to traditional pyrolysis.

Indonesia stands as one of the leading producers of coconuts globally, with yearly yields estimated between 18 and 19 million tons. This substantial production results in millions of tons of coconut shell waste as by-products from the food, coconut oil, and traditional charcoal sectors (Atapattu & Udumann, 2024). On a mass basis, the shells represent around 12 to 15 percent of the total weight of the fruit, suggesting that the potential coconut shell waste generated in Indonesia alone surpasses 2 million tons annually. If this waste is not managed adequately, it may lead to environmental contamination and unregulated carbon emissions. Nevertheless, from materials and energy engineering perspectives, coconut shells serve as an excellent precursor for producing biochar and activated carbon due to their significant lignin content approximately 35 to 40 percent, compact cellular structure, and high fixed-carbon yield post-pyrolysis (Ioannidou & Zabaniotou, 2007; Danish & Ahmad, 2018).

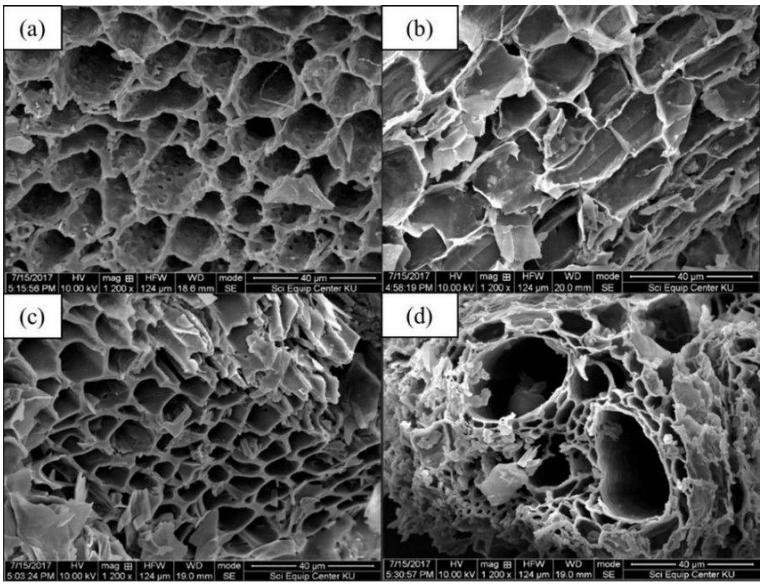

Fig. 5 (a) SEM images of biochars derived from corncob; (b) Coconut husk; (c) Coconut shell biochar; (d) Rice straw

In the realm of Microwave-Assisted Pyrolysis (MAP), coconut shell biochar is essential as a microwave susceptor, which is a material that can effectively absorb microwave energy and convert it to heat within its solid matrix. Unlike traditional heating methods that depend on heat transfer from the reactor walls to the material surface, microwave heating operates volumetrically, meaning heat is generated internally through the interaction of electromagnetic fields with matter (Menéndez et al., 2010). Coconut shell biochar shows a relatively high dielectric loss tangent (tan δ) compared to unprocessed biomass, allowing it

to act as a starter heater that speeds up the achievement of pyrolysis temperatures, especially during the initial phases of MAP.

The enhanced efficiency of coconut shell biochar as a microwave susceptor is largely due to its advanced micro-mesoporous structure and substantial specific surface area. Non-activated coconut shell biochar typically has a BET surface area between 150 and 400 m^2/g, while activated biochar, whether physically or chemically treated, can reach levels of 600 to 1200 m^2/g, and occasionally go beyond 1500 m^2/g (Ioannidou & Zabaniotou, 2007). This expansive surface area provides numerous sites for interaction with electromagnetic fields, boosts interfacial polarization, and significantly enhances the conversion of microwave energy to heat through conduction loss and dipolar rotation.

From a mechanical perspective, the microwave heating of coconut shell biochar takes place through three main processes: polarization loss, which occurs from the oscillation of surface functional groups like –OH, –COOH, and –C=O in an alternating electric field; conduction loss, which is due to the movement of free electrons in the conjugated aromatic carbon framework; and Maxwell–Wagner interfacial polarization, which is caused by differences in dielectric constants between biochar and the adjacent biomass or plastic matrix (Menéndez et al., 2010;). The synergy of these mechanisms leads to the creation of localized hot spots, which notably expedite devolatilization, thermal cracking of heavier hydrocarbons, and the formation of radicals in the gas phase. The performance of coconut shell biochar as a microwave absorber in MAP systems has been clearly shown in various experimental studies. Utilizing activated carbon from coconut shells as a microwave absorber at power levels between 593 and 600 W boosted the bio-oil yield to about 34 to 35 wt%, whereas in systems lacking absorbers, yields remained under 25 wt%. (Anggraini et al., 2024).In studies targeting solid carbon production, several MAP experiments with coconut shells revealed that biochar yields could reach 83 to 91 wt% at microwave power levels of 550 to 650 W, contingent on factors like residence time and the ratio of susceptor to feed. These results clearly demonstrate that biochar serves both as a final product and an effective internal heating agent in MAP systems.

From the perspective of thermal kinetics, the addition of biochar as a microwave absorber significantly improves the heating rate of the system (Menéndez et al., 2010) Highlighted that carbon-based absorbers in MAP reactors can attain heating rates above 100 to 300 °C/min, which is considerably higher than traditional electric pyrolysis systems that generally operate between 10 and 30 °C/min. Such elevated heating rates are crucial in influencing product distribution: rapid heating tends to promote bio-oil and light gas production, while slower heating leads to the generation of highly aromatic biochar with a high fixed carbon content and increased higher heating value (HHV). Beyond its role as a microwave absorber, coconut shell biochar also provides a secondary catalytic effect owing to trace minerals such as K, Ca, and Mg that are naturally present. These minerals can facilitate tar cracking reactions and improve the aromatization of the carbon structure during MAP processes (Danish & Ahmad, 2018). Thus, coconut shell biochar works simultaneously as a susceptor, a mild heterogeneous catalyst, and a medium for thermal energy storage, which offers advantages over synthetic susceptors like silicon carbide (SiC) and pure graphite, particularly regarding cost, sustainability, and the availability of raw materials in Indonesia.

In the design of MAP reactors ranging from laboratory to semi-industrial scale, coconut shell biochar can be utilized in two primary configurations: co-feeding mode, where biochar is mixed directly with the biomass or plastic feed, and fixed susceptor bed mode, where biochar is arranged as an absorbing layer either at the bottom or surrounding the reactor. The co-feeding arrangement improves the uniformity of heating at the particle level, while the fixed-bed setup ensures more consistent temperature control for ongoing operations. Both configurations are highly applicable for the advancement of biomass-plastic hybrid MAP reactors in Indonesia, particularly for local renewable energy and integrated waste-to-energy initiatives. Hence, Coconut shell acts as an internal heating agent, a secondary catalyst, and a valuable carbon product simultaneously. However, its overall efficacy is significantly influenced by crucial operational parameters of the MAP process, especially

microwave power, the ratio of susceptor to feed, particle size, starting moisture content, and the atmosphere in the reactor such as N_2, vacuum, or other inert gases. Thus, thorough experimental optimization and energy assessment are vital steps before moving to pilot and large-scale applications in Indonesia.

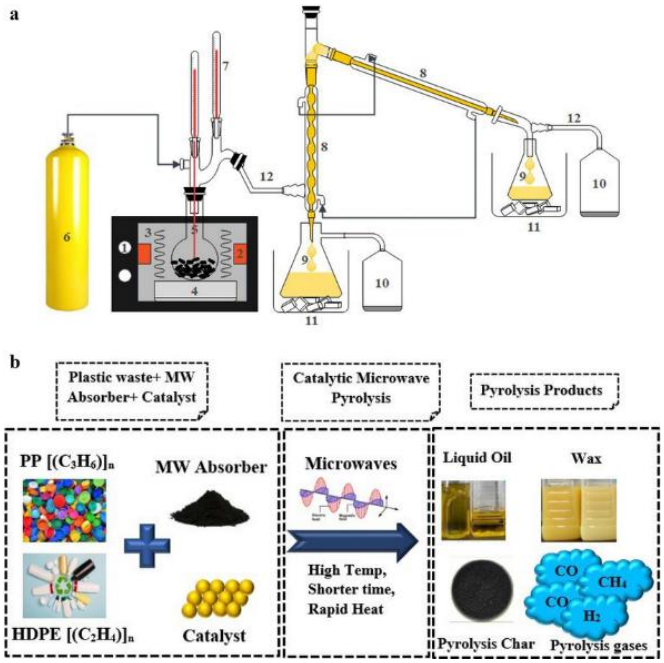

Fig. 6 (a) Schematic of pyrolysis setup: (1) microwave reactor; (2) waveguide; (3) microwaves; (4) ceramic fibred block; (5) pyrolysis reactor; (6) nitrogen gas inlet; (7) thermometer; (8) Liebig condensers; (9) oil collecting flasks; (10) gas sampling; (11) cold traps; (12) connecting tubes; (b) Mechanism involved in destruction of plastic into liquid fuel and gaseous products through catalytic microwave pyrolysis

The main liquid product produced by the microwave-assisted pyrolysis (MAP) of plastic waste is referred to as plastic-derived bio-oil. This oil is a complicated blend of hydrocarbons created by the thermal breakdown of long-chain polymer structures. In contrast to traditional pyrolysis, MAP facilitates quick heating throughout the material, leading to more consistent bond breaking and a reduction in secondary cracking reactions, which enhances both the selectivity and quality of the resultant liquid products (Arshad et al., 2017). The liquid yields obtained from the microwave-assisted processing (MAP) of polyolefin plastics like polyethylene (PE) and polypropylene (PP) typically vary from 45% to 75% by weight. This variation is influenced by factors such as microwave power, residence time, and the application of susceptors or catalysts (Li et al., 2023). From a chemical perspective, bio-oil produced from plastics primarily consists of alkanes, alkenes, cycloalkanes, and aromatic hydrocarbons. The carbon chain lengths generally range from C5 to C28, aligning with the boiling temperatures associated with gasoline, kerosene, and diesel fuels (Maqsood et al., 2021). GC-MS analyses consistently show that MAP promotes the creation of lighter hydrocarbons and decreases aromatic content 20 wt%, leading to reduced acidity, better thermal stability, and less corrosiveness (Sharuddin et al., 2016).

In terms of physical properties, plastic oil derived from MAP typically has a density ranging from 0.75 to 0.88 g/cm^3 and a kinematic viscosity between 1. 5 and 4. 5 cSt at a temperature of 40 °C. These values are considered to be within the acceptable operational limits for diesel-type fuels (Sharuddin et al., 2016). Nonetheless, the existence of plastics that contain chlorine such as PVC can produce HCl and organochlorine substances, which can pollute the oil and increase corrosion. This highlights the importance of sorting feedstock and implementing post-treatment processes (Arshad et al., 2017). In contrast to fuels obtained from crude oil processing, MAP plastic bio-oil provides significant benefits: it serves as a secondary source of hydrocarbons, promotes the recycling of carbon, and

attains improved net energy recovery efficiency through volumetric microwave heating (Li et al., 2023). However, its wider range of boiling points and high olefin content continue to restrict direct replacement without enhancement. Consequently, MAP bio-oil is ideally suited as a key transitional fuel for decentralized energy recovery and integrated systems aimed at enhancing the value of plastic waste.

2. Methods

The approach taken in this research utilized a quantitative and systematic review of existing literature, with the objective of gathering, contrasting, and integrating empirical data concerning Microwave-Assisted Pyrolysis (MAP) for converting non-hazardous plastic waste. The review involved pinpointing pertinent peer-reviewed articles, filtering them using established criteria for inclusion and exclusion, and extracting important operational, thermal, and performance metrics reported across the various studies. The selection of articles was performed through a methodical search within major scientific databases, guaranteeing that every published work had an equal chance of inclusion based on relevance to the topic and the availability of data.

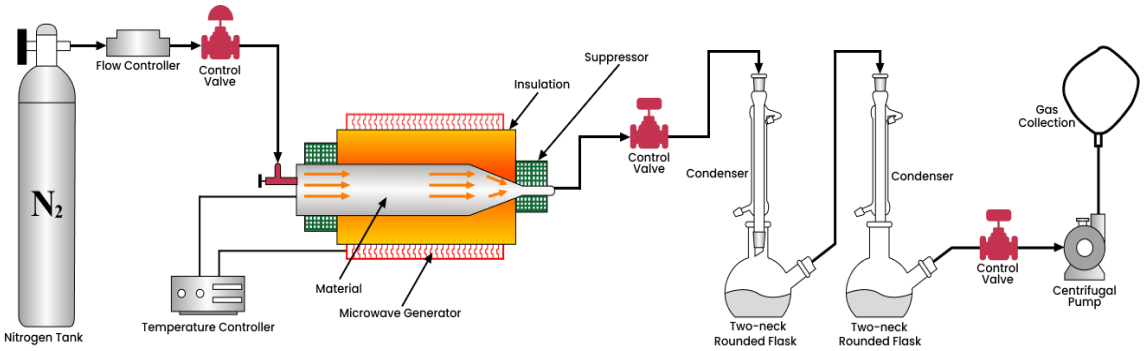

Fig. 7. Microwave-assisted pyrolisis process flow diagram

The analysis aimed to outline the MAP process flow, which included stages such as feedstock preparation, characteristics of the absorber, microwave heating settings, product separation, and energy demands, followed by standardizing numerical information to facilitate comparisons between studies. This methodological strategy guarantees that the assessment of MAP's performance, efficiency, and practicality relies on cohesive, reproducible, and systematically verified scientific evidence. The process flow diagram of MAP itself is shown in Figure 7.

2.1 Feedstock preparation and production and activation of coconut shell biochar

In the feedstock preparation process, there are two main parts which preparing coconut shell biochar as a microwave absorber and solid catalyst, and using food waste as the main material. Food waste has lots of carbohydrates, fats, and proteins, which break down well when exposed to microwaves, creating a lot of bio-oil and gas. The feedstock preparation includes sorting the material, washing it with a neutral detergent to get rid of dirt and other unwanted stuff, drying it until its moisture level is below 5%, and cutting it into small pieces <5 mm to increase surface contact. This blend has been demonstrated to yield bio-oil amounts reaching 56% and hydrogen output of 126.9 mmol/g within a brief reaction time of 2-4 minutes.

The creation of biochar from coconut shells occurs through a process also part of the MAP, which involves heating the material to temperatures between 400-500°C in the absence of oxygen, using an inert gas like nitrogen or carbon dioxide. This method transforms the lignocellulosic parts of the coconut shell into solid residues that are rich in carbon, possess aromatic structures, have low ash content, and offer high energy value. To improve its ability to adsorb substances and absorb microwaves, chemical activation is

often utilized. The biochar is immersed in a 1M KOH solution for a duration of 12 to 24 hours, then dried and heated to temperatures between 600°C and 700°C. This activation process boosts the specific surface area to over 800 m^2/g, generating micropores along with essential active functional groups (-OH, -COOH) that play a vital role in catalytic interactions during the microwave-assisted pyrolysis (MAP). Activated biochar from coconut shells exhibits a 32% improvement in microwave absorption efficiency compared to non-activated biochar, significantly enhancing the rate of pyrolysis for food waste.

2.2 Microwave heating and pyrolysis reaction and product separation

The process of microwave heating in MAP employs electromagnetic waves at a frequency of 2.45 GHz, which are taken in by the active biochar, allowing for swift and even heating throughout the substance. The ideal temperature range for breaking down food waste is between 400-600°C, with heating durations varying based on the type of feedstock and the power of the reactor. Using coconut-shell biochar as a microwave absorber can enhance the heating speed up to 5°C/s, enabling rapid achievement of the necessary temperature. In MAP, the pyrolysis reaction is a type of thermochemical breakdown that takes place in the absence of oxygen. The microwave energy that the biochar absorbs produces internal heat, which hastens the disintegration of organic substances in food waste. As the temperature increases, larger organic compounds break down into smaller molecules, resulting in bio-oil, syngas, and biochar. This process consists of two primary phases, the first phase, known as primary devolatilization, involves the melting of organic material and the release of vapors, which then condense into bio-oil and lighter gases (H_2, CH_4, CO, CO_2). The second phase, called secondary cracking, happens at elevated temperatures or during prolonged residence times, producing additional gases and solid carbon.

The makeup of the final products is influenced by various factors, including the temperature of the reaction, the duration of residence, microwave power, and the catalysts used. At a power setting of 1000 W and a temperature of 550°C, the yield of bio-oil can be as high as 33.38%, while biochar can account for 15 to 25% depending on the feedstock and the ratio of the absorber. The leftover biochar is then filtered, dried, and examined for potential recycling. This process illustrates the overall thermal breakdown of biomass materials like food waste. Under anaerobic circumstances, intricate organic substances with a common formula (break down into bio-oil, syngas, and biochar, typically at temperatures ranging from 400 to 600°C and over brief durations.

2.3 Monitoring and control using IoT

Within the MAP framework, utilizing the Internet of Things (IoT) facilitates the real-time tracking of temperature, pressure, and gas composition through sensors linked to microcontrollers like the ESP32. The information gathered can be displayed via a digital interface that supports adaptive management during the pyrolysis process. This method employs the Human-in-the-Loop Cyber-Physical System (HiL-CPS) model, which merges human oversight with automated sensors to maintain the stability of the reactor. The below illustration depicts the IoT-driven monitoring system incorporated into MAP-ID, aimed at facilitating the effective and immediate transformation of food waste into alternative energy sources. The Modular Microwave-Assisted Pyrolysis (MAP) reactor is crafted for versatile and expandable use, making it suitable for rural or small-scale locations dealing with organic waste management issues. Its small and adaptable design occupies little space and can be tailored to meet local demands. Possible users consist of local communities, small waste management organizations, and energy cooperatives in search of decentralized and eco-friendly energy alternatives.

Fig. 8. IoT-driven system design

3. Results and Discussion

3.1 Performance of MAP in plastic waste conversion

Microwave-Assisted Pyrolysis (MAP) efficiency in transforming plastic waste is significantly affected by how well the feed or additive can effectively absorb microwave energy. Most plastics have low dielectric loss factors, making them inefficient at heating during microwave exposure, which leads to gradual thermal breakdown and reduced oil output. To overcome this challenge, materials like coconut-shell biochar are added to improve the heating speed, temperature distribution, and catalytic cracking performance during the MAP process. Coconut-shell biochar is especially beneficial due to its high carbon content, its porous nature, and its excellent ability to absorb microwaves, enabling it to quickly turn microwave energy into heat.

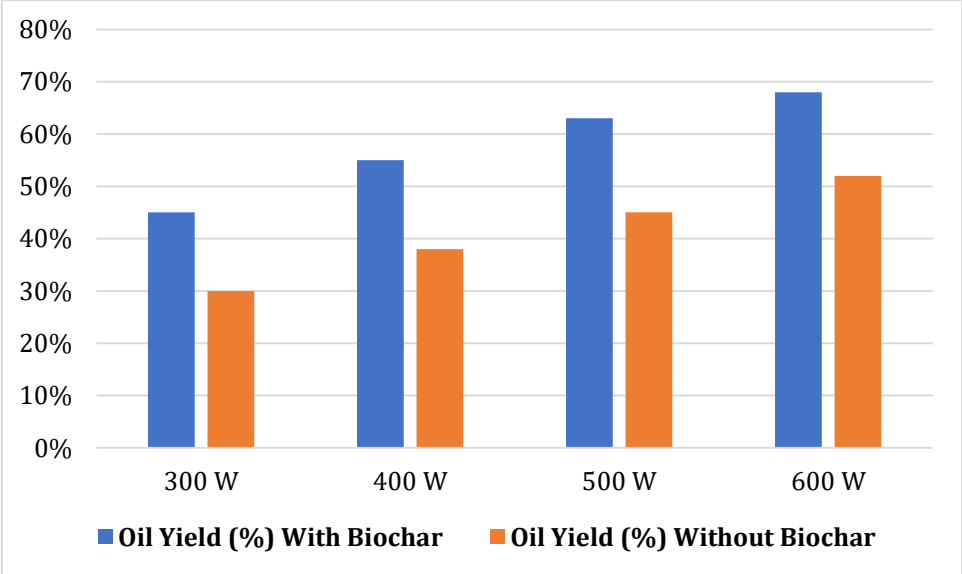

Fig. 9. Liquid oil yield at various microwave power levels during MAP processing of plastic waste, comparing systems with and without coconut-shell biochar (Islam et al., 2025)

This results in a more consistent and quicker increase in temperature within the reaction area, facilitating a more thorough breakdown of polymers and the conversion of heavier vapors into lighter hydrocarbons. To assess the level of this enhancement, Figure 8 illustrates the liquid oil yields generated at different microwave power settings for MAP

setups with and without the addition of coconut-shell biochar. Figure 9 illustrates a straightforward comparison of liquid oil yields from the Microwave-Assisted Pyrolysis (MAP) of plastic waste, both with and without the inclusion of coconut-shell biochar. The data indicates a notable and consistent increase in oil yield when biochar is used as a microwave absorber. As the microwave power steps up from 300 W to 600 W, both setups show an overall increase in oil output, demonstrating that more energy is available for breaking polymer bonds and producing vapor. However, the configuration with coconut-shell biochar shows a significantly sharper enhancement, underscoring the vital role of biochar in improving heat transfer efficiency and cracking reactions in the reactor.

The significant performance disparity between the two setups can be attributed to the varying characteristics of microwave absorption by plastics and biochar. Materials like LDPE, PP, and PET naturally have low dielectric traits, which means they are not good at absorbing microwave energy. In the absence of a microwave absorber, heating mainly depends on slow thermal conduction from limited areas of heat, leading to uneven temperature distributions and increasing the chances of incomplete depolymerization. This results in lower oil yields and a greater production of heavier waxes or char residues. Conversely, coconut-shell biochar has a high dielectric loss tangent, allowing it to absorb microwave energy quickly and convert it to heat almost immediately. This helps create localized areas of high temperature that speed up the breakdown of long-chain polymers, resulting in higher liquid oil outputs.

Furthermore, the catalytic properties of coconut-shell biochar also enhance the variety of products. The porous carbon surface offers active sites for secondary cracking processes, turning heavier hydrocarbon vapors into lighter, more desirable fractions. This catalytic interaction not only boosts oil yield but also improves oil quality by decreasing the presence of waxy or tar-like substances that are often found in MAP systems lacking absorbers. The steady increase in oil yield observed with different microwave powers from 45% at 300 W to 68% at 600 W with biochar demonstrates the combined effect of microwave heating and biochar facilitated catalytic cracking. At higher power levels 500-600 W, the gap in performance between the two systems broadens, indicating that the benefits of biochar become increasingly pronounced as additional microwave energy is applied. Under these conditions, biochar enables swift and uniform heating, eliminating thermal delays and reducing energy losses.

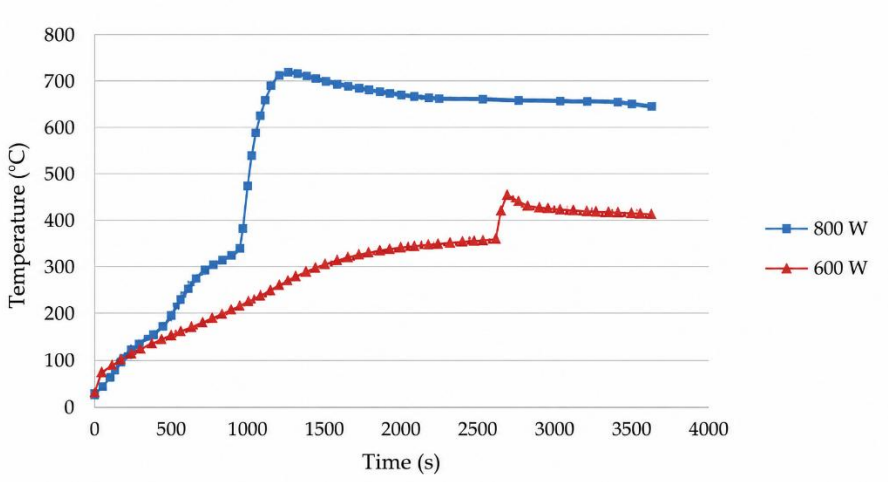

Fig. 10. Temperature profiles of PET and LDPE during microwave-assisted pyrolysis, PET at 600 W and 800 W
(Caroko, 2021)

Meanwhile, the system without biochar continues to face challenges with inadequate microwave absorption, leading to inefficient use of the available power. As a result, even with the same external energy input, the MAP system that incorporates biochar can reach higher temperatures more rapidly, maintain superior thermal stability, and create optimal

environmental conditions for hydrocarbon vapor production. Collectively, The findings illustrated in Figure 10 and 11 convincingly back the idea that biochar made from coconut shells greatly boosts MAP efficiency. Its ability to serve both as an effective microwave absorber and a gentle catalyst improves the speed and energy aspects of the pyrolysis process. Incorporating biochar not only raises the amount of liquid oil produced but also encourages clearer, more consistent cracking reactions while minimizing solid by-products.

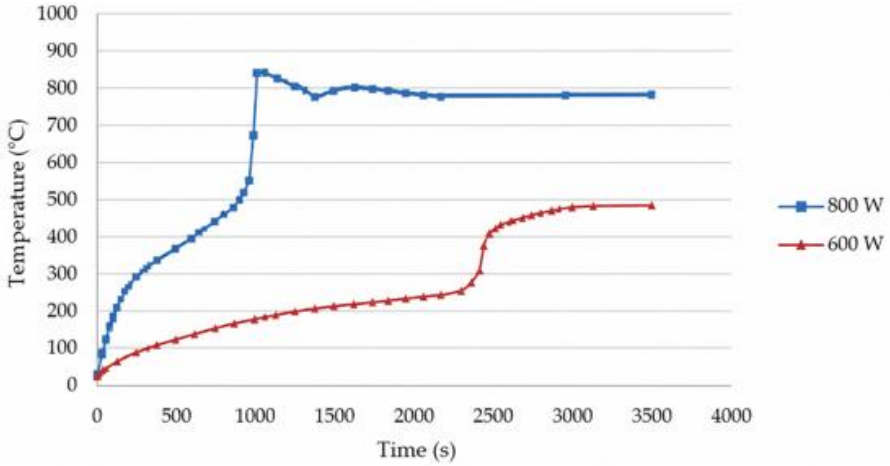

Fig. 11. Temperature profiles of PET and LDPE during microwave-assisted pyrolysis, LDPE at 600 W and 800 W
(Caroko, 2021)

The effectiveness of Microwave-Assisted Pyrolysis (MAP) in transforming plastic waste can be directly assessed by observing the heating patterns and the maximum temperatures reached during the process, as shown by Caroko (2021). Based on the temperature data illustrated in Figure 10 and 11, both PET and LDPE display a similar trend where increased microwave power correlates with higher peak temperatures and quicker heating rates. Specifically, for PET at 600 W, there is a notable temperature increase at 2,610 seconds, jumping sharply from 354°C to 453°C. Conversely, at 800 W, a significant temperature spike takes place much sooner at 960 seconds when the temperature of PET rises abruptly from 337°C to 713°C. This earlier and more intense increase indicates that higher microwave power enhances energy uptake and internal heating, allowing PET to attain pyrolysis temperatures more rapidly. LDPE shows a comparable trend at 600 W, the temperature of LDPE rises from 301°C to 385°C by 2,473 seconds, while at 800 W, a substantial temperature escalation occurs at 1.095 seconds, with the temperature climbing from 549 °C to 845°C. This suggests that LDPE is generally more sensitive to microwave heating than PET, consistent with its polymer structure characterized by weaker C–C bonds that decompose more easily at higher temperatures.

Table 2. Maximum temperature achieved by PET and LDPE during microwave-assisted pyrolysis at 600 W and 800 W

Daya (W)	PET(°C)	LDPE(°C)
600	486.44	458.88
800	638.31	861.30

(Caroko, 2021)

The variations in heating behavior between PET and LDPE are linked to the unique dielectric properties of the polymers and their capacity to absorb microwave energy. The study notes that in MAP systems, heat is produced through molecular friction generated by the movement of dipoles and charged particles in the presence of microwave radiation. Materials that can efficiently absorb microwave energy tend to undergo more rapid molecular agitation, leading to a quicker temperature increase. PET, with its aromatic C=C bonds that have a lower ability to absorb microwaves, heats up more slowly than LDPE.

Additionally, the moisture content plays a role in differing heating rates, as water molecules enhance the absorption of microwave energy due to their strong dipolar characteristics. The higher heating efficiency seen in LDPE is further evidenced by its greater volatile matter content compared to PET, which facilitates quicker thermal decomposition once the required pyrolysis temperatures are achieved.

Caroko's research (2021) also emphasizes the benefits of MAP compared to traditional pyrolysis methods. For both PET and LDPE, MAP at 600 W succeeded in reaching pyrolysis temperatures beneath 500°C significantly lower than the 500°C minimum required for fixed-bed pyrolysis reactors. This clearly illustrates that microwave heating allows for more effective energy transfer, permitting depolymerization and the creation of oil at reduced thermal conditions. The capacity of MAP to produce pyrolytic oil at lower temperatures is particularly valuable for energy-efficient practices, suggesting that microwave heating can facilitate more localized, rapid, and effective thermal degradation of plastic polymers than reactors heated externally. It results in faster temperature increases, leads to an earlier start of pyrolysis, and improves the energy efficiency of the overall process for both PET and LDPE.

3.2 Effect of microwave absorbers on heating efficiency

The data shown in Table 3 clearly indicates that raising the microwave output power results in a simultaneous increase in the heating rate during microwave-assisted pyrolysis. At a power level of 600 W, the heating rates observed for PET and LDPE were 9.43°C/min and 7.85°C/min, respectively. When the power was increased to 800 W, PET showed a small rise to 9. 86°C/min, while LDPE saw a significant jump to 42.96°C/min. These results clearly show that as the amount of microwave energy provided increases, the more quickly the material can attain its pyrolysis temperature.

Table 3. Heating rate of PET and LDPE

Daya (W)	PET(℃/min)	LDPE(℃/min)
600	9.43	7.85
800	9.86	42.96

(Caroko, 2021)

The increase in heating rate is not only due to microwave power; it is also significantly affected by the inclusion of a 50% microwave absorber combined with the plastic feedstock. The absorber improves microwave coupling, allowing for better absorption of electromagnetic energy and speeding up heat production in the sample. PET shows a more moderate rise in heating rate than LDPE due to its aromatic structure, which is heavily influenced by stable C=C bonds. This structure makes it more resistant to thermal decomposition and necessitates a greater amount of energy to decompose. In contrast, LDPE, which is primarily made up of long saturated hydrocarbon chains, breaks down more easily. This property causes its reaction to heat to be significantly more responsive to increases in microwave power, especially at 800 W.

These findings align with earlier research, including that of Nuryosuwito (24), who indicated that increased heating rates of 10, 15, or 20°C/min facilitate the production of liquid, gas, and solid products within the pyrolysis temperature range of 400-600°C. Plastic waste made up of HIPS, OPS, and EPS generated larger quantities of liquid products when the heating rate was raised. Taken together, these findings demonstrate that increased microwave power and the application of absorbers significantly boost heating efficiency, speed up the process of pyrolysis, and allow for more successful transformation of plastic waste into valuable materials.

Table 4. Compound group distribution in pyrolysis oils from microwave-assisted and conventional pyrolysis

Compound group	MW-assisted pyrolysis (wt%)	Conventional pyrolysis (wt%)
Paraffins, isoparaffins, olefins +cycloalkenes	97.3	90.7
Mono Aromatics	1.9	7.3
Benzothiophenes & Diaromatics	0.6	1.72
Dibenzothiophenes & Triaromatics	0.0	0.1
Tetraromatics	0.0	0.02
Other molecules	0.0	0.1
Total	100.0	100

(Fresneda-Cruz et al., 2025)

Figure 12 and 13 demonstrates the distinct impact of microwave heating on the chemical makeup of the pyrolysis oils derived from plastic waste. The product of microwave-assisted pyrolysis (MAP), the gas chromatogram shows a well-organized and repetitive pattern of three distinct peaks for each carbon number: a terminal diene, a terminal monoalkene, and an alkane. This three-peak pattern shows that MAP significantly encourages the creation of unsaturated hydrocarbons, particularly terminal olefins and dienes. The prevalence of these species indicates the special heating conditions created by microwaves, where quick, three-dimensional heating of the reactor bed and strong temperature differences speed up primary chain-scission reactions while hindering secondary changes.

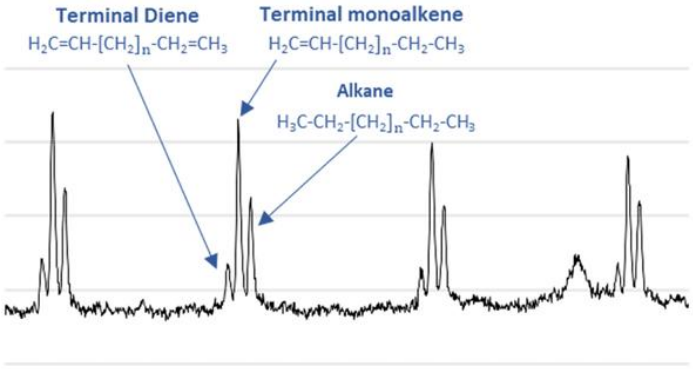

Fig. 12. GC chromatogram showing hydrocarbon compounds produced from microwave-assisted pyrolysis
(Fresneda-Cruz et al., 2025)

As a result, highly reactive intermediates like dienes and terminal monoalkenes leave the heated area before they can participate in hydrogen-transfer or cyclization reactions that usually happen in traditional systems. This is consistent with the compositional, indicating that MAP produces a notably high percentage of paraffins, isoparaffins, olefins, and cycloalkenes (97.3 wt%), while the formation of aromatics is very low (1.9 wt%). In comparison, the chromatogram shown in Figure 13, which represents traditional electrically heated pyrolysis, displays a significantly distinct distribution of products. Only two primary peaks are noted for each carbon number these correspond to terminal monoalkenes and alkanes whereas the distinct terminal diene peaks present in MAP are not detected. The vanishing of dienes and the decrease in olefin products suggest significant secondary reactions caused by the slower and conductive heating typical of traditional pyrolysis.

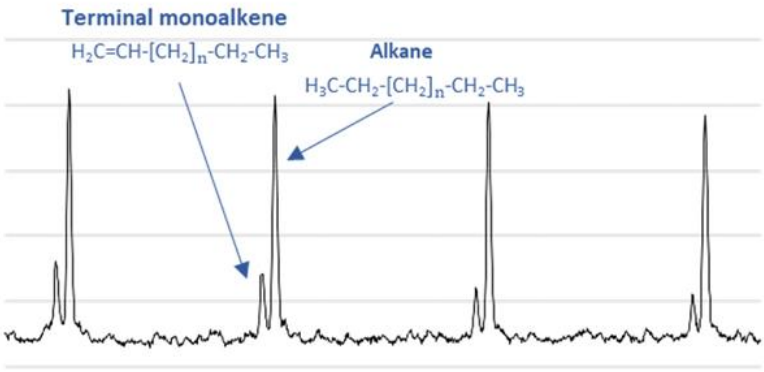

Fig. 13. GC chromatogram showing hydrocarbon compounds produced from conventional pyrolysis (Fresneda-Cruz et al., 2025)

In these systems, unstable intermediates are subjected to high temperatures for extended durations, promoting processes such as hydrogen abstraction, rearrangement, and the formation of aromatic compounds. This aligns with the higher production of monoaromatics 7.3 wt%, benzothiophenes, di-aromatics, and even small amounts of triaromatics found in the traditional pyrolysis oil, as demonstrated in Table 4. The increased aromatic content, along with a reduced amount of unsaturated hydrocarbons, indicates a greater level of molecular rearrangement and thermal breakdown during standard heating. These chromatograms emphasize the essential distinctions in the reaction conditions produced by microwave heating compared to traditional heating methods. MAP establishes a rapid, targeted, and energetically focused cracking process that maintains the integrity of unsaturated hydrocarbons and reduces further transformations, while traditional pyrolysis promotes more extensive cracking and significant molecular rearrangements, leading to increased aromaticity and saturation (Fresneda-Cruz et al., 2025).

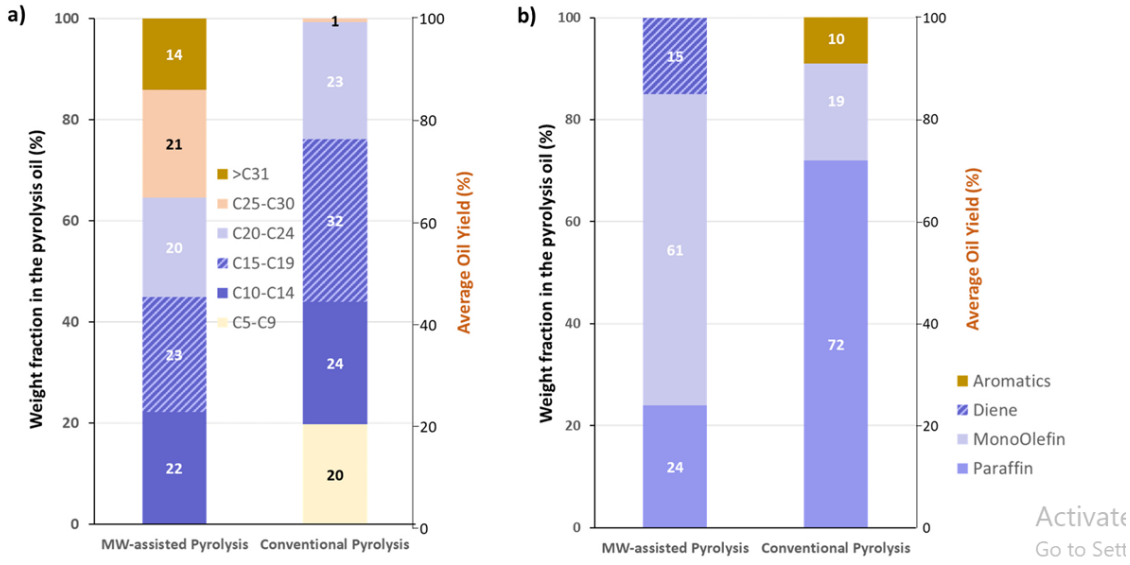

Fig. 14. (a) Carbon chain length distribution of pyrolysis oils under microwave-assisted pyrolysis and conventional pyrolysis, and (b) Chemical compound group distribution quantified via GC–MS (Fresneda-Cruz et al., 2025)

Figure 14(a) shows a comparison of the distribution of carbon chain lengths in pyrolysis oils generated through microwave-assisted pyrolysis (MAP) and traditional pyrolysis methods. MAP produces a wider variety of hydrocarbons, particularly in the mid-chain area (C10–C24). This outcome indicates quick depolymerization and minimal

secondary cracking. In comparison, traditional pyrolysis generates a higher amount of lighter hydrocarbons (C5–C9) and heavy residues (>C31), suggesting that it involves slower heating, extended vapor exposure time, and more extensive secondary reactions. This distinction is also consistent with the elevated average oil yield noted in MAP.

Figure 14(b) illustrates the arrangement of significant chemical groups. Oils derived from MAP consist mainly of paraffins and also have a considerable amount of olefins (both mono- and dienes), indicating that microwave heating encourages the creation and maintenance of unsaturated hydrocarbons. Traditional pyrolysis, however, produces a greater amount of aromatics and a smaller quantity of olefins because the volatiles are subjected to high temperatures for a longer duration. This prolonged exposure encourages reactions such as hydrogen transfer, cyclization, and aromatization. In summary, MAP generates hydrocarbons that are cleaner, less fragrant, and more chemically valuable compared to traditional pyrolysis methods (Fresneda-Cruz et al., 2025).

3.3 Economic feasibility analysis

The economic viability of Microwave-Assisted Pyrolysis (MAP) for converting non-hazardous plastic waste was analyzed through a techno-economic evaluation framework developed from existing literature and a small-scale implementation example. This examination emphasizes the necessary capital investments, ongoing operating costs, potential revenue, and basic economic metrics to determine the feasibility of using MAP at community or landfill.

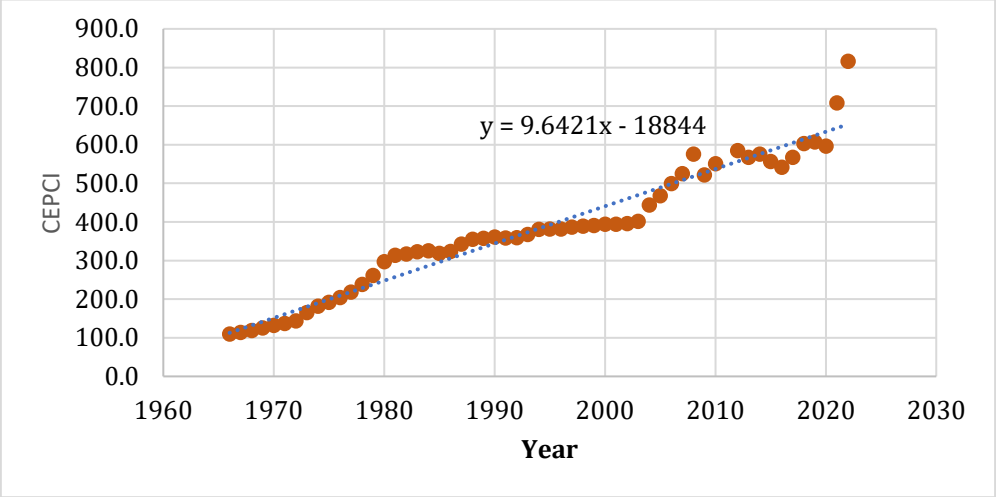

Fig. 15. Chemical engineering plant cost index (CEPCI) annual average chart

y	=	9.6421	x	-	18844
CEPCI	=	9.6421	year	-	18844

Year	CEPCI
2025	681.25

So,
Cost Index at 2025= 681.25
Dollar kurs at 2025 = IDR16,215
Here are the economic calculations:

3.3.1 Water suply unit

Water is primarily required for cooling systems and cleaning within the MAP system.
Water required: 0.02 m^3/day

Annual requirement: ≈ 7.3 m^3/year
Safety factor: 25%
Total annual water needed = 7.3 m^3 × 1.25
= 9.125 m^3/year

3.3.2 Electricity supply unit (Using PLN)

The table below shows the electricity supply requirements in the MAP process on a community scale.

Table 5. Electricity supply unit of MAP (Using PLN)

No.	Equipment	Power (kW)	Operating time (h/day)	Daily usage (kWh/day)
1	Microwave Heater	5	10	50
2	Biochar Bed Heater	2	8	16
3	Condenser Cooling Pump	0.75	12	9
4	IoT Microcontroller System	0.1	24	2.4
Total				77.4

Annual electricity consumption = 77.4 x 300 day
= 23220 kWh/year

3.3.3 Operating cost

3.3.3.1 Operating labor cost

Table 6. Operating labor cost

No	Position	Total	Salary/month (USD)	Annual expenditure (USD)
1	MAP Technology Operator	2	$181	$2,175
2	Maintenance and Calibration Technician	1	$242	$2,900
3	Operations Manager	1	$363	$4,350
4	IT/IoT Monitoring Expert	1	$303	$3,625
Total		5	$1,089	$13,050

3.3.3.2 Raw material calculation

Table 7. Raw material of MAP calculation

No.	Raw material	Unit Price (USD)	Annual requirement (kg/tahun)	Total cost (USD)
1	Coconut Shell (for Biochar)	$0.08/kg	5,000 kg	$363
2	Non-B3 Plastic Waste	0/kg	8,000 kg (assumption)	$0
3	Zeolite (Catalyst)	$0.25/kg	100 kg	$25
4	Activated Carbon (Microwave Abs.)	$1.21/kg	200 kg	$242
Total Raw Material				$630

Process Raw Material
Working Time = 24 hours
Operation Time/year = 350 day
Bio-fuel Target = 10000 year
Bio-oil density = 0.8 kg/L
Biofuel to mass convertion = 8000 kg biofuel/year
Conversion efficiency = 60%
Plastic waste needs = 13333.3333 kg/year
Plastic waste input per day = 38.0952 kg/day
Production per hour = 1.5873 kg/hour

3.3.3.3 Calculate operating cost

3.3.3.3.1 Purchased equipment cost (PEC)

The table below shows the purchase equipment cost based on the matches' engineering to chemical energy manufacturing website.

Table 8. Purchase equipment cost of MAP

No	Equipments	Specification	Quantity	Estimated Price (USD)	Total (USD)
1	Kondensor IWAKI Glass Ware Condenser Liebig	2340-500 500x740mm	2	$59	$118
2	Labu Leher 2 IWAKI Boiling Flask Round Bottom with TS Joint 2 Neck	500ml	2	$68	$134
3	Centrifugal pump	Hp 1 Phase Rotor W1000	1	$139	$139
4	Kegco High Pressure Nitrogen Air Tank	22 ft^3	1	$205	$205
5	Digiten Water Flow Controller G1 Flow Sensor Meter G1 Solenoid Valve	-	1	$109	$109
6	OMRON Temperature Controller Digital	E5CC-QX3A5M-000	1	$215	$215
7	Flow Control Motorized Electric Ball Valve	2 INCH DN50 2 WAY AC 220 VOLT	3	$41	$123
8	IoT Sensor System (ESP32 + GUI)	1 set	1	$725	$725
9	Microwave Reactor (Modular)	1 set	1	$1,812	$1,812
10	Biochar Reactor Chamber	1 set	1	$2,114	$2,114
Total					$5,692

3.3.3.3.2 Direct plant cost (DPC)

Table 9. Direct plant cost of MAP

Item	% of PEC	Total (USD)
Equipment Installation	25%	$3,805
Piping System	10%	$1,522
Instrumentation and Control	8%	$1,217
Electrical Installation	10%	$1,522
Total DPC		$8,066

3.3.3.3.3 Indirect plant cost

Table 10. Indirect plant cost of MAP

Item	% of DPC	Total (USD)
Engineering & Supervision	10%	$ 807
Total IPC		$ 807

3.3.3.3.4 Fixed capital investment (FCI)

Table 11. Fixed capital investment of MAP

Component	Total (USD)
Direct Plant Cost	8,066
Indirect Plant Cost	807
Total FCI	8,873

3.3.3.3.5 Working capital investment (WCI)

Table 12. Working capital investment of MAP

Component	Total (USD)
15% of FCI	1,331
Total WCI	1,331

3.3.3.3.6 Total capital investment (TCI)

Table 13. Total capital investment of MAP

Component	Value (USD)
FCI	$8,873
WCI	$1,332
Total TCI	$10,205

Return on Investment (ROI) Estimation
Assumptions:
Plastic waste processed/year = 8,000 kg
Conversion to fuel = 60%
= 4,800 kg
Fuel selling price = $ 0.79/L
Fuel density = 0.8 kg/L
= 6,000 L/year
Revenue from fuel = 6,000 × $ 0.79
= $4,708 /year
Co-product (biochar) = 1,000 kg/year × $ 0.24
= $ 240 /year

Income Summary:

Table 14. Overall income summary of MAP

Item	Annual Revenue (USD)
Biofuel Sales	$ 4,711
Biochar Sales	$ 242
Total Revenue	$ 4,952
Cost Summary	
Item	Value (USD)
Annual OPEX	$ 2,744
Net Profit (A-B)	$ 1,846

4. Conclusions

Microwave-Assisted Pyrolysis (MAP) is a cutting-edge and effective method for transforming organic waste into valuable products like bio-oil, biochar, and syngas. This research illustrates how MAP, when combined with biochar from coconut shells as a renewable microwave absorber and catalyst, proves to be more effective than traditional pyrolysis techniques. Quantitative findings reveal that MAP yields a bio-oil rich in favorable hydrocarbon components, where paraffins, isoparaffins, olefins, and cycloalkenes make up 97. 3 wt%, while aromatic substances comprise just 1. 9 wt% of mono-aromatics and less than 1 wt% of sulfur-containing and polyaromatic compounds, which points to a cleaner and higher quality fuel outcome. Regarding thermal efficiency, MAP achieves swift and even heating, with heating rates of 9. 86 °C/min for PET and 42. 96 °C/min for LDPE at 800 W, notably surpassing traditional heating methods. The method also reaches high temperatures up to 638 °C for PET and 861 °C for LDPE, allowing effective polymer breakdown in shorter reaction times and reduced overall energy use. From a financial standpoint, MAP shows encouraging viability, projecting an annual income of

approximately USD 4,952, mainly from biofuel sales (USD 4,711) and additional income from biochar use (USD 242). With a Total Capital Investment (TCI) of USD 10,205, consisting of USD 8,873 for Fixed Capital Investment (FCI) and USD 1,332 for Working Capital Investment (WCI), this system has strong prospects for successful large-scale or modular implementation. In summary, MAP provides a sustainable, clean, energy-efficient, and economically feasible method for managing organic waste, adhering to circular economy principles and aiding the shift toward a low-carbon future.

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Author Contribution
N.A.A.: Writing-original draft, Writing–review & editing, Methodology, Conceptualization, Economic analysis, Data acquisition. G.E.G.: Writing-original draft, Writing–review & editing, Visualization, Formal analysis, Data curation, Conceptualization, Project administration. S.: Supervision, Writing–review & editing, Validation, Resources, Conceptualization.

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Ethical Review Board Statement
This study did not involve human participants, animals, or activities requiring institutional ethical approval.

Informed Consent Statement
This study did not involve human participants.

Data Availability Statement
No new datasets were created in this study. All data supporting the findings of this manuscript are derived from previously published articles cited in the reference list.

Conflicts of Interest
The authors declare no conflict of interest. The study was conducted independently, and no funding bodies influenced the design, data interpretation, manuscript preparation, or the decision to publish the results.

Declaration of Generative AI Use
An AI-enabled grammar and style refinement tool was utilized to support the linguistic polishing of the manuscript. The authors reviewed and validated all generated suggestions and accept full responsibility for the scientific accuracy and integrity of the published work.

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