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The Role of Dielectric Properties in Microwave-Assisted Pyrolysis of Forest Biomass

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Microwave-assisted pyrolysis (MAP) is a promising thermochemical conversion method for converting forest/lignocellulosic biomass into valuable bio-based products. The efficiency of MAP strongly is governed by the dielectric properties of the feedstock, particularly the dielectric constant (ε'), dielectric loss factor (ε"), and loss tangent (tan δ), which govern how effectively microwave energy is converted into heat. This study focuses on the dielectric properties of different types of forest biomass (hardwoods, softwoods) and their effects on microwave pyrolysis efficiency and yield. The study also aims to show how the usage of catalysts, additives, and feedstock blending affects product selectivity, heating rates, and product yield.

KEYWORDS
dielectric properties, MAP, tan δ, heating efficiency, forest biomass

Orman Biyokütlelerinin Mikrodalga Destekli Piroliz Sürecindeki Dielektrik Özelliklerinin Rolü

Mikrodalga Destekli Piroliz (MAP), orman kökenli veya lignoselülozik biyokütlenin daha değerli biyo-bazlı ürünlere dönüştürülmesinde umut vadeden bir termokimyasal dönüşüm yöntemidir. MAP'in verimliliği büyük ölçüde, kullanılan biyokütlenin dielektrik özellikleriyle belirlenmektedir. Özellikle dielektrik sabiti (ε'), dielektrik kayıp faktörü (ε") ve kayıp teğet değeri (tan δ) gibi parametreler, mikrodalga enerjisinin ısıya ne kadar etkili dönüştürüldüğünü belirleyen temel faktörlerdir. Bu çalışma, farklı orman biyokütlesi türlerinin (sert ağaçlar ve yumuşak ağaçlar) dielektrik özelliklerine odaklanmakta ve bu özelliklerin mikrodalga piroliz verimliliği ile ürün çıktıları üzerindeki etkilerini incelemektedir. Ayrıca çalışmada, katalizör kullanımı, katkı maddeleri ve biyokütle harmanlama yöntemlerinin ürün seçiciliği, ısınma hızı ve ürün verimi üzerindeki etkilerini ortaya koymak da amaçlanmaktadır.

ANAHTAR KELİMELER
dielektrik özellikleri, MP, tan δ, ısıl verim, orman biyokütlesi

1. INTRODUCTION

Forest operations produce substantial amounts of lignocellulosic residues, such as bark, sawdust, and thinning waste, which are often discarded despite their considerable energy potential. As the pressure grows to find low-carbon alternatives to fossil fuels, interest in converting these forest by-products into renewable energy carriers has increased. Their high lignin content, low ash levels, and consistent composition make them particularly well-suited for thermochemical conversion processes.

In the pyrolysis process, a widely used thermochemical conversion method, a wide range of organic materials and wastes are exposed to elevated temperatures (mostly between 300–700 °C) in the absence of oxygen (Zhao et al., 2010). Pyrolysis is generally classified into slow, fast, and flash types based on heating rate, temperature, and vapor residence time. Each type yields different proportions of gas, liquid, and solid products depending on process conditions (Mohan et al., 2006). In addition to these conventional methods, microwave-assisted pyrolysis (MAP) has emerged as an alternative approach. These methods differ mainly in how heat is transferred to biomass and the resulting product distribution. Separately, microwave-assisted pyrolysis (MAP) applies microwave energy to heat biomass volumetrically, offering faster and more uniform heating compared to conventional methods. As a variation of the pyrolysis process, MAP has attracted growing interest due to its potential to improve heating efficiency and product quality. Since many aspects of microwave heating in MAP remain not fully understood and require further investigation, there is still a need to better understand MAP.

Microwave radiation occupies the electromagnetic spectrum between 300 and 300,000 MHz (wavelength between 1 mm and 300 mm). Due to its advantages, such as volumetric heating, energy, and time saving, the microwave has been used in many industrial fields and applications with increasing demand. In general, while 2.45 GHz is preferred for domestic purposes, frequencies in the range of 915 MHz - 2.45 GHz are used in industrial processes (Vollmer, 2004). Microwave-based applications show diversity depending on applied temperature. Food and textile applications can be grouped in (1) low-temperature processing (up to 500°C): (2) Carbon-nanotubes synthesis and glass melting are categorized in medium temperature (500-1000°C): (3) high-temperature applications (more than 1000°C) include processing of ceramic matrix composites (Mishra & Sharma, 2016). Microwaves cause molecular motion by moving ionic fragments and/or rotation of dipolar fragments. The process of heating a material with a microwave is highly dependent on the material's dissipation factor (also called dielectric loss tangent). This factor is expressed as the ratio of the dielectric loss (ε″) to the dielectric constant (ε′) of the material.

$$\tan \delta = \varepsilon'' / \varepsilon' \quad (1)$$

The dielectric constant indicates the material's ability to retain microwave energy as it passes through the material. The loss factor is a measure of energy consumption of the material. In other words, the dielectric loss factor gives the amount of energy lost as the input microwave energy is depleted as heat in the material. Therefore, a high loss factor material can be efficiently heated with microwave energy. The loss tangent shows the material's susceptibility to microwave. Table 1 shows the dielectric loss factors of some polymers, biomass-based materials and carbon-based materials used in microwave as an absorber. Besides polymers and carbon-based substances, different types of biomasses, particularly those originating from forest and agriculture, have been evaluated for their interaction with microwave energy. In a recent study, Yao et al. (2025) examined biomass residues such as straw, grass, sawdust, bark, and fiber reject, reporting that their dielectric loss tangents (tanδ) increased significantly at elevated temperatures, particularly between 500 and 650 °C at 912 MHz, reaching values up to 0.42 (Yao et al., 2025). Similarly, other research has shown that oil palm shell exhibits moderate microwave absorption behavior (tanδ ≈ 0.08) at 2.45 GHz (Salema & Ani,

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2012). Forest biomass types differ substantially in their dielectric properties, and consequently in their suitability for microwave-assisted pyrolysis (Ramasamy & Moghtaderi, 2010).

Table 1. *Dielectric properties of some materials*

Materials	tanδ = ε'' / ε'	Frequency/Temperature	Reference
Distilled water	0.118	2.45 GHz, 25 °C	(Menéndez et al., 2010)
Teflon	0.0003	2.45 GHz, at 37 °C	(Erbulut et al., 2008)
Polymers			
HDPE	0.0002-0.0045	85-100 GHz, ambient temp.	(Elhawil et al., 2007)
LDPE	0.004	100 GHz, ambient temp.	(Elhawil et al., 2007)
Nylon 66	0.014	2.45 GHz, 25 °C	(Meredith, 1998)
PE	0.0001-0.0002	2.45 GHz, ambient temp.	(Tan et al., 2006)
	below 0.0005	0.5 to 6 GHz, ambient temp.	(Bigelow & Farr, 2022)
PET	0.009	2.45 GHz, 23 °C	(Erbulut et al., 2008)
PP	0.0003-0.0004	2.45 GHz, ambient temp.	(Zhang et al., 2017)
	0.00043	60 GHz, -	(Afsar et al., 1999)
	0.0001	100 MHz, -	(Bur, 1985)
PS	0.004	9 GHz, 20 °C	(Geyer, 1990)
	0.00031	2.45 GHz, 25 °C	(Meredith, 1998)
PVC	0.0056	2.45 GHz, 20 °C	(Meredith, 1998)
Rubber	0.0027	2.45 GHz, 20 °C	(Meredith, 1998)
Biomass-based materials			
Grass	~0.38	911 MHz, ~500 °C	(Yao et al., 2025)
Straw	~0.35	911 MHz, ~550 °C	(Yao et al., 2025)
Sawdust	~0.32	911 MHz, ~650 °C	(Yao et al., 2025)
Fiber Reject	~0.42	911 MHz, ~500 °C	(Yao et al., 2025)
Bark	~0.31	911 MHz, ~650 °C	(Yao et al., 2025)
Oil palm shell	0.13	2.45 GHz, 25 °C	(Salema et al., 2013)
Oil palm fiber	0.08	2.45 GHz, 25 °C	(Salema et al., 2013)
Wood	0.11	2.45 GHz, 25 °C	(Torgovnikov, 1993)
Pine bark	~0.18	2.45 GHz, 25 °C	(Torgovnikov, 1993)
Pine wood sawdust	~0.11	2.45 GHz, 25 °C	(Torgovnikov, 1993)
Carbon materials			
Activated carbon	0.62	2.45 GHz, room temp.	(Ramasamy & Moghtaderi, 2010)
Carbon	0.28	2.45 GHz, room temp.	(Salema & Ani, 2012)
Carbon black	0.03-0.06	1 MHz, -	(Shivashankar et al., 2021)
Carbon foam	0.02-0.2	2.45 GHz, room temp.	(Fang et al., 2007)
Carbon nanotube	0.25-1.14	2.45 GHz, room temp.	(Haiyan et al., 2008)
Charcoal	0.11	2.45 GHz, 148 °C	(Menéndez et al., 2010)
Coal	0.02-0.08	2.45 GHz, room temp.	(Yang & Wu, 1987)
Silicon carbide	0.02-1.05	2.45 GHz, room temp.	(Zhang et al., 2017)

The dielectric features of material should be evaluated by considering some other characteristic properties (such as moisture content, geometry, density, etc.) and/or temperature frequency (Fernández Diez et al., 2011). At the room temperature and 2.45 GHz, the loss tangent of coal, water, SiC, polypropylene is between 0.02 and 0.1, 0.123, 0.58-1, and 0.0003–0.0004, respectively. The materials can be classified into four groups according to their interaction with the microwave: Transparent, conductors, absorbers, and mixed. These interactions are schematically illustrated in Figure 1.

In this perspective, transparent materials (quartz, teflon) have low dielectric loss properties and are

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highly transparent to microwaves; conductors (all bulk metals), also called reflectors, are materials that microwaves reflect and cannot penetrate; absorbers (like water, SiC) are high-loss insulators that absorb microwave radiation and provide direct energy transfer. Mixed materials like composites have multi-phases, including high and low loss insulators. While the high insulator phase absorbs microwave energy, the other is heated by conventional heating (Gamit & Chudasama, 2020; Mishra & Sharma, 2016). The equation can be followed to see the relationship between the microwave power and the power absorption ability of the given material (Fan et al., 2021):

$$P = 2\pi f \varepsilon_0 \varepsilon' E^2 \tan\delta \ [W/m^3] \quad (2)$$

Where,

P is Microwave power absorbed (W/m^3),

E is the internal electric field strength (V/m),

f is microwave frequency (Hz),

ε_0 is the permittivity of free space (8.85418782 F/m),

ε′ is the dielectric constant of the material,

tanδ is the dielectric loss tangent of the material.

This review asserts that the dielectric properties, particularly the loss tangent (tan δ), of forest biomass play a pivotal role in microwave-assisted pyrolysis (MAP), and that optimizing these properties through feedstock selection, pretreatment, and additives is essential for enhancing energy absorption, thermal performance, and product yield in MAP systems.

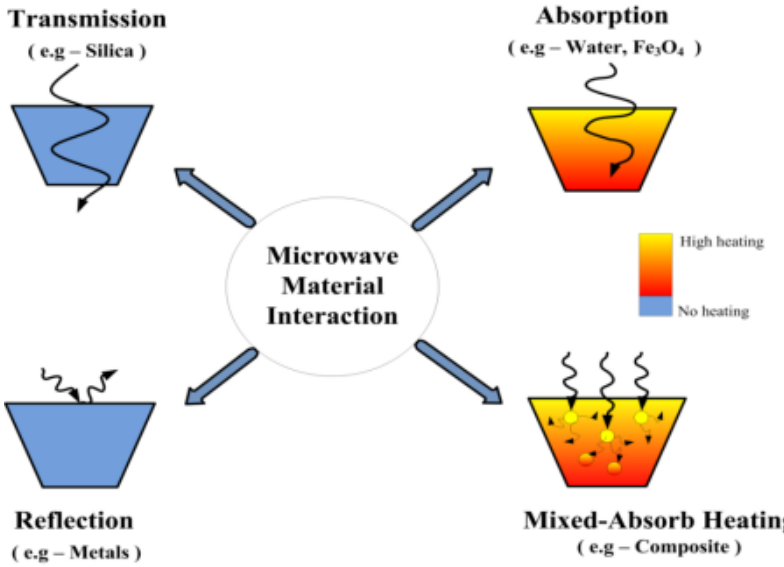


Figure 1. *Principal groups of microwaves- materials interaction (Gamit & Chudasama, 2020)*

2. MICROWAVE HEATING MECHANISM

Convention and conduction are applied for heat transfer from outside to the center of the materials in conventional heating. Microwave energy, on the other hand, enables volumetric heating. This means that the microwave energy interacts directly with the material, supplying energy throughout its entire volume and causing heat to generate uniformly inside the material. Microwave energy is not heating transfer but rather a conversion of energy (from electromagnetic to thermal energy) (Fernández Diez et al., 2011; Sun et al., 2016).The heating process is realized by absorbing microwave radiation by water and various ions in the material structure to be heated. Many recent

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studies have gained tremendous attention due to the advantages of microwave heating over conventional heating.

Advantages of microwave heating

1) No direct contact between the heating systems and the material: non-contact heating enables wide-range application in the industry (Jones et al., 2002).

2) Selective Heating: Depending on the dielectric properties of the material, the microwave can target a particular material and heat it. Thus, energy saving is achieved by adjusting the required temperature.

3) Rapid and Uniform Heating: Unlike conventional heating, there are no thermal gradients through the material. The heating can be adjusted according to the desired region and geometry. Besides, microwave heating is very rapid since it can reach high temperatures in a short time (Thostenson & Chou, 1999).

4) High energy efficiency

5) Fast and flexible processes that can also be controlled remotely, easily adaptable to existing facilities, and small volume (Fernández Diez et al., 2011)

6) Initiating and terminating heating is quick

7) Reduced waste volume

8) Cost reduction

Disadvantages of microwave heating

1) Microwave heating process has material limitations for reactor construction and design. For that reason, scale-up and optimization studies have to be investigated within a specific group of materials (Lam & Chase, 2012).

2) Even though the Faraday cage is used for keeping microwave radiation, there is still extra risk compared with conventional heating (Lam & Chase, 2012).

3) If the targeted material is plastic, transparent material for microwave radiation, the system needs microwave absorbers.

4) Essential components of microwave heating systems, such as power units and magnetrons, increase the overall cost of these systems. In large-scale industrial applications, the higher power requirements can further raise expenses.

3. FOREST BIOMASS AND ITS BEHAVIOR IN MICROWAVE-ASSISTED PYROLYSIS

Microwave-assisted pyrolysis is a thermochemical conversion process that uses microwave heating to decompose substances in an oxygen-free environment. MAP has gained popularity since it can produce highly efficient and high-quality byproducts (oil, gas, char) (Fernández et al., 2024). Many studies have investigated the product distribution of microwave pyrolysis depending on various operating conditions and several feedstocks like biomass, plastic, and their wastes. Microwave pyrolysis can accelerate reaction rates, reduce costs, save energy, and increase yields.

Forest biomass is lignocellulosic material from forest-based sources like sawdust, bark, logging residues and fiber rejects, by-products mainly generated through wood processing and forest operations. These are a sustainable and underutilized carbon neutral resource, especially in countries with plenty of forest cover like Finland where forest biomass was over 70% of renewable energy reserves in 2020 (Pardé, 1980). Forest biomass has three main organic components: cellulose, hemicellulose and lignin. The proportion of these components vary across species; for

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example, pine wood is 40-45% cellulose, 25-30% hemicellulose and 25-30% lignin. Hardwoods like oak may have higher lignin content 20-30% and cellulose 40-50% and hemicellulose 15-25% (Kandhola et al., 2017). Compared to agricultural biomass, forest biomass mostly has more lignin, less ash, better heat stability, and more predictable dielectric behavior. Because of these reasons, it is a good raw material for making bio-oil and biochar. Also, forest biomass has low ash and alkali metal content compared to agricultural residues. It can minimize risks like slagging, catalyst poisoning, and equipment fouling during pyrolysis process (Saidur et al., 2011). Thus, forest biomass is a good feedstock for thermochemical conversion methods like microwave-assisted pyrolysis (Antar et al., 2021), and the amounts of its components influence the final products, with cellulose and hemicellulose breaking down at lower temperatures to produce more bio-oil, while lignin is harder to break and mainly forms solid char and aromatic compounds (Bridgwater, 2003).

First studies have focused on microwave heating to solve the limitations of conventional pyrolysis, namely slow heating rates and uneven temperature distribution. According to the research, microwave heating can provide rapid and uniform heating resulting in more efficient pyrolysis processes (Fernández Díez et al., 2011). A study designed a special reactor with infrared sensors to heat pine sawdust from ambient temperature to 400–800 °C in about ten minutes under an inert gas. This setup allowed very fast pyrolysis with full conversion in between 1–3 minutes (Xian-Hua et al., 2009). Domínguez et al. (2007) investigated microwave-assisted pyrolysis of sawdust to analyze product distribution and heating performance. Their findings indicated that microwave heating led to a notable increase in gas yields, particularly H_2 and CO, while also decreasing liquid tar production compared to conventional electric heating (Dominguez et al., 2007). Although much of the research emphasis has been on the efficiency of microwave heating, it is important to consider the fundamental interaction between microwave energy and biomass.

Starting in the mid-2000s, researchers began investigating how individual components of biomass react when exposed to microwave energy. Experiments were carried out using pure cellulose, xylan (presented hemicellulose), and lignin. These samples were placed in specially designed microwave systems. Their ability to absorb microwave energy was observed (Robinson et al., 2022). According to the results, lignin and especially carbon-rich residues like biochar more effectively absorb microwave energy than cellulose or hemicellulose. Since lignin contains aromatic ring structures, it interacts strongly with the microwave field.

These structures enable lignin to convert microwave energy into heat more efficiently. Moreover, the heating process becomes faster when biochar is added to raw biomass. The reason is that biochar has a higher tan δ, which means it loses more microwave energy as heat—an advantage in pyrolysis processes where quick and uniform heating is desired (Ellison et al., 2017). This understanding led researchers to focus more on lignin-rich biomass sources, such as forest residues, since they respond better to microwave heating. For example, wood from pine trees, which is naturally rich in lignin, produces more char during microwave pyrolysis compared to pure cellulose. Over time, many studies and reviews have supported the idea that forest biomass, especially its mix of cellulose, hemicellulose, and lignin—is one of the most suitable and sustainable feedstocks for MAP (Ellison et al., 2017; Fernández et al., 2024).

4. DIELECTRIC BEHAVIOR, HEATING EFFICIENCY, AND MEASUREMENT TECHNIQUES

This deeper understanding of component-specific microwave interactions led to a new wave of research. As a result, modern MAP research has increasingly moved toward the use of dielectric property data—not only as a characterization tool, but as a core parameter for controlling heating behavior, optimizing energy input, and tailoring product selectivity in forest biomass conversion. Some forest residues such as pine wood, bark, and sawdust have low dielectric loss tangents (tan δ ≈ 0.11–0.18), which make them weak absorbers of microwave energy if directly exposure. To solve

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this, Khelfa et al. (2020) mixed raw pine feedstocks (tan δ≪0.2) with carbonaceous additives to raise the overall loss factor. Carbonaceous additives (activated carbon (AC), biochar, graphite) have much higher tan δ (~0.57–0.80), so even 5–20 wt% additions greatly accelerate heating. According to the results, 10 wt% AC adding can double the bio-oil yield (reaching ≈24 wt% at 800 W) by elevating temperature with suppressing char formation (Khelfa et al., 2020). Ellison et al. (2017) reported that the mixtures of wood and char can have much higher tan δ and hence heat generation than wood alone (Ellison et al., 2017). Another study shows that adding biochar (up to 10%) fourfold increase the maximum temperature in pine-sawdust pyrolysis (Ellison et al., 2020).

As pyrolysis proceeds, the dielectric loss factor of the material increased since char is a very strong absorber via interfacial polarization, so the heating becomes partially volumetric. While most studies focus on catalytic effects from a chemical perspective, some also suggest that catalysts. When combined with high-loss materials like SiC, catalyst may influence microwave heating behavior. Due to its high tan δ, SiC efficiently converts microwave energy into heat and initiates thermal decomposition externally, transferring heat to the biomass through conduction. As pyrolysis progresses and the biomass carbonizes, its own microwave absorption improves, shifting heating from external to internal. This sequential heating behavior has been shown to affect product distribution and enhance the overall efficiency of MAP systems (Huang et al., 2016; Lin et al., 2014; Shi et al., 2020). Some studies reported that presence of a catalyst changed the fraction of product. In a study, where a Ni–HZSM-5 catalyst with SiC used, while the bio-oil yield in the system reduced, the gas production increased. Increasing the tanδ value through additives generally results in less solid residue (char) formation, more gas and, in some cases, slightly higher liquid product (bio-oil) by providing faster and more homogeneous heating have been stated as the reason for this change. It can be deduced that forest biomass with low dielectric properties can be better integrated into microwave systems and product orientation can be actively controlled when processed with appropriate additives and catalysts (Khelfa et al., 2020).

Moisture content has a significant effect on the dielectric properties of biomass. Şahin and Ay (2004) have reported that both the dielectric constant (ε′) and dielectric loss factor (ε″) increase markedly with increased moisture content resulting in enhanced absorption rate. These properties vary with the anatomical grain direction of the wood such that longitudinal orientation typically exhibiting higher dielectric values (Sahin & Ay, 2004). This dual influence of moisture and anisotropy plays a crucial role in optimizing microwave heating efficiency and product selectivity. Table 2 summarizes the dielectric properties and resulting main products of some biomass types with/without catalyst/additives as discussed in the preceding sections. These comparative insights support the argument that tan δ value can be tuned to favor specific pyrolysis outcomes through careful feedstock selection and material modification.

Table 2. *Dielectric properties, additive effects, and product yields of forest biomass in map studies*

Biomass Type	tan δ	Frequency (GHz)	Temperature (°C)	Main Product(s)	Additives/ Catalysts	Reference
Softwood						
Pine Sawdust	~0.11	2.45	400–600	Char	None	(Torgovnikov, 1993)
Pine Bark	~0.18-0.31	2.45/0.912	500–650	Gas, bio-oil	Biochar, SiC	(Yao et al., 2025)
Wood + Biochar (mix)	0.25–0.60	2.45	500–800	bio-oil, char	5–20 wt% Biochar	(Ellison et al., 2017)
Bark + AC / SiC	0.3–0.6	2.45	500–650	bio-oil, tar	Activated carbon, SiC	(Khelfa et al., 2020)
Spruce Wood	~0.12	2.45	500–600	bio-oil	None	(Huang et al., 2016)
Hardwood						
Eucalyptus Wood	0.12–0.15	2.45	450–600	Aromatic bio-oil	Ni–HZSM-5, SiC	(Teng et al., 2025)

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Biomass Type	tan δ	Frequency (GHz)	Temperature (°C)	Main Product(s)	Additives/ Catalysts	Reference
Eucalyptus+ MoO_3	~0.15	2.45	550	N-rich oil	MoO_3 + N-rich co-feedstock	(Li et al., 2022)
Douglas-fir*	0.086	0.05	25	NG	NG	(James, 1975)
Oak (radial)*	0.068	0.05	25	NG	NG	(James, 1975)
Poplar*	~0.02	9.8	20-24	NG	NG	(Sahin & Ay, 2004)
Alder	~0.024	9.8	20-24	NG	NG	(Sahin & Ay, 2004)
Oriental beech	~0.036	9.8	20-24	NG	NG	(Sahin & Ay, 2004)
Fiber Reject (Mixed)	~0.42	0.912	~500	H_2-rich gas	None	(Yao et al., 2025)

*Relative humidity:0%

To quantify these characteristics more accurately, more researchers have focused on advanced dielectric measurement tools, such as vector network analyzers (VNAs), open-ended coaxial probes, and cavity perturbation systems. After using an open-ended coaxial probe with a VNA (0.5–20 GHz) to measure wood/biochar mixtures, Ellison et al. (2017) found that both ε′ and ε″ rise sharply as biochar fraction increases (Ellison et al., 2017). More advanced systems combine resonant cavities and in-situ heating too. Catalá-Civera et al. (2015) developed a dual-mode cylindrical cavity that simultaneously heats the sample and probes resonance with a VNA, enabling ε′, ε″ vs. temperature profiles up to ~1000 °C (Catalá-Civera et al., 2015). This study shows that during MAP, the dielectric properties of biomass first decrease during drying and pyrolysis but then increase again as char forms. Therefore, measurements using high-sensitivity resonators or waveguides have become a common method for monitoring the temperature-dependent dielectric behavior of biomass. As shown in Figure 2, the results reported by Yao et al. (2025) indicate that the dielectric constants of different forest biomass samples decrease with increasing temperature during the initial stages, and then increase markedly at higher temperatures as char formation progresses.

Among up-to-date studies, dielectric spectroscopy and resonant cavity methods are advanced new technologies which map ε′ and ε″ of wood residues over frequency and temperature ranges. In a study, a broadband cavity perturbation technique measured ε′ and ε″ of pine sawdust, bark, and other wood wastes from 25–700 °C over 397–2985 MHz (Yao et al., 2025). According to the results, both ε′ and ε″ decrease during drying and devolatilization (25–400 °C) as moisture and volatiles are lost but then rise sharply during char formation (400–700 °C) as carbonaceous structure builds (Fig. 2).

This directly affects the heating uniformity. The half-power penetration depth of the microwave field (at 912 MHz) peaks around 300–350 °C (≈3–5 cm thickness) for grass and wood/bark samples, implying that up to ~350 °C one can heat large volumes, whereas above ~500 °C only thin layers (<1 cm) absorb energy effectively. Thanks to the ε′/ε″ data obtained with these methods; optimized reactor design can be possible with uniformly heated biomass and efficiently used energy.

On the other hand, material and catalyst modification of forest biomass studies have shown that blending with plastics or adding catalysts/absorbers can boost oil yields or shift chemistry. A hydrogen-type multilayer MFI zeolite (HMMN) and a conventional HZSM-5 have been compared through microwave co-pyrolysis of eucalyptus wood. The HMMN catalyst roughly quintupled the fraction of monocyclic aromatic hydrocarbons in the bio-oil with ~25.8 wt% oil yield (with ~24 wt% aromatics) at 550 °C (Teng et al., 2025).

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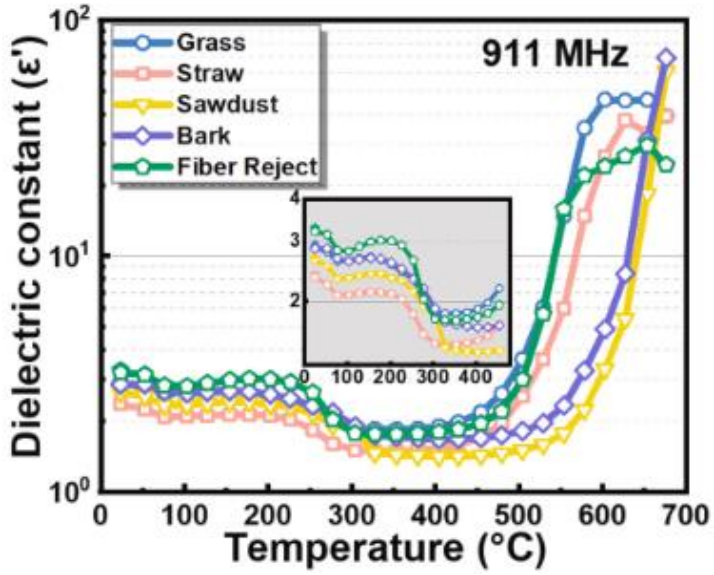


Figure 2. *Dielectric constants of grass (GR), straw (ST), sawdust (SD), bark (BK), and fiber reject (FR) as a function of temperature (Yao et al., 2025)*

Similarly, Wang et al. (2018) mixed eucalyptus with MoO_3 and nitrogen-rich co-feedstocks. This increased nitrogen incorporation (EW:MoO_3=2:1) gave the highest oil yield of approximately 41.7 wt%. Besides, the addition of 40 wt% soybean straw increased the N content in bio-oil to approximately 24 wt%, mostly nitriles and heterocycles (Li et al., 2022). Even it is an inert additive, adding silicon carbide powder (a strong microwave susceptor) to eucalyptus leaf biomass increased heating efficiency and yielded up to ~39.3 wt% bio-oil at optimized power and temperature (Kashif et al., 2024). In addition to improving bio-oil quality with more aromatic or N-containing compounds and gas or hydrogen yield, many of mentioned and some other additives function as high-loss microwave susceptors indirectly improve dielectric heating uniformity and enhancing product selectivity in MAP of low-tan δ forest biomass.

5. DISCUSSION

This study has explored how microwave-assisted pyrolysis (MAP) of forest biomass has developed over the years. What began with basic investigations into individual biomass components has gradually evolved into more complex research, where dielectric property measurements are now playing a role in reactor design. While the field has moved forward in many ways, there are still several important gaps that need to be addressed.

One of the main issues is most of dielectric measurement studies have been done under ideal lab conditions, using dry or finely milled biomass (Ellison et al., 2017). These setups don't really capture the complex behavior of real forest residues. They often contain a lot of moisture and are far from uniform. To better understand how these materials behave in actual processes, more studies need to be done focusing on measuring dielectric properties in real time inside working reactors. This would give much more relevant data on how ε′ and ε″ values shift during process. There is also growing interest in enhancing MAP by additives and catalysts with high dielectric loss, such as silicon carbide (SiC), and Ni–HZSM-5. These materials can improve heating uniformity and product yields (Ellison et al., 2017; Wang et al., 2018). Still, there are still unanswered questions such as how these additives affect energy consumption, the balance between gas, bio-oil, and char production. After answering these questions, there is also needs for more targeted studies, especially ones that take both economic and environmental impacts into account.

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The integration of dielectric property data into process control is still in its early stages, but combining real-time measurements with multiphysics models could enable dynamic optimization of the MAP process. To achieve this, reliable dielectric sensors are needed under pyrolysis conditions, predictive models must be validated with experimental data, and control algorithms should manage multiple input variables in real time. Overcoming these challenges could significantly improve process efficiency and flexibility.

6. CONCLUSION

Microwave-assisted pyrolysis of forest biomass has gained increased attention. To enhance the yield of final products and selective cracking, it is essential to effectively and more accurately characterize dielectric properties. The distinctive structural characteristics of forest residues, particularly their lignin content and uniformity, make them favorable feedstocks for efficient and targeted thermal conversion. In this context, the loss tangent (tan δ) should not only be seen as a characterization tool. If it is applied as a dynamic control parameter, tan δ can optimize pyrolysis outcomes. This approach provides a promising roadmap for sustainable biofuel production and advanced biomass conversion strategies. Most dielectric measurements are performed under controlled laboratory conditions using dry and uniform samples, which do not accurately represent the variability of real biomass in terms of moisture and structure. Therefore, there is an increasing need for real-time dielectric measurement systems integrated into actual reactor environments. On the other hand, studies indicate that increasing the tan δ value with suitable additives can enhance heating rates and thermal efficiency. It can improve product yield and selectivity. Additionally, lignin-rich biomass, which absorbs microwaves more effectively, is naturally better suited for MAP, often resulting in higher yields of aromatic bio-oils and valuable gases due to rapid, volumetric energy transfer.

This review clearly demonstrates the critical role of dielectric properties in microwave-assisted pyrolysis (MAP) processes of forest biomass. Specifically, the dielectric constant (ε′), dielectric loss factor (ε″), and loss tangent (tan δ) are fundamental parameters that determine how effectively microwave energy is converted into thermal energy. In this context, forest biomass with low tan δ values has restricted microwave's absorption capacity. To overcome this limitation, the usage of additives (activated carbon, biochar, or silicon carbide (SiC) is proposed.

Author Declarations and CRediT Roles

There is no conflict of interest. No funding was received. Ethical committee approval is not required. Generative artificial intelligence (ChatGPT 5.0) was used for language editing. It has not been previously presented or published. No data were analyzed or generated in this study.

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