

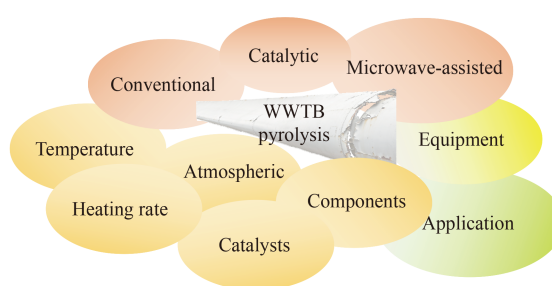
Research advances in the pyrolysis recycling of waste wind turbine blades

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Abstract: The global energy landscape is undergoing a profound transformation, with wind energy, especially wind power, gaining increasing prominence due to its clean, renewable nature. However, as the installed capacity of wind power continues to expand, the disposal of waste wind turbine blades (WWTB) has emerged as a significant challenge. These blades are predominantly composed of epoxy resin (EP) polymers, carbon fibers (CFs), and glass fibers (GFs). Improper disposal not only exacerbates environmental concerns but also leads to the loss of valuable resources, particularly carbon-based materials. Pyrolysis technology, a versatile and environmentally sustainable method for resource recovery, has garnered considerable attention in the context of WWTB disposal. This work presents a comprehensive review of the pyrolytic recycling of WWTB, focusing on the principles and classifications of pyrolysis technology, key factors influencing the pyrolysis process, as well as the pyrolysis methods, equipment, products, and their applications. Through an in-depth analysis of the current research on the pyrolytic recycling of WWTB, this review identifies critical unresolved issues in the field and provides a forward-looking perspective on emerging research trends.

Key words: waste wind turbine blades; epoxy resin polymers; carbon fibers; glass fibers; pyrolysis recycling; resource recovery



With the rapid growth of the global economy, the demand for energy worldwide has been gradually shifting from traditional fossil fuels to clean energy sources. At present, the development of society and industry still relies heavily on fossil fuels such as coal, oil and natural gas, but this dependence has placed immense pressure on the environment^[1-4]. Owing to their environmentally friendly characteristics, clean energy sources are assuming an increasingly important role in national energy structures^[5-7]. The vigorous expansion of clean energy not only reduces reliance on fossil fuels but also alleviates environmental burdens, thereby addressing the escalating challenge of climate change^[8-9]. Among the major categories of clean energy, solar energy, wind energy, and hydropower stand out as the three primary branches^[10]. Of these, wind energy,

owing to its renewability and vast development potential, has been steadily increasing its share within the clean energy sector year by year^[11]. With the introduction of the “dual carbon goals” renewable energy sources such as wind power and biomass energy are demonstrating even greater development potential. Simultaneously, the rapid expansion of the wind power industry is increasing both the frequency and scale of wind turbine blade material usage. However, the limited lifespan of these blades is expected to result in a significant decommissioning peak in the coming years. Consequently, the rational recycling and utilization of WWTB has become an urgent environmental priority. Developing greener, more sustainable disposal technologies is of practical importance for alleviating ecological pressure, mitigating emissions, and ensuring that the rapid

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expansion of the wind energy industry does not inadvertently undermine its climate benefits^[12–13].

At present, the primary recycling approaches applied to the composite constituents of WWTB include mechanical recycling, chemical recycling, pyrolysis, and other emerging techniques^[14–18]. Mechanical recycling involves fragmenting WWTB into smaller particles or short fibers through processes such as mechanical cutting, shredding, or grinding. The chemical recycling method relies on the use of targeted chemical reagents to degrade the resin matrix in composite materials, through this process, the resin is broken down into monomers, oligomers, or other smaller molecular fragments, which can then be separated from the reinforcing fibers. Pyrolytic recycling involves heating WWTB to controlled temperatures in an oxygen-free or inert atmosphere, triggering thermal decomposition that generates pyrolytic gas, oil and solid residues. The underlying mechanism is dominated by bond cleavage, free radical formation, and subsequent recombination reactions. Depending on process design, pyrolysis can be implemented through conventional heating, catalytic pathways that enhance selectivity and efficiency, or microwave-assisted systems that provide rapid and uniform energy transfer.

Given the significant advantages and vast potential of pyrolysis for the treatment of WWTB, together with its recognition as an environmentally sustainable recycling strategy, this work provides a comprehensive and critical review of pyrolytic recycling processes applied to WWTB. The discussion centers on the most prevalent pyrolytic approaches, namely, conventional pyrolysis, catalytic pyrolysis, and microwave-assisted pyrolysis. Critical parameters governing the pyrolytic transformation of WWTB are examined in depth, including reaction temperature, heating rate, atmospheric environment, catalytic systems, and the influence of feedstock composition on process performance. Furthermore, this review synthesizes current knowledge on process design, equipment configurations, and the valorization of pyrolysis-derived products. Finally, the paper concludes with an integrative summary and offers a forward-looking perspective, highlighting emerging challenges and future research priorities in the field of WWTB pyrolysis.

1 Pyrolysis recycling method

1.1 Conventional pyrolysis

Conventional pyrolysis entails heating WWTB to the designated temperature under rigorously controlled thermal and pressure conditions, thereby inducing thermal decomposition. Pyrolysis of WWTB was conducted in a fixed-bed reactor under both inert (N₂) and oxidative (air) atmospheres^[19]. Thermogravimetric profiles (Figure 1 (a) and (b)) revealed distinct decomposition pathways: under nitrogen, a single dominant weight-loss peak emerged at 372 °C, whereas in air, two discrete peaks appeared at 270 and 473 °C. Guided by these thermal transitions, pyrolysis under N₂ was examined at 380 and 450 °C, while oxidative trials were systematically explored at 450, 480 and 550 °C to delineate optimal conditions. Despite its operational simplicity and cost-effectiveness, conventional pyrolysis remains constrained by modest efficiency and suboptimal product quality.

Product distributions from pyrolysis under varied atmospheres and temperatures are depicted in Figure 2^[19]. In nitrogen, the cumulative weight loss of WWTB, corresponding to combined gas and oil fractions, increased progressively with temperature, reflecting the staged decomposition of the EP matrix. In contrast, total weight loss in air consistently exceeded that under nitrogen due to oxygen-driven degradation of the resin. Moreover, oxygen promoted secondary oxidation of pyrolysis oil into low-molecular-weight volatiles such as CO₂ and H₂O, thereby suppressing liquid yields.

After pyrolysis, the solid residue obtained was primarily composed of GFs. Figure 3 illustrates the mechanical properties of the GFs produced under various pyrolysis conditions^[19]. As the pyrolysis temperature increased, both tensile strength and fracture strain showed a gradual decline. This reduction was attributed to the structural degradation of the GFs and the formation of defects during the pyrolysis process. On the other hand, the Young's modulus exhibited a steady increase with higher pyrolysis temperatures^[20–22].

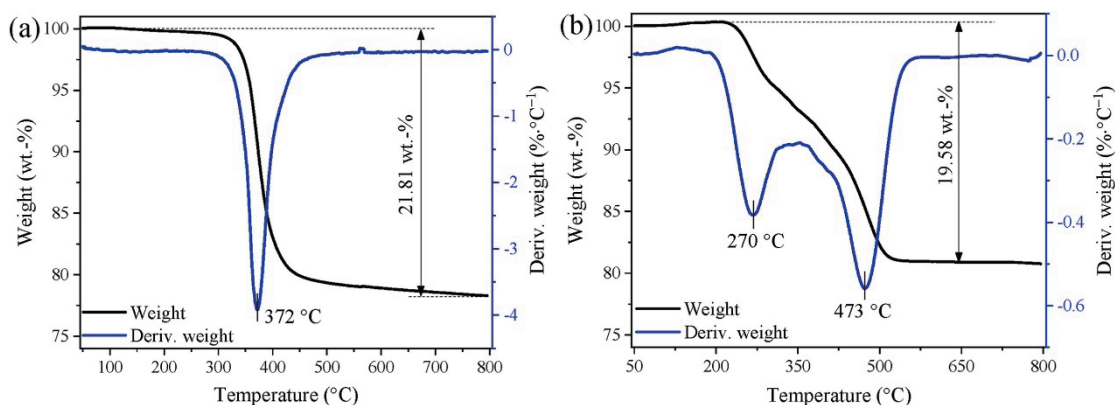


Fig. 1 Thermogravimetric curves of WWTB in N₂ (a) and air (b) atmospheres^[19]
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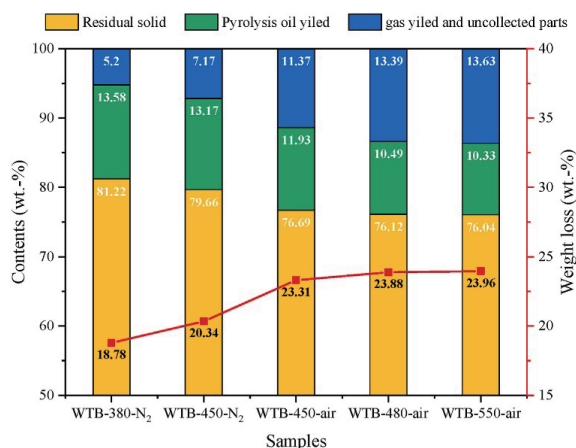


Fig. 2 Yields of gas, liquid and solid phases of WWTB under different pyrolysis conditions^[19] (with permission from Elsevier)

This improvement was linked to the desorption of water within the GFs during heat treatment, resulting in a more rigid structure with reduced plasticity^[23–24].

During pyrolysis, a complex mixture of pyrolytic oil was generated. Notably, the oils derived from WTB-480-air and WTB-380-N₂ exhibit highly similar chemical distributions, dominated by phenolic compounds alongside significant fractions of ketones and aromatic hydrocarbons. Among these constituents, phenolics are particularly abundant, with major components including 3-(1-methylethyl)-phenol, 2,5-diisopropylphenol, 4-isopropylphenol, and bisphenol A. These findings are consistent with previously reported compositional characteristics of pyrolytic oils obtained from WWTB^[25–26].

During the pyrolysis process, in addition to pyrolytic residues and oil, gaseous products were also generated. The CO concentration in the WTB-480-air gas reached 24.80%, markedly higher than the 3.71% observed in WTB-380-N₂, representing an increase of 21.09%. This rise can be attributed to hydrocarbon oxidation during EP degradation. In contrast, the concentration of hydrocarbon gases in WTB-480-air was lower than in WTB-380-N₂, due to oxygen-facilitated oxidation, which promoted the breakdown of EP into smaller molecular gases. This further suggests that the oxidative influence of oxygen contributes

to a reduced yield of pyrolysis oil.

1.2 Catalytic pyrolysis

The introduction of catalysts into the pyrolytic process, commonly referred to as catalytic pyrolysis^[27–31], markedly reduces the activation energy barrier, thereby accelerating the reaction rate and improving overall pyrolysis efficiency. Alumina (Al₂O₃) has been extensively employed as a catalyst support owing to its high surface area and stability, which facilitate the dispersion and anchoring of metal oxides, nonmetal oxides, and other catalytically active species. Among these systems, Al₂O₃-supported catalysts incorporating metal oxides as active centers have attracted substantial scholarly interest.

As illustrated in Figure 4(a)–(d), the incorporation of Fe₂O₃, NiO, CuO, CaO and MgO onto Al₂O₃ markedly augments both selectivity and yield of phenolic compounds during WWTB pyrolysis^[32]. Among them, NiO/Al₂O₃ and CuO/Al₂O₃ exhibit superior performance relative to the non-catalytic baseline, not only enhancing phenol selectivity and yield but also suppressing bisphenol A formation in favor of lighter derivatives formation such as methyl-, isopropyl-, and isopropenylphenols. This transformation underscores the catalysts' efficacy in depolymerizing heavier aromatics into lighter liquid-phase products, thereby enriching phenolic output while simultaneously promoting gaseous byproducts (H₂, CH₄). NiO/Al₂O₃ demonstrates the most pronounced catalytic activity, establishing it as the optimal candidate for WWTB pyrolysis. Its performance exhibits a volcano-type dependence on NiO loading, pyrolysis temperature, and heating rate: phenol selectivity and yield initially increase, reach a maximum, and subsequently decline. The optimal catalytic performance occurs at 10% NiO loading, 500 °C, and a heating rate of 10 °C/min, where peak selectivity and yield converge. Table 1 provides a summary of the feedstock designations, catalyst categories, reaction parameters, and experimental outcomes associated with the catalytic pyrolysis of WWTB. Given the compositional similarity between waste printed circuit boards (WPCB) and WWTB, the pyrolytic results obtained for WPCB are likewise incorporated into Table 1.

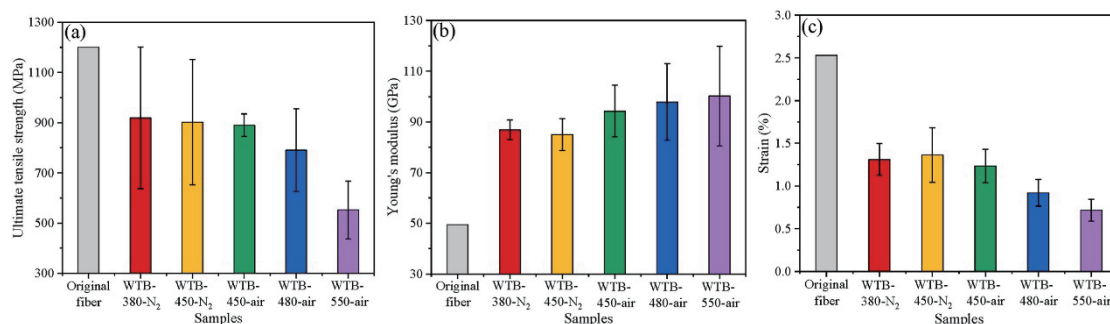


Fig. 3 Mechanical properties of GFs from WWTB under different pyrolysis conditions; (a): tensile strength; (b): Young's modulus; (c): fracture strain from single fiber tensile tests^[19] (with permission from Elsevier)

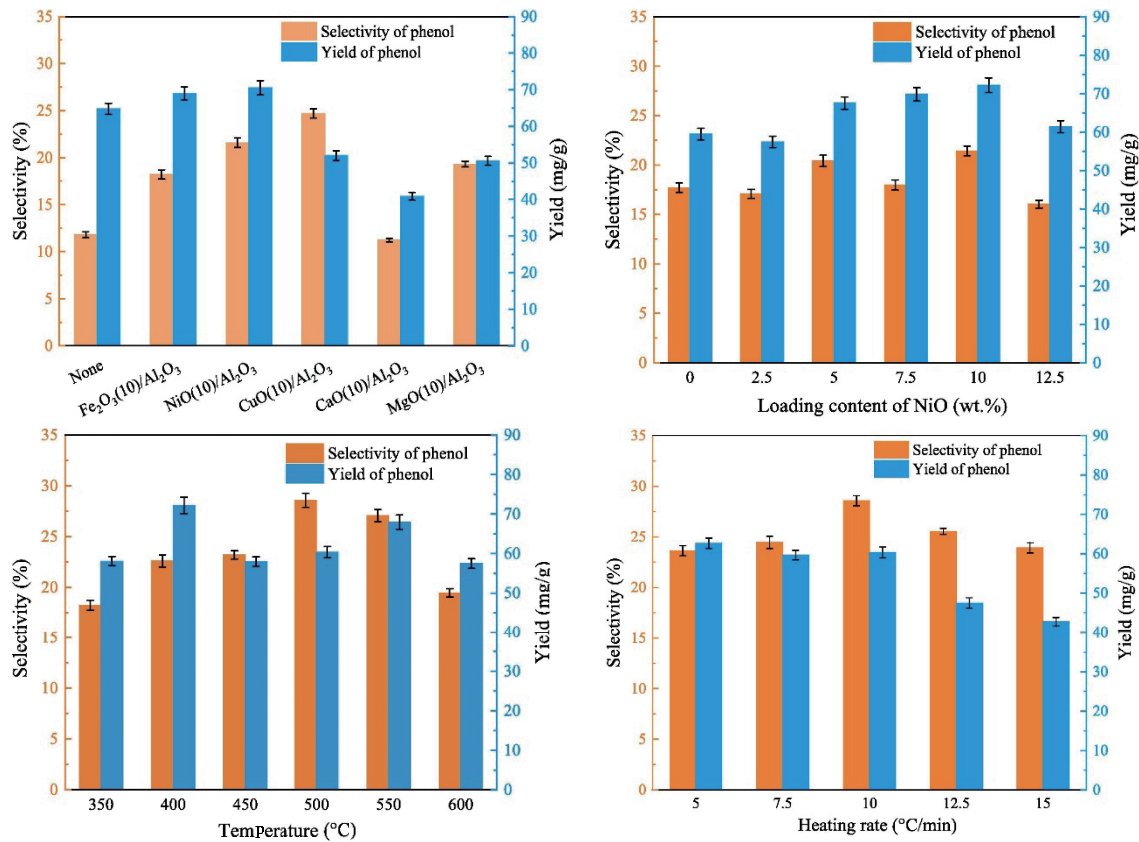


Fig. 4 (a): Effects of different metal oxide loadings; (b): NiO loading; (c): pyrolysis temperature; (d): heating rate on phenol selectivity and yield^[32] (with permission from Elsevier)

Table 1 Summary of WWTB or WPCB catalytic pyrolysis

Sample	Catalyst	Reaction conditions	Conclusion	Ref.
WWTB	ZSM-5	25–900 °C at six different heating rates (5–30 °C/min)	efficiently recovers phenols and acetic acid	[33–34]
WWTB	Al ₂ O ₃ as the support, with Fe ₂ O ₃ , NiO, CuO, CaO and MgO loaded separately	350–600 °C at heating rates of 5–15 °C/min and held for 30 min	a competitive relationship between the formation of phenols and gaseous products	[32]
WWTB	ZSM-5 and Y-type zeolite catalysts	25–900 °C at heating rates of 5, 10, and 15 °C/min	the catalytic pyrolysis process can significantly reduce reaction complexity	[30]
WWTB	α-Al ₂ O ₃ , γ-Al ₂ O ₃ , ZSM-5 and MCM-41	N ₂ and methanol vapor were continuously introduced into the microwave pyrolysis reactor	γ-Al ₂ O ₃ exhibits the best catalytic reforming activity; a methylation reaction pathway has been proposed	[35]
WWTB	ZMS-5, β30, MOR, MCM-41	350–650 °C and the microwave power was 500–800 W	the catalyst can promote the cleavage of bisphenol A and thereby increasing the production of phenol	[36]
WPCB	the <i>in situ</i> metals such as Cu, Fe, Sn, Pb, etc	25–800 °C at a heating rate of 10 °C/min	the <i>in situ</i> metals accelerate the generation of light hydrocarbons and aromatic compounds	[37]
WPCB	transition metal bimetals (Ni/Fe, Cu/Fe, Pd/Fe)	500–600 °C, rapid heating	high debromination efficiency, low energy consumption	[38]
WPCB	copper slag	500, 700 and 900 °C	reduce the activation energy of the reaction and increase the yield of H ₂	[39]

1.3 Microwave-assisted pyrolysis

Microwave pyrolysis employs rapid dielectric heating to rapidly elevate composite waste to reaction temperatures, enabling efficient thermal transfer, high energy utilization, and selective reactions. However, large-scale deployment remains limited by high equipment costs. Under microwave-assisted acetic acid-hydrogen peroxide treatment, the resin matrix of WWTB is fully degraded while the recovered glass fibers maintain excellent mechanical integrity and strength^[40]. Degradation efficiency shows minimal dependence on irradiation time, but solvent ratios of 20%–50% yield resin removal rates exceeding 90%. The recovered fibers exhibit superior tensile strength, modulus, and failure strain compared with virgin fibers, confirming this as an optimal recovery route. Microwave-assisted molten salt pyrolysis similarly enables efficient carbon fiber reclamation from CFRP waste, with product distribution strongly governed by temperature. Microscopic analyses confirm that the recovered fibers preserve both structural integrity and mechanical performance. Overall, microwave-assisted methods, whether solvent-based or molten salt, represent promising, sustainable, and high-efficiency strategies for composite waste recycling^[41].

Microwave pyrolysis has proven to be an effective method for CF reclamation, achieving recovery rates over 87% under optimized conditions (550 °C). Product analysis indicated that the liquid fraction mainly consisted of hydrocarbons, carboxylic acids, and aromatics, while the solid residue contained fibers with clean surfaces^[42]. Moriwaki et al.^[43] further demonstrated that the use of absorptive additives like activated carbon significantly enhanced PVC decomposition and HCl removal during microwave irradiation. Similar results have been reported for CF recovery from CFRPs, with the tensile strength of reclaimed fibers nearly matching that of virgin CFs. The recovery process can be divided into three stages^[44], resulting in fibers with superior surface quality and mechanical properties compared to those produced by fluidized bed pyrolysis^[45]. In contrast, GFs recovered from WWTB exhibited a ~25% reduction in strength compared to pristine GFs^[46]. These findings collectively emphasize microwave pyrolysis as a superior recovery method, offering shorter reaction times (56.67% reduction compared

to conventional pyrolysis) and improved yields (15% increase)^[47]. Table 2 presents the estimated energy consumption for glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) recycling, with microwave-assisted pyrolysis being the second most energy-efficient method after mechanical recycling^[48–49]. Notably, microwave-assisted pyrolysis is distinguished by its ability to reduce CO₂ emissions, making it a highly promising and environmentally beneficial technique for sustainable fiber recycling^[50].

In summary, the conventional pyrolysis, catalytic pyrolysis, and microwave-assisted pyrolysis technologies of WWTB have attracted considerable scholarly attention owing to their technological maturity, streamlined operational protocols, and practical feasibility. Substantial advancements have been realized to date, primarily directed toward optimizing pyrolysis parameters and equipment design, elucidating and fractionating pyrolysis products, and investigating their downstream applications. Collectively, these findings underscore the pivotal role of pyrolysis in enabling the closed-loop recycling of composite materials and in informing the life-cycle assessment of WTB.

2 Factors influencing the pyrolysis of WWTB

2.1 Effect of pyrolysis temperature

2.1.1 Effect of temperature on pyrolysis products

The thermochemical decomposition of WWTB yields three distinct product phases: pyrolysis gas, pyrolysis oil, and pyrolysis residue. In the primary pyrolysis stage, volatile components from WWTB condense to form pyrolysis oil^[51], while secondary pyrolysis facilitates the thermal cracking of residual pyrolysis oil into lighter molecular species, contributing to the formation of pyrolysis gas^[52]. The solid material remaining after these processes is classified as pyrolysis residue^[53]. Pyrolysis gas primarily consists of CO, CO₂, H₂ and hydrocarbons from C₁ to C₄. Pyrolysis oil is mainly composed of aromatic compounds (e.g., benzene, toluene, ethylbenzene), phenolic derivatives, and oxygen-containing organic species. Pyrolysis residue consists of CFs, GFs and residual char.

Table 2 Estimated energy consumption of GFRP/CFRP recycling processes^[48–49]

Recycling Technologies	Energy Consumption (MJ/kg FRP)	Avoided equivalent CO ₂ emissions (tCO _{2eq} /y)	Raw materials and reagents	Recycled products (kg/kg FRP)
Mechanical recycling	0.1–4.8	1.9	electricity	short fibers and powdered fibers
Chemical recycling	21–91	16.4	electricity, CH ₃ COOH, H ₂ O, NaOH	fibers and EP
Conventional pyrolysis	24–30	18.5	electricity and natural gas	fibers, gaseous hydrocarbons (C ₁ –C ₃), liquid hydrocarbons (C ₄ –C ₆), esters and alcohols
Microwave-assisted pyrolysis	5–10	20.4	electricity	fibers, gaseous hydrocarbons (C ₁ –C ₃), liquid hydrocarbons (C ₄ –C ₆), esters and alcohols

Temperature modulation plays a key role in product distribution and composition. The optimal pyrolysis temperature for WWTB ranges from 500 to 650 °C^[25,54], with studies showing that higher temperatures promote the breakdown of recalcitrant macromolecular organics into lower-carbon-number substances *via* thermally activated bond-scission mechanisms^[54].

Compositional analysis of condensable gases from WWTB pyrolysis, conducted *via* Py-GC-MS, revealed marked temperature-dependent variations. As shown in Figure 5(a), phenolics constituted the dominant products at lower temperatures, with their relative abundance decreasing progressively due to thermally induced ring-opening and deoxygenation reactions^[55]. In contrast, alkanes and alkenes increased with temperature, reflecting side-chain cleavage and aromatic degradation processes^[56], culminating in near-complete elimination of aliphatic substituents at 650 °C. At 500 °C, alcohols, aldehydes, and ketones were prevalent, consistent with carboxylic acid reduction pathways^[57–58]. Carbon-chain distributions (C₉–C₁₆) dominated the product spectrum (Figure 5(b)). With rising temperature, a shift from C₉–C₁₆ toward shorter

chains (<C₉) was observed, underscoring enhanced fragmentation of macromolecular organics and stabilization of low-molecular-weight species^[54]. Collectively, these results highlight the decisive role of temperature in governing molecular pathways and shaping the compositional profile of pyrolysis products.

Figure 6(a) delineates the yield distribution of gas, oil, and solid phases during WWTB pyrolysis across different temperatures. Analysis reveals near-constant solid-phase yields with temperature elevation, confirming near-complete pyrolytic conversion of WWTB constituents. Oil and gas yields exhibit inverse trends: oil production declines while gas yield escalates with rising temperatures. This divergence stems from thermally enhanced secondary reactions that drive macromolecular organic decomposition into low-molecular-weight volatiles^[54]. Figure 6(b) quantifies the compositional profile and yield dynamics of pyrolysis gases. Temperature elevation markedly amplifies CO and CH₄ yields, a phenomenon directly linked to accelerated thermal cracking of oxygenated organics and aliphatic moieties under high-temperature regimes.

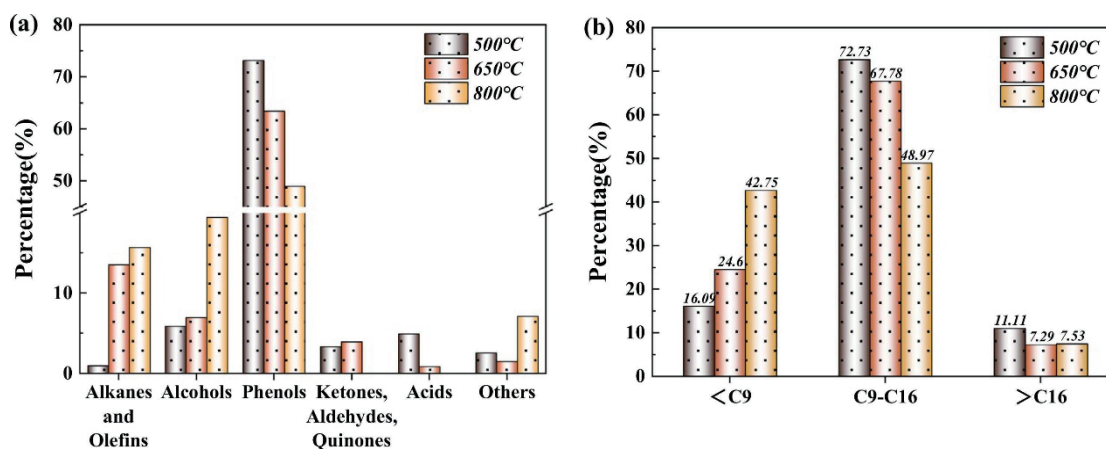


Fig. 5 (a): Classification and composition of major pyrolysis products of WWTB at different temperatures; (b): carbon distribution diagram^[54] (with permission from Elsevier)

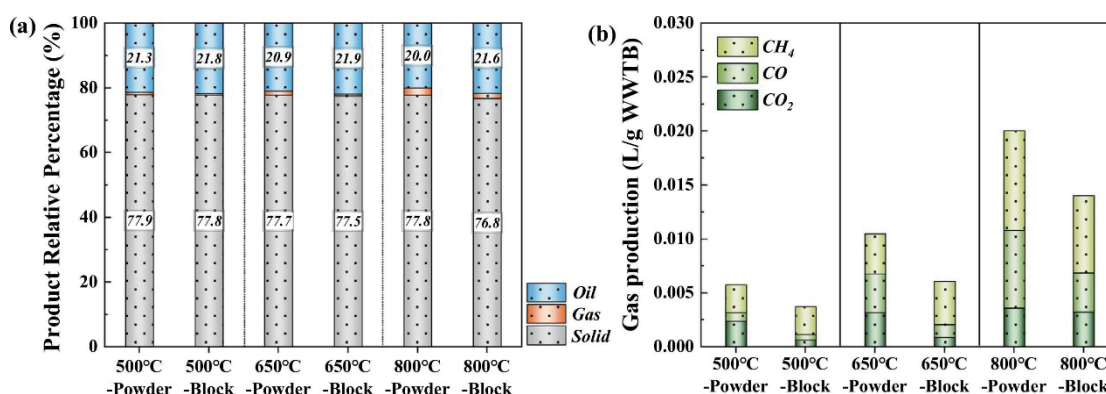


Fig. 6 (a): Yields of pyrolysis gas, oil and solid phase from WWTB at different temperatures; (b): distribution of pyrolysis gas components and yields^[54] (with permission from Elsevier)

Pyrolysis temperature critically governs product distribution and composition. Temperature elevation drives two concurrent processes: (1) pyrolysis oil-to-gas conversion *via* intensified thermal cracking of resin matrices, and (2) enhanced liberation of high-value fuel gases (H_2 , CO , CH_4) through decomposition of oxygen-rich macromolecules. Reasonable temperature modulation enables targeted recovery of premium hydrocarbons and combustible gases. Table 3 quantifies temperature-dependent yield variations, with observed product fluctuations reflecting inherent compositional heterogeneity within WWTB feedstocks.

2.1.2 Effect of temperature on the recovery fibers

Upon pyrolyzing WWTB, the resulting residues primarily consist of GFs or CFs with a small fraction of pyrolysis carbon. To achieve clean fibers, these residues can undergo oxidation treatment in a muffle furnace to remove the carbon deposited on the fiber surfaces. Figure 7(a) and (b) display the SEM images of GFs subjected to different pyrolysis and oxidation temperatures. The presence of

carbon results in a rough and irregular surface on the pyrolyzed GFs. After 20 min of oxidation, the surface of the GFs becomes significantly cleaner and smoother. GFs treated at an oxidation temperature of 600 °C show the cleanest and most uniform surface, indicating that an oxidation temperature of 600 °C for 20 min may be optimal for producing clean GFs. However, higher pyrolysis and oxidation temperatures can compromise the mechanical integrity of the GFs. As shown in Figure 7(c)^[63], extended oxidation times negatively impact the mechanical properties of the GFs^[12,59]. To preserve the mechanical properties of the recovered GFs, an optimal oxidation condition is 500 °C for 40 min for obtaining clean GFs^[59].

The mechanical performance of recovered fibers is generally the determinant factor for their potential reuse. Strong mechanical integrity ensures that GFs or CFs can be effectively employed as reinforcement fillers in the fabrication of WTBs. Table 4 provides a summary of the mechanical properties of recovered fibers under specific pyrolysis conditions, thereby highlighting the relationship between processing parameters and the retention of fiber strength and stiffness^[60,62,64–66].

Table 3 The relationship between pyrolysis temperature and pyrolysis product yields of WWTB

Temperature/°C	Pyrolysis gas ϕ /%	Pyrolysis oil w/%	Pyrolysis char w/%	Ref.
400–700	5.7–26.1	26.2–42.8	47.7–51.5	[59]
400–600	3.1–10.1	25.9–27.5	64.0–69.4	[60]
500–800	0.8–2.2	20.0–21.3	77.7–77.9	[54]
600–1000	10–40	5–10	45–85	[61]
450	5.8	39.6	54.6	[62]

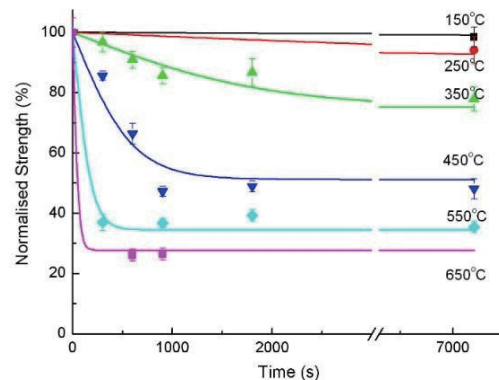
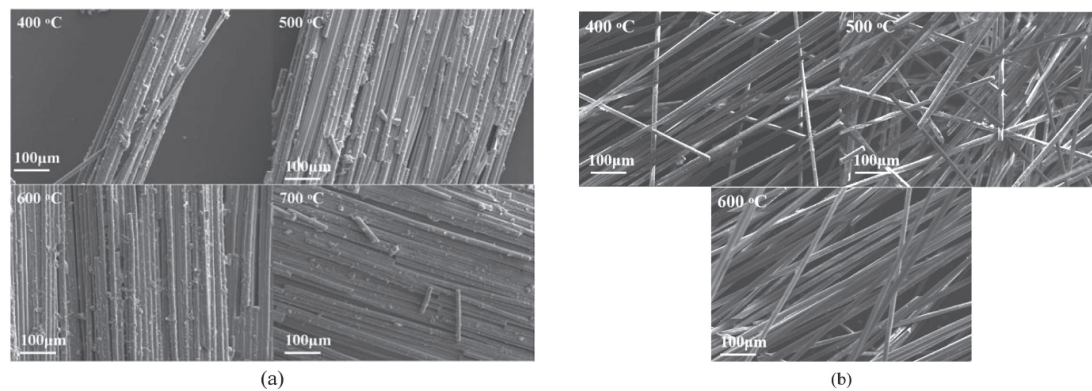


Fig. 7 SEM images of GFs under (a): different pyrolysis temperatures; (b): different oxidation temperatures^[59]; (c): oxidation temperature and time variation images^[63] (with permission from Elsevier)

Table 4 Mechanical properties of recovered fibers

Fiber type	Reaction conditions	Fiber post-treatment conditions / applications	Mechanical properties					Ref.
			Tensile strength /MPa	Young's modulus /MPa	Flexural strength /MPa	Flexural modulus /MPa	Elongation at break	
GF	500 °C, 30 min	preparation of bulk compounds	24	—	68.9	11100	—	[64]
	450 °C, 90 min	450 °C oxidation	—	—	89	7300	1.7 mm	[62]
CF	500 °C, 20 min	500 °C oxidation for 40 min	3331	—	—	—	—	[60]
	500 °C, 150 min	500 °C oxidation for 60 min	—	1800	93	—	8.7%	[65]
	500 °C, 15 min	550 °C oxidation for 30 min	3042.9	239390	—	—	—	[66]

2.2 Effect of heating rate

2.2.1 Effect of heating rate on pyrolysis products

The heating rate exerts a pronounced influence on the pyrolytic behavior of WWTB. Accelerated heating enhances pyrolysis efficiency by facilitating a more thorough decomposition of organic constituents into low-molecular-weight gaseous products^[67–68].

However, it often induces nonuniform heat transfer. Conversely, a slower heating regime promotes uniform thermal distribution, albeit at the expense of prolonged pyrolysis duration and diminished efficiency. To date, the majority of investigations addressing the role of heating rate in WWTB pyrolysis have concentrated on kinetic evaluations via thermogravimetric analysis (TGA), whereas systematic studies concerning its effect on the composition of pyrolysis products remain comparatively scarce. Kinetic analyses provide essential insights into the reaction mechanisms and activation energies underlying WWTB pyrolysis, thereby elucidating the relative difficulty of distinct pyrolytic stages and the overall transformation pathways.

TGA of WWTB model compounds different heating rates, alongside corresponding kinetic calculations, are depicted in Figure 8^[69]. The data reveal the emergence of a “thermal hysteresis” phenomenon at the temperature of maximum weight loss as the heating rate increases. This effect is attributable either to the shortened reaction times induced by rapid heating, which constrain reaction completion, or to the steep thermal gradients between the sample and the carrier gas, which suppress internal heat conduction and culminate in thermal hysteresis^[70–71]. To further elucidate the pyrolytic mechanism of model compounds, the Coats–Redfern (C–R) kinetic model method was applied within the principal weight-loss temperature range under different heating rates^[72].

Model-fitting calculations indicated that the activation energy estimated *via* the diffusion-controlled Dz model was in close agreement with those derived from the KAS, FWO

and Starink methods^[69]. Consequently, the governing kinetic mechanism of model compounds pyrolysis was established as diffusion-controlled, conforming to the Dz model.

The heating rate is crucial in determining both heat transfer efficiency and the overall dynamics of WWTB pyrolysis. Additionally, the careful selection of heating rates can significantly influence the distribution of pyrolytic products^[73]. For example, experiments on high-density polyethylene in a fluidized-bed reactor revealed that flash catalytic pyrolysis produced a greater proportion of gaseous products compared to slow pyrolysis, while the yield of condensable volatiles (liquid phase) was comparatively reduced^[74]. Similarly, studies on food waste pyrolysis under different heating rates showed that the maximum bio-oil yield occurred at 50 °C/min, whereas the highest gas yield was attained at 100 °C/min. Notably, the impact of heating rate on biochar production was minimal^[75]. Higher heating rates not only enhance the formation of volatile species but also promote secondary reactions. These secondary processes, in turn, significantly affect the yields and compositions of pyrolysis-derived oil and gas, highlighting the intricate dependence of product selectivity on thermal parameters.

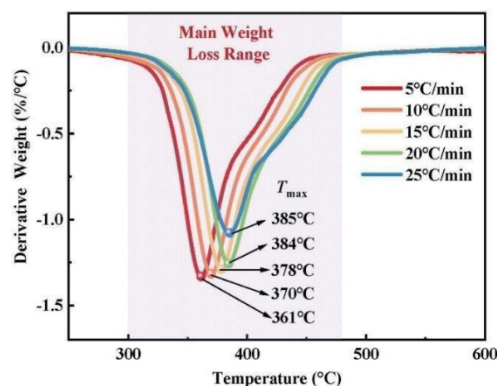


Fig. 8 DTG curves of WWTB model compounds at different heating rates^[69]
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2.2.2 Effect of heating rate on the recovery fibers

An elevated heating rate accelerates the pyrolysis of WWTB, though its impact on recovered fibers has been less thoroughly investigated^[12]. Yang et al.^[76] reported that increasing heating rates markedly enhanced the tensile modulus of polyimide (PI) fibers (from 45 to 60 GPa), while tensile strength and elongation at break declined (from 1.12 to 0.96 GPa and from 3.9% to 2.2%, respectively). This reduction in mechanical resilience was attributed to insufficient conformational adjustment of PI chains during rapid heating, leading to a relaxed lattice structure, enlarged interaxial crystal spacing, elevated residual stress, and premature fracture. Given the inherent structural and property differences between GFs and CFs, their responses to heating rate variations diverge. For CFs, precise heating rate control is essential to balance resin removal with fiber preservation^[77]. Excessively rapid heating induces oxidation and structural defects^[78], whereas overly slow heating reduces pyrolysis efficiency and increases energy demand. In contrast, GFs, with their superior thermal stability, exhibit less sensitivity to heating rate. Nonetheless, excessively rapid heating may hinder complete resin pyrolysis, leaving residues that impair fiber performance. Such residues, however, can be effectively eliminated through subsequent oxidation, thereby restoring or even enhancing GF mechanical properties^[26,78].

2.3 Effect of atmospheric conditions

2.3.1 Effect of atmospheric conditions on pyrolysis products

Reactive atmospheres critically modulate the pyrolysis of WWTB, governing product distributions and dominant reaction pathways. Inert gases (N_2 , Ar) primarily yield solid residues with minimal volatiles, whereas steam markedly enhances gas formation with concurrent suppression of solids and oils, as evident in Figure 9(a)–(c)^[26]. The steam environment promotes CO release and drives EP depolymerization, enriching phenolic derivatives such as phenol and bisphenol A. In contrast, CO_2 stabilizes polymeric matrices, increases solid and oil fractions, and suppresses light gases, particularly CH_4 and CO, while limiting phenolic generation. Overall, H_2O induces oxidative fragmentation and phenolic liberation, whereas CO_2 retards chain scission and constrains volatile and phenolic outputs^[26].

The compositional profiles and distributions of pyrolysis products are markedly influenced by the surrounding atmosphere. Nevertheless, investigations specifically addressing the pyrolysis products of WWTB under different atmospheric conditions remain limited. Considering that the product distributions derived from complex mixtures, such as plastic, exhibit notable parallels to those of WWTB, this study consolidates and analyzes the distribution patterns of such mixtures across diverse atmospheres, as summarized in Table 5.

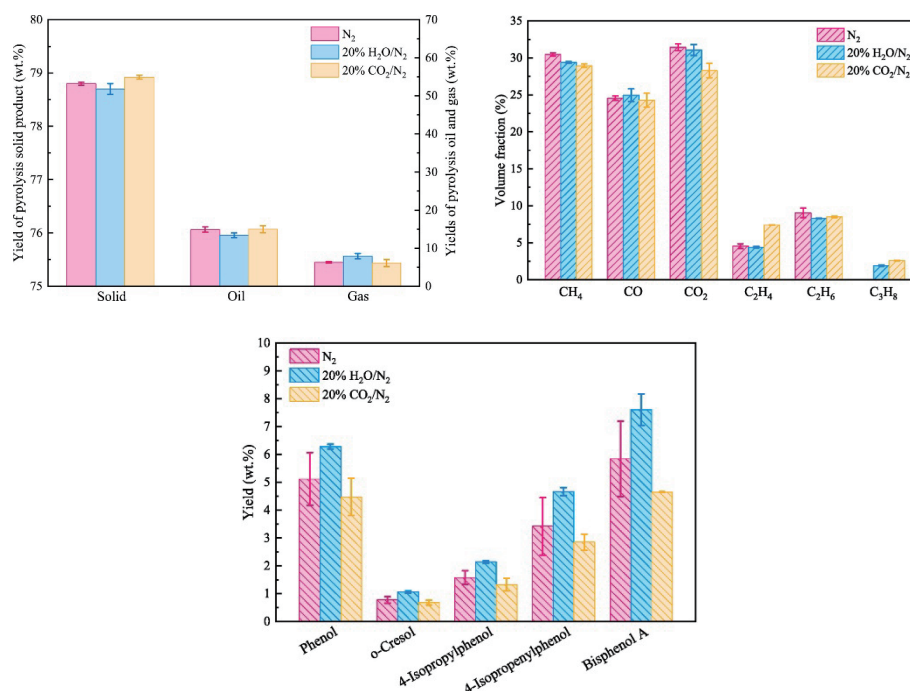


Fig. 9 (a): Yield of pyrolysis products of WWTB under different atmospheric conditions; (b): composition and volume fraction of pyrolysis gases; (c): composition and yield of pyrolysis oil^[26]
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Table 5 Effect of different pyrolysis atmospheres on the distribution of pyrolysis products of complex mixtures

Sample	Reaction atmosphere	Effect of products	Ref.
WWTB	N ₂	suitable for obtaining bisphenol A, but requires higher energy input	[79]
	CO ₂	suppresses gas generation, reduces energy consumption	
WWTB	N ₂	the product has low added value	[35]
	N ₂ +CH ₃ OH	the added values of the products are significantly improved	
WWTB	N ₂	recyclable GFs help reduce pollutants	[80]
	N ₂ +CO ₂	<550 °C, nitrogen release is promoted; >550 °C, NO _x and HCN are suppressed	
CF/CFRP	N ₂	retains the strength of CFs, but the residue left at high temperatures affects performance	[78]
	air/O ₂	high temperatures cause severe damage to CFs	
	steam	effectively removes residue and reduces fiber damage	
Waste plastic	N ₂	a higher pyrolysis temperature is conducive to the positive synergistic effect of plastics	[81]
	CO ₂	a low pyrolysis temperature and a low activation energy lead to a negative synergistic effect	

2.3.2 Effect of atmospheric conditions on the recovery fibers

Atmospheric environment exerts a decisive influence on the pyrolytic conversion of WWTB-derived fibers. In H₂O, reduced carbon deposition enhances resin decomposition and promotes gas-phase products, though tensile strength decreases slightly (5.97%). CO₂, conversely, inhibits resin breakdown, accelerates residue accumulation, and reduces carbon reactivity, leading to higher solid yields and a pronounced decline in tensile strength (16.02%).

Despite these degradations, inorganic constituents (Si, Ca, Al) remain embedded within the carbon matrix, imparting high-temperature resistance suitable for refractory applications. Furthermore, carbothermal shock enables direct SiC synthesis from WWTB^[79,82–83].

Atmosphere-modulated treatments offer opportunities to optimize fiber properties. Li et al.^[84] reported that introducing controlled O₂/CO₂ mixtures mitigates degradation through O₂-assisted protection and CO₂-driven defect healing, significantly improving fiber strength. Specifically, 15% CO₂ during oxidation enhances defect repair, while 25% CO₂ during pyrolysis minimizes water-induced weakening. Process design analysis revealed that single-step O₂-containing pyrolysis integrates resin decomposition with surface stabilization, reducing costs by 34% while strengthening fibers. Although multi-step strategies yield superior mechanical performance, their reduced cost-effectiveness constrains industrial adoption.

2.4 Effect of catalysts

2.4.1 Effect of catalysts on pyrolysis products

Catalysts play a crucial role in enhancing the efficiency and product quality of WWTB pyrolysis. Different catalysts exert different effects on the pyrolysis reaction, and selecting the most suitable catalyst depends on factors such as activity, selectivity, stability, and cost. Zeolite molecular sieves are among the most commonly used catalysts in the pyrolysis of WTB due to their high surface area, excellent thermal stability and exceptional catalytic properties. Specifically, ZMS-5 and Y-type zeolites have demonstrated remarkable catalytic activity in WTB pyrolysis. As illustrated in Figure 10, the distribution of liquid-phase products of WTB varies under different catalytic conditions. Notably, the Y-type zeolite catalyst shows superior catalytic activity for producing benzene, toluene and ethylbenzene (BTE), along with enhanced BTE selectivity. This improvement is attributed to the larger pore structure and higher acidity of the Y-type zeolite, which aids in the efficient diffusion of products^[30].

Further pyrolysis experiments on WPCB have shown that acidic catalysts, such as HZSM-5, encourage the formation of aromatics *via* acidic sites due to their high acidity and appropriate pore structure. Conversely, alkaline catalysts (like CaO) are effective in de-brominating materials due to their strong affinity for bromine.

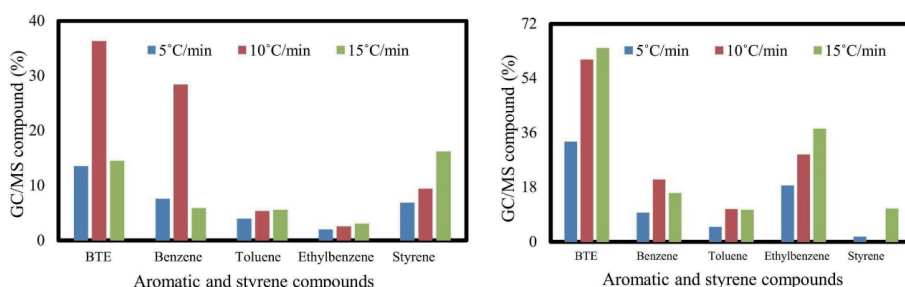


Fig. 10 Distribution of liquid-phase products of WWTB under different catalytic conditions; (a): ZSM-5; (b): Y-type^[30] (with permission from Elsevier)

The combined use of both acidic and alkaline catalysts offers a balanced approach, enhancing both aromatic yield and de-bromination efficiency^[85]. Table 1 summarizes the influence of various catalysts on the distribution of pyrolysis products from WWTB and WPCB, providing a comparative overview of catalytic effects. However, the detailed data from these experiments are not elaborated here. In conclusion, the careful selection and combination of catalysts, based on their properties and the desired products, is critical to maximizing the efficiency and sustainability of WWTB pyrolysis, especially in industrial applications. Indeed, the utilization of catalysts offers numerous advantages to the WWTB pyrolysis process. In the future, researchers should place more emphasis on the recovery and stability of the catalysts, as these factors are crucial to the overall pyrolysis procedure.

2.4.2 Effect of catalysts on the recovery fibers

The incorporation of catalysts during the pyrolytic conversion of WWTB markedly enhances the progression of the reaction. In general, catalysts accelerate the thermal degradation of organic constituents within composite matrices, thereby transforming them into condensable pyrolytic oils, non-condensable gaseous products, and residual carbon. Owing to the chemical inertness of GFs and CFs, these fibers remain unreactive under pyrolytic conditions. Consequently, the catalyst does not manifest significant catalytic activity toward either GFs or CFs. Of course, catalysts facilitate the thermal decomposition or selective transformation of resins in WWTB during pyrolysis, which simultaneously enables the recovery of fibers. However, the recovered fibers generally exhibit diminished mechanical properties owing to thermal degradation. Hence, based on current research progress, a central question arises: is it possible to design a catalyst that not only promotes the efficient thermal degradation of resins but also enhances the mechanical performance of the recovered fibers? Achieving this dual objective would yield substantial economic benefits for the recycling and treatment of WWTB.

2.5 Effect of different components of WTB

2.5.1 Effect of different components on pyrolysis products

The primary constituents of WTB include core foams, wood, and protective coatings. PVC is the main component of the core foam, while the wood fraction consists of balsa wood or bamboo fibers. The coatings are primarily composed of polyurethane, fluorinated polymers, and polyacrylates, which together ensure long-term structural stability and operational reliability. Polyurethane, in particular, is widely used due to its strong interfacial adhesion, oil resistance, and excellent wear resistance^[86–88].

Previous studies have demonstrated that key wind turbine blade materials, EP, thermoplastic polyurethane (TPU), GF and CF, undergo pyrolytic testing at 600 °C under isothermal conditions, yielding a comprehensive range of pyrolysis products, including gases, condensable oils, and solid residues^[89]. As shown in Figure 11(a), TPU exhibits the highest gas evolution rate, peaking at 2.12 mL/(g·s) at 150 s, nearly double that of EP (1.03 mL/(g·s)). In contrast, GF and CF exhibit much lower gas generation rates, at 0.23 and 0.36 mL/(g·s), respectively. These findings suggest that EP and TPU are more prone to decomposition under pyrolytic conditions at 600 °C, whereas GF and CF display substantial resistance to thermal degradation. Figure 11(b) further reveals that CO and CO₂ are the dominant gaseous products from all materials, with only trace amounts of other species detected in the gas composition.

The GC-MS analysis demonstrates that pyrolysis oils derived from EP and TPU exhibit distinct compositional profiles due to differences in their molecular structures and synthesis routes. Figure 12 illustrates EP-derived oils are dominated by phenolic compounds (~71%), reflecting the bisphenol A and phenolic precursors used in EP synthesis, while nitrogen-containing species (~8.1%) originate from curing agents incorporated during crosslinking. These findings highlight the strong influence of precursor chemistry on the distribution of organic products in pyrolysis oils.

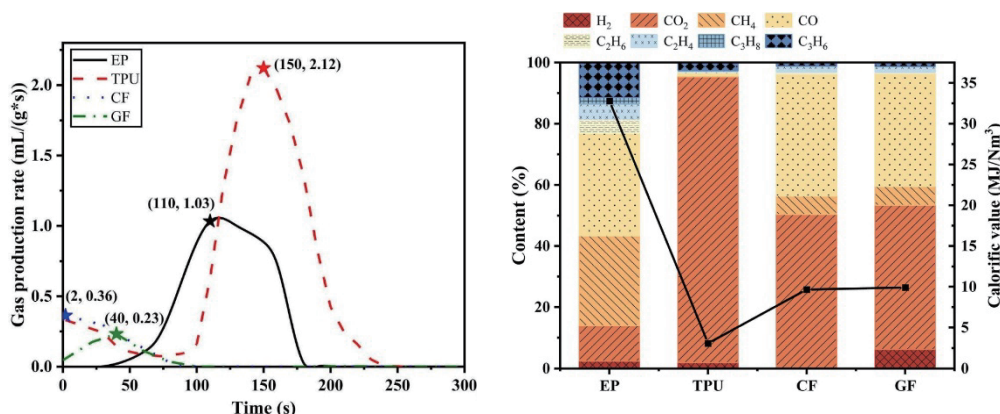


Fig. 11 (a): Gas generation rate of EP, TPU, GF and CF; (b): component distribution of gas-phase products^[89] (with permission from Elsevier)

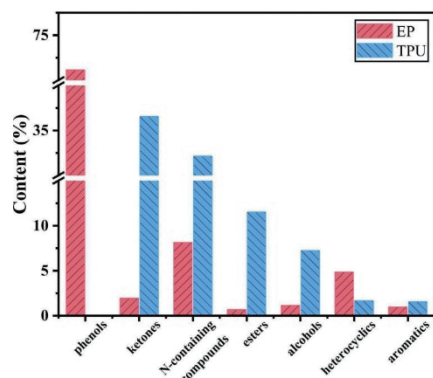


Fig. 12 Distribution of pyrolysis oil products of EP and TPU^[89]
(with permission from Elsevier)

The pyrolytic residues exhibited distinct morphological changes. Initially, EP and TPU displayed irregular block-like structures, which transformed into lamellar forms after pyrolysis (Figure 13). Vesicular surface features resulted from gas release during thermal degradation.

The inclusion of core materials like polyethylene foam and balsa wood altered the product distribution, enhancing CO₂ dominance and increasing the complexity of the condensable phase^[86]. Pyrolysis of pristine GFRP produced high-calorific-effluent gases and phenolic-rich condensates. Epoxy-rich compositions favored the generation of alkanes, alkenes, and carbon oxides, while suppressing CH₄ and H₂ formation. Conversely, higher CFs content inhibited epoxy decomposition, lowered the onset temperature, slowed mass-loss kinetics, and increased carbon yield. CFs further influenced the pyrolytic pathways through adsorption and heat-transfer effects, promoting the formation of low-molecular-weight gaseous species^[25].

2.5.2 Effect of different components on the recovery fibers

The various constituents of WTB can influence surface morphology of the recovered fibers. Figure 14(a)–(f) illustrates the macroscopic morphology of GFs and CFs both prior to and following pyrolysis. It is evident that the surface characteristics of both GFs and CFs remain largely unchanged after pyrolysis. The particles adhering to the fiber surfaces serve to shield the fibers from external damage and enhance their adhesion to the polymer matrix^[90].

As illustrated in Figure 15(a) and (b), the XRD results highlight clear differences in pyrolytic response among matrix and fiber components. After pyrolysis, EP and TPU exhibited peak shifts and broadening consistent with aromatic structural disorder^[89], whereas GF and CF maintained crystalline stability, underscoring their suitability for thermal recovery. Core materials such as polyethylene foam and balsa wood increased residual carbon but compromised fiber strength and surface integrity^[86]. Higher CF content lowered the onset of pyrolysis and stabilized fiber morphology, though excessive CF led to carbon accumulation and diminished recovery quality. Conversely, increasing EP accelerated pyrolysis with reduced carbon yield, but high-temperature exposure intensified surface defects and degraded mechanical performance^[25].

3 Pyrolysis process and equipment for WWTB

The pyrolysis process of WWTB is illustrated in Figure 16 and can be broadly divided into four principal stages: pretreatment, pyrolysis reaction, product collection, and separation.

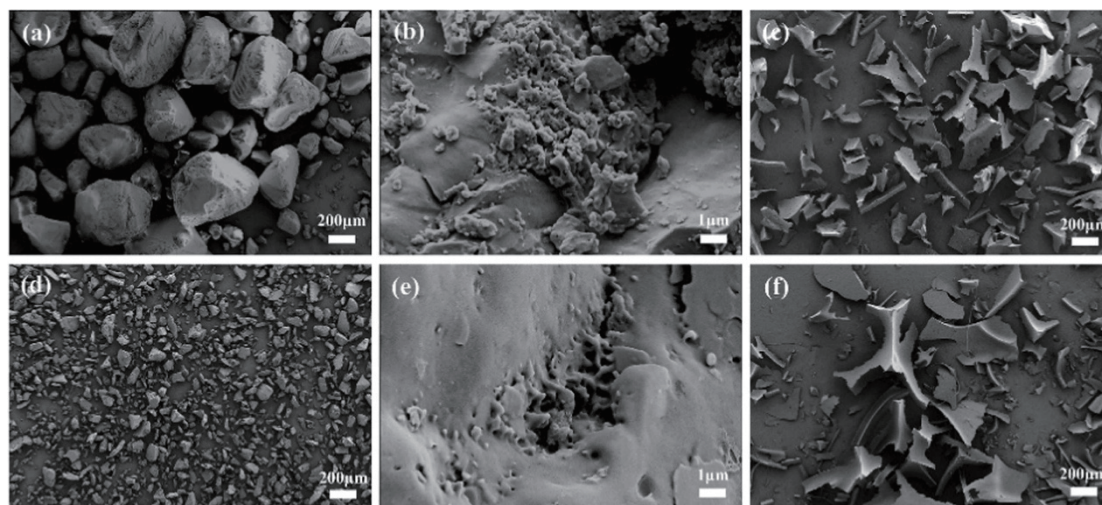


Fig. 13 SEM images before and after pyrolysis of different resins; (a), (b): EP before pyrolysis; (c): EP after pyrolysis; (d), (e): TPU before pyrolysis; (f): TPU after pyrolysis^[89]
(with permission from Elsevier)

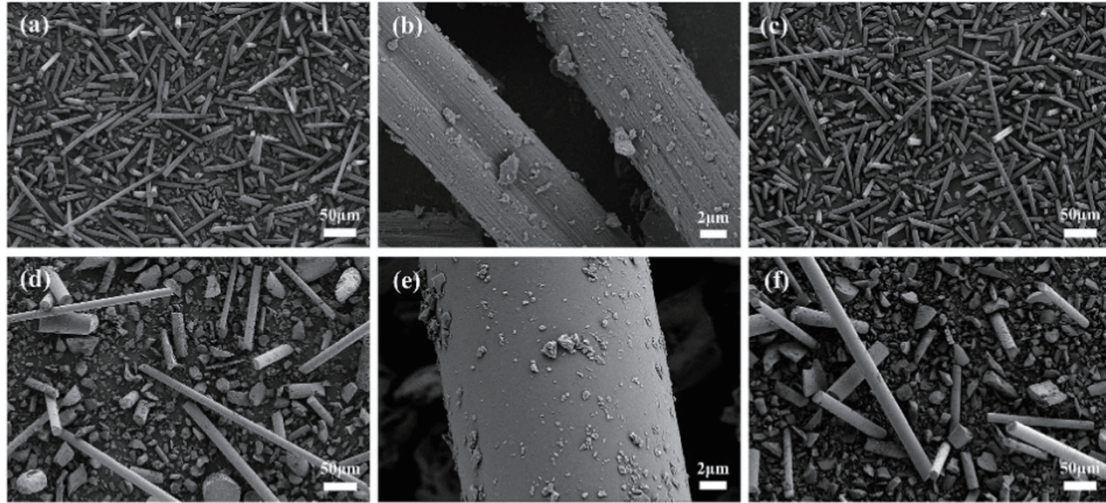
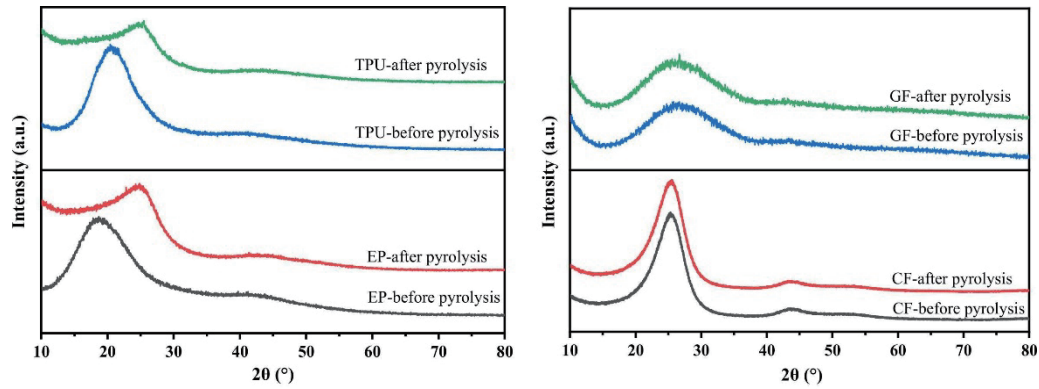


Fig. 14 SEM images of different fibers before and after pyrolysis; (a), (b): CFs before pyrolysis; (c): CFs after pyrolysis; (d), (e): GFs before pyrolysis; (f): GFs after pyrolysis^[89]
(with permission from Elsevier)



(a) Resins (b) Fibers
Fig. 15 XRD spectra of EP, TPU, GF and CF before and after the reaction^[89]
(with permission from Elsevier)

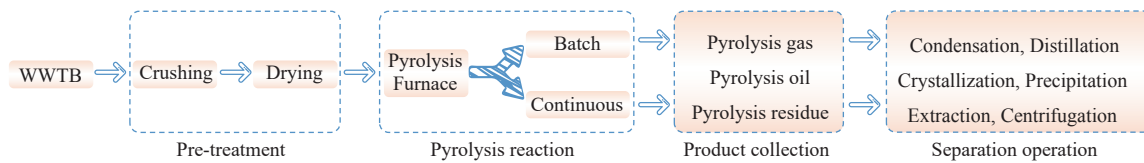


Fig. 16 Pyrolysis process of WWTB

Pretreatment typically encompasses operations such as crushing and drying, which serve to enhance the efficiency and uniformity of the subsequent pyrolytic reaction. The pyrolysis reaction itself is conducted within a dedicated furnace, which may be designed as either a batch-type or a continuous system, depending on the technological configuration adopted. Following pyrolysis, product collection and separation involve the systematic recovery of gaseous, liquid, and solid residues. Each fraction is subsequently subjected to further purification and refinement, ensuring the effective utilization of the pyrolysis products.

3.1 Batch pyrolysis equipment

Batch pyrolysis systems are generally employed for small-scale experimental and production purposes. As shown in Figure 17(a), a typical batch pyrolysis reactor consists of a reactor, condenser, oil and char collectors, nitrogen cylinder, and a PID controller. The reactor is heated using an electric ring furnace. A stirrer is employed to agitate the feedstock inside the reactor, thereby enhancing the heat transfer process within the material. Nitrogen is used to purge the system, effectively displacing oxygen. The top inlet of the reactor is designed for feeding the materials, while the bottom is used for collecting the

pyrolytic residues. The heating rate and temperature of the reactor are controlled by the PID controller. The condenser serves to collect the pyrolysis oil and expel the pyrolysis gases. After the pyrolysis process is complete, the pyrolysis residues are removed from the container and transferred to a collection bin^[91].

Figure 17(b) depicts a conventional fixed-bed batch pyrolysis system^[89]. A pre-weighed sample is positioned at the center of the fixed bed to ensure efficient heat transfer, after which the equipment is carefully sealed. An inert purge gas (N₂ or Ar) is introduced, followed by a controlled heating sequence wherein the temperature is raised at a prescribed rate to the desired setpoint, before natural cooling to ambient conditions. The resulting pyrolytic gas is collected in gas sampling bags, whereas the condensable fraction is recovered using condensation–separation apparatus. Experimental studies with a 20 L fixed-bed batch equipment revealed highly accurate temperature regulation, underscoring its suitability for pilot-scale investigations^[91]. A comparative overview of product distribution, feedstock requirements, and the respective advantages and drawbacks of batch pyrolysis systems is provided in Table 6^[91–92].

3.2 Continuous pyrolysis equipment

Continuous pyrolysis systems are essential for large-scale industrial applications. Figure 18(a) illustrates the continuous pyrolysis pilot system. The feedstock for the pyrolysis process is pre-dried to remove moisture and then fed into the reactor through a screw feeder, ensuring continuous delivery. When the particle size of the post-pyrolysis material is less than 5 mm, it is transferred to a secondary reactor, where the primary purified pyrolysis gas is introduced, facilitating the further cracking of long-chain hydrocarbons in the gas phase. The produced pyrolysis gas

undergoes a three-stage purification process, with part of it being utilized as fuel for the reactor, while the remaining portion is combusted externally^[93].

A fluidized-bed pyrolysis equipment (Figure 18(b)) uses a high-velocity gas stream to fluidize the feedstock, causing rapid thermal decomposition. Vapors are condensed in cyclone units, recovering pyrolysis oils, with non-condensable gases either vented or stored^[94]. Spiral continuous drying furnaces are employed for large-scale biochar production, though mechanical compression in these systems can collapse biochar pores, limiting surface area^[95].

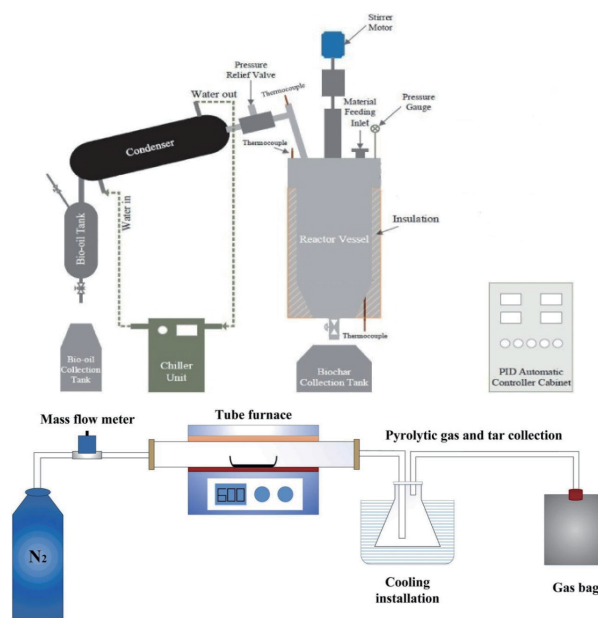


Fig. 17 (a): Batch pyrolysis equipment^[91]; (b): conventional fixed-bed pyrolysis equipment^[89] (with permission from Elsevier)

Table 6 Summary of characteristics of batch pyrolysis equipment^[91–92]

Classification	Description of characteristics
Product distribution	pyrolysis gas: fuel gases (such as CO, CH ₄ and H ₂), which can be used for power generation or heating; pyrolysis oil: liquid phase products that require further separation and purification to produce platform small molecules; pyrolysis residue: contains a certain amount of carbon and can be used as fuel or filler material, among other applications
Raw material size and requirements	optimal size: 5–50 mm (crush evenly to improve pyrolysis efficiency); adaptability: can process irregular or mixed materials; pre-treatment: drying (moisture < 15%) and impurity removal
Advantages	the equipment was simple, cost-effective, with high unit energy consumption and precise temperature control; strong adaptability, capable of processing various raw materials; flexible operation, suitable for small-scale production or laboratory research
Disadvantages	low efficiency, poor continuity; raw material variations lead to unstable product quality; difficult to achieve large-scale continuous production

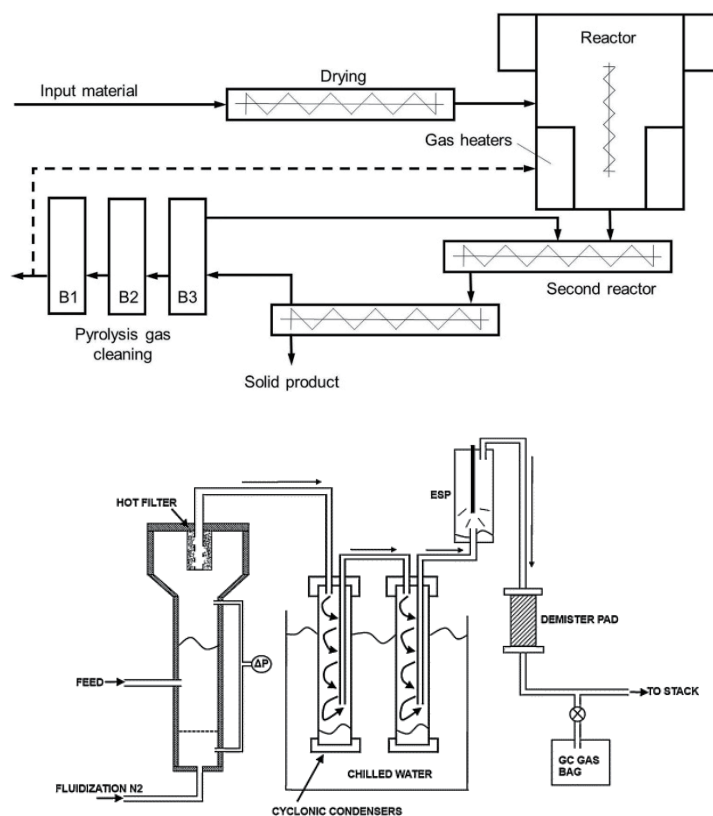


Fig. 18 (a): Continuous pyrolysis equipment^[93]; (b): fluidized bed pyrolysis equipment^[94] (with permission from Elsevier)

Pagano et al.^[92] compared continuous and batch equipments for lignocellulosic residue pyrolysis. Key advantages of continuous systems include: (1) higher aromatic carbon yield at 450 °C, (2) minimized fluctuations in feedstock feeding, (3) reduced catalyst deactivation at high temperatures and (4) improved bio-oil quality through lower oxygen content. Continuous systems excel in efficiency, stability, and scalability compared to batch systems^[96]. Further studies on continuous versus batch microwave-assisted pyrolysis of WPCBs confirmed these benefits, including superior aromatization, lower bromide content, and enhanced energy efficiency.

Table 7 provides a summary of product distribution, feedstock specifications, and the operational advantages and disadvantages of continuous pyrolysis systems^[92, 96], while Table 8 contrasts the production characteristics of batch and continuous equipments.

These advanced pyrolysis technologies, including microwave- and plasma-assisted systems (Figure 19(a) and (b)), provide significant improvements over conventional methods. Microwave-assisted pyrolysis enables continuous feedstock conversion under rapid and uniform heating, while plasma-assisted pyrolysis facilitates efficient decomposition and selective secondary reactions through controlled plasma-material interactions^[97–100]. Both configurations exhibit rapid heating, high thermal efficiency, and improved product selectivity, underscoring their strong potential for scalable industrial application.

4 Pyrolysis products of WWTB and applications

4.1 Gas products and applications

The pyrolysis products of WWTB are predominantly classified into three fractions: gaseous products, liquid oils, and solid residues. The gaseous fraction primarily consists of H₂, CH₄, CO, CO₂, C₂H₄, C₂H₆, C₃H₆ and C₃H₈, which are mainly evolved at elevated temperatures. This clean, combustible gas can serve as a versatile energy carrier for power generation, heating, and related applications, in addition to functioning as a valuable chemical feedstock for methanol synthesis and other downstream processes. An isothermal pyrolysis study conducted at 600 °C on the principal constituents of wind turbine blades provided further insights into the compositional distribution of gaseous products^[89]. As shown in Figure 11(b), EP yielded a gas phase enriched in CO and CH₄. This outcome is attributable to random scission of both main and terminal polymer chains, resulting in the liberation of hydrogen atoms and reactive organic radicals^[90]. In contrast, the pyrolysis of TPU produced a gas stream containing as much as 93.45% CO₂, which originates from the cleavage of urethane linkages^[101]. For GF and CF composites, the gaseous products were dominated by CO and CO₂. These species are primarily derived from the decomposition of ether and carbonyl moieties in the polymer matrix, as well as from the breakdown of ester and carboxyl functionalities

in aromatic structures. Furthermore, H₂ evolution was resulting from thermal cleavage of aromatic rings^[70]. observed under high-temperature conditions (> 550 °C),

Table 7 Summary of continuous pyrolysis equipment characteristics^[92,96]

Classification	Description of characteristics
Product distribution	pyrolysis gas: high gas yield, stable composition, can be directly used for power generation or heating systems; pyrolysis oil: fewer liquid products (secondary reactions are more complete at high temperatures), easy to utilize directly; pyrolysis residue: the proportion of solid products was slightly lower than that of batch processes, but the product quality was more stable, making it suitable for use in industrial carbon materials or adsorbents
Raw material size and requirements	optimal size: 3–30 mm (prevent clogging of the feeding system); adaptability: consistency in raw material types and sizes was maintained; mixed raw materials can lead to system fluctuations; pre-treatment: deep drying (moisture < 10%), fine grinding, and sorting to remove impurities
Advantages	continuous production, high efficiency, low energy consumption per unit, suitable for scaled production; the reaction conditions are easy to control and precise, ensuring stable product quality; high degree of automation and integration
Disadvantages	high investment and operating costs; strict control of raw material types, sizes, and humidity was required; difficult to meet the needs of small batch production or production with frequent changes in raw materials

Table 8 Comparison of batch and continuous equipments

Equipment type	Comparison item				
	scale	energy consumption	flexibility	cost	product stability
Batch	small batch, experimental	high energy consumption per unit (batch production)	high (mixed or irregular materials)	low	suboptimal
Continuous	large scale, industrialized	low energy consumption per unit (continuous production)	low (homogenized materials)	high	relatively high

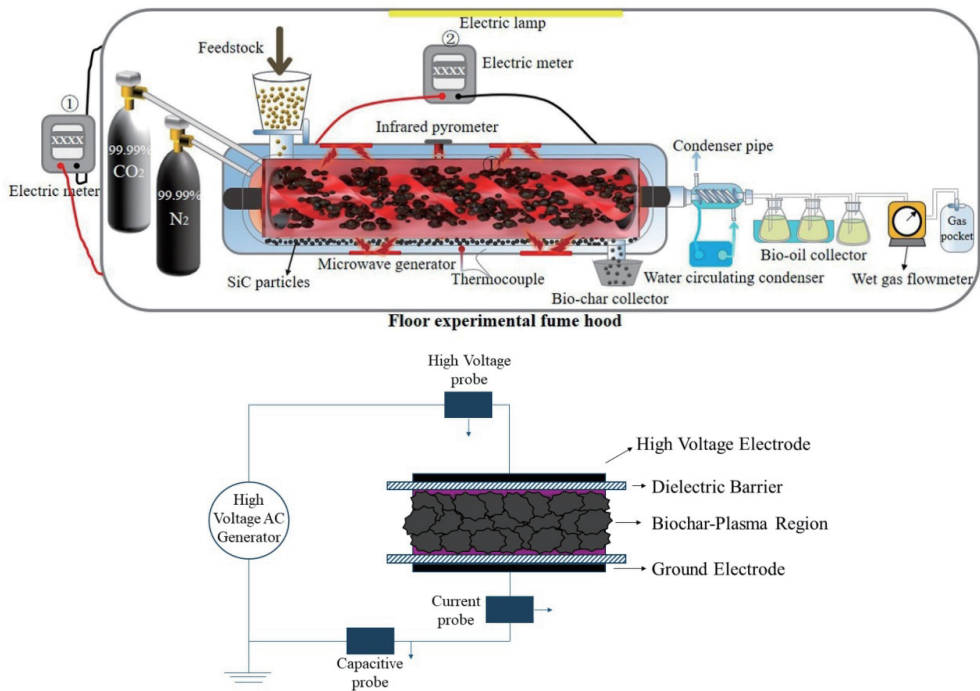


Fig. 19 (a): Continuous microwave pyrolysis device^[97]; (b): plasma pyrolysis device^[98] (with permission from Elsevier)

Pyrolysis experiments were carried out using the principal constituents of wind turbine blade composites: WTB-A, WTB-B and WTB-C^[86]. Figure 20 illustrates the compositional profiles of pyrolysis gases evolved from WTB-A (the spar cap of the blade), WTB-B (polyethylene terephthalate (PET) foam) and WTB-C (balsa wood). For WTB-A, the concentration of CO₂ progressively diminishes with increasing temperature, whereas the abundance of CH₄ rises, attributed to the intensification of demethylation pathways during thermal degradation. Beyond 500 °C, the formation of CO and H₂ is markedly enhanced, primarily due to the acceleration of dehydrogenation and polycondensation reactions^[86]. In contrast, the elevated O/C ratios inherent to PET foam and balsa wood render CO₂ the predominant gaseous product in WTB-B and WTB-C^[102]. Moreover, the absence of methyl functionalities in these materials results in a pronounced suppression of CH₄ generation during pyrolysis. Nonetheless, trace amounts of unsaturated (C₂H₄) and saturated (C₂H₆) hydrocarbons are concomitantly produced.

Moreover, the pyrolysis gases generated during the WWTB degradation process can be purified or fractionated to yield syngas, which may subsequently be harnessed for power generation, electric furnace heating, or other energy-intensive applications. A practical illustration of this is provided by the Danish company ReFiber ApS, which employs pyrolysis to convert resin into usable energy^[103]. Market analyses of syngas utilization reveal that it can be further upgraded to hydrogen fuel, with the resultant

hydrogen priced in the range of approximately 8.874–19.82 USD per kilogram. Such valorization strategies underscore the considerable economic advantages associated with the secondary exploitation of pyrolysis-derived gases^[104].

4.2 Liquid products and applications

The composition of pyrolysis oil is notably intricate, comprising primarily aromatic hydrocarbons, aliphatic hydrocarbons, phenolic derivatives, and various other organic constituents. This material represents a highly heterogeneous organic matrix. Through advanced separation and purification techniques, specific fractions can be selectively recovered and subsequently employed as chemical feedstocks for the synthesis of plastics, rubbers, and related products. The residual fractions, which are comparatively more challenging to recycle, can be utilized as fuel oils for boilers, kilns, and similar thermal applications.

Figure 21 illustrates the product distribution of pyrolysis oils derived from WTB-A, WTB-B and WTB-C^[86]. In the case of WTB-A, five representative phenolic compounds were identified, namely bisphenol A, phenol, 4-isopropylphenol, 4-isopropenylphenol, and methylphenol^[89]. Elevation of pyrolysis temperature facilitates the cleavage of Ph–O–C linkages in EP^[105–106], resulting in an increased yield of bisphenol A.

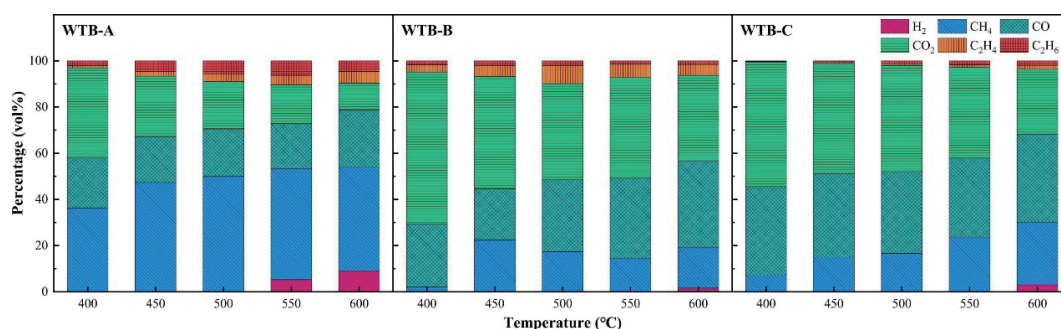


Fig. 20 Composition of pyrolysis gases for WTB-A, WTB-B and WTB-C^[86]
(with permission from Elsevier)

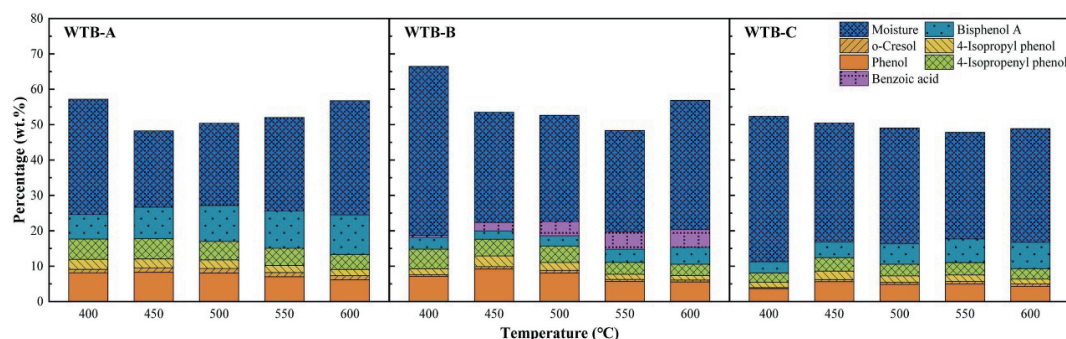


Fig. 21 Composition of pyrolysis oils from WTB-A, WTB-B and WTB-C^[86]
(with permission from Elsevier)

Concurrently, the concentrations of other phenolic species progressively decline, owing to secondary reactions occurring under elevated thermal conditions. This same mechanism also accounts for the enhanced generation of C_2H_4 and C_2H_6 within the pyrolysis gas phase. For WTB-B, increasing pyrolysis temperature induces a gradual reduction in phenolic content, while simultaneously promoting the accumulation of benzoic acid, attributable to the thermal decomposition of PET foam polymers^[107]. In the case of WTB-C, a diverse array of hydrocarbons, including 2,6-dimethoxyphenol, phenanthrene, and eugenol, was detected, necessitating additional separation and purification strategies to enable efficient recycling of the phenolic fractions^[108].

Microwave-assisted pyrolysis of EP generates phenolic-rich products. Introduction of methanol vapor, in the presence of a suitable catalyst, initiates a methylation coupling reaction. The resultant liquid products predominantly comprise methylated phenolic derivatives (e.g., ortho-methylphenol, meta-methylphenol) as well as hexamethylbenzene. Ortho-methylphenol serves as an intermediate for herbicide synthesis and finds additional application in disinfectants and preservatives. Meta-methylphenol is widely employed as a precursor for the production of pesticides, pharmaceuticals, and aromatic agents. Hexamethylbenzene, on the other hand, is a valuable precursor for polyimide synthesis and exhibits significant utility in high-temperature applications, particularly in microelectronics and aerospace engineering^[35]. Pyrolysis of WWTB using a small-scale reactor at 500, 550 and 600 °C yielded an oil production rate of 44.5%. Notably, the styrene fraction accounted for as much as 48.53% of the oil. Following separation, styrene can be directed toward the synthesis of novel unsaturated polyester resins, polystyrene, and a variety of other polymeric materials^[109].

4.3 Solid products and applications

The pyrolysis residues mainly consist of GFs or CFs, accompanied by residual carbon. Subsequent oxidation enables efficient regeneration of GFs or CFs. TGA demonstrates that A-GFs retain the lowest residual carbon,

while B-GFs and C-GFs exhibit higher carbon contents. Increasing pyrolysis temperature further reduces carbon formation, highlighting the suppressive effect of elevated thermal conditions. Notably, the oxidation reactivity of the residues remains largely invariant across different pyrolysis temperatures, underscoring the intrinsic stability of their oxidative behavior^[86].

Post-oxidation effectively removes residual carbon from GF surfaces, with recyclability governed primarily by the fibers' intrinsic mechanical integrity. As illustrated in Figure 22(a) and (b), the recovered fibers (A-rGFs, B-rGFs and C-rGFs) display maximum tensile strength at 400 °C, followed by progressive degradation at higher temperatures due to surface defect diffusion^[63,86].

In contrast, Young's modulus remains essentially unaffected by pyrolysis temperature^[63,110]. Compared with direct-combustion recovery, the pyrolysis–post-oxidation route yields fibers with superior tensile strength, confirming its efficacy for producing high-quality recycled GFs^[111].

Recovered and unrecovered GFs have diverse applications across industries like cement manufacturing, asphalt modification, and concrete production. Notably, companies such as ReFiber ApS use pyrolysis to recover GFs for use in insulation products, fillers, and as short-fiber reinforcement in polymeric materials^[103]. Similarly, Fiberline Composites A/S, a Danish producer of GFRP materials, leverages the chemical compatibility between GFs and cement, both containing SiO_2 . As a result, GF fragments can replace sand in cement, and the resin fraction can serve as auxiliary fuel during cement production.

However, GFs' interaction with alkaline cement components can cause fiber degradation in the matrix^[112]. In asphalt systems, recycled fibers (0.075–9.5 mm) and powder (<0.075 mm) fractions help reduce rutting and cracking. Studies show that 10% powder combined with 0.3% fibers enhances high-temperature rutting resistance by 44.5%, while a mix of 10% powder and 0.1% fibers improves flexural strength and durability^[113]. In the U.S., Global Fiberglass Solutions Inc. (GFSI) has developed a mechanical comminution process to break down wind turbine blades into small fragments.

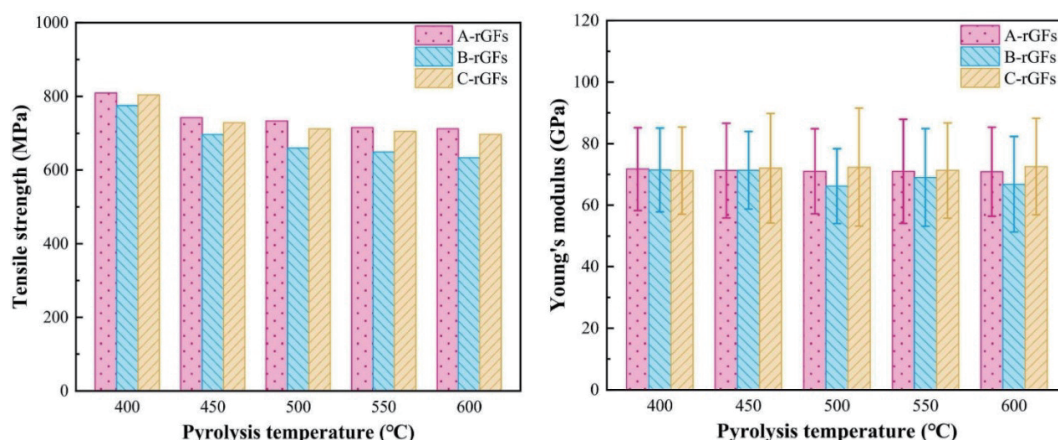


Fig. 22 (a): Tensile strength; (b): Young's modulus of recovered GFs^[86]
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This process liberates GFs or CFs from the resin matrix, which are then reprocessed into composite materials for secondary applications such as railroad ties, utility poles, and particle boards^[103]. Research by Asokan et al. has also shown that adding recycled GFs to concrete increases density by about 15%, thanks to the high density of GFs. Their study found that incorporating fibers into cement at elevated temperatures (800–1200 °C) extended the setting time and reduced alkali-aggregate reactions, helping to prevent matrix degradation^[114]. These applications demonstrate the versatility of recycled GFs across various sectors, contributing to sustainability and enhancing material performance. Collectively, these studies underscore the diverse potential applications of WWTB pyrolysis products. A systematic overview of these application

domains is summarized in Table 9 and Figure 23.

5 Conclusion and future perspective

5.1 Conclusion

This review provides a comprehensive overview of prevailing pyrolytic recycling strategies for WWTB. It further synthesizes recent advances in WWTB pyrolysis technologies, recycling pathways, process parameters influencing pyrolysis, equipment configurations, and the spectrum of pyrolysis-derived products and their potential applications. The principal conclusions drawn from this review are summarized as follows:

Table 9 Specific applications of WWTB pyrolysis products^[112,115–117]

Pyrolysis products	Application fields	Applications	Challenges and limitations
Pyrolysis gas	energy supply (heating supply /power generation)	pyrolysis gas can be directly burned to provide energy; synthetic gas as a basic raw material for chemical production	pyrolysis oil needs to be supplemented adjust the pyrolysis gas ratio to meet the syngas specifications
Light hydrocarbons gases	chemical raw materials	after separation and purification, the pyrolysis gas is used for the production of plastics or synthetic resins	the cost of pure separation technology is high
Pyrolysis oil	fuel substitution chemical raw materials	the refined and desulfurized pyrolysis oil can replace some fossil fuels; phenolic compounds can be used as intermediates in chemical production	phenolic compounds were toxic and must be handled with strict care; market circulation was restricted
Pyrolysis carbon	adsorbent materials composite material additives	pyrolysis carbon can be used for wastewater treatment or as electrode material for batteries	the pyrolysis carbon yield was low and the economic benefits were poor
Recovered GF	building materials composite material raw materials	GF can be used to manufacture concrete, cement reinforcement materials, or recycled plastic products	GF strength loss is 15%–30%, which is only suitable for low strength scenarios; the decarbonization process has high energy consumption
Recovered CF	building materials automotive and aerospace	CF can be used as a reinforcing material for concrete structures or building templates; CF can be reused for automotive components and aerospace secondary load-bearing structures	residual resin on the surface can affect its bonding performance with concrete; CF strength shows a loss of 10%–20% and must be designed to meet aerospace material standards

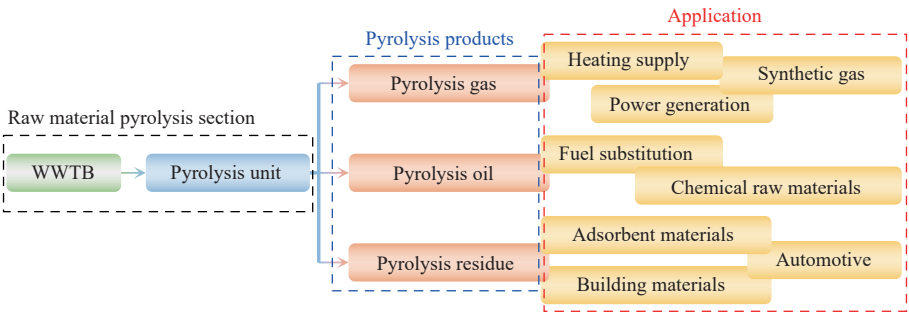


Fig. 23 Application of pyrolysis products

(1) Mitigating the environmental burden associated with WWTB necessitates the identification of both economically viable and technically feasible recycling strategies. Mechanical recycling is advantageous for its operational simplicity, low cost, and minimal environmental footprint; however, the resulting products are generally relegated to low-value applications such as fillers in construction materials, concrete, or cement. Chemical recycling can yield high-purity recovered fibers, but the process generates substantial volumes of waste effluents, complicating treatment and elevating costs. Although pyrolysis is constrained by high energy consumption, the recovery of value-added pyrolysis products can provide sufficient economic return to render it a particularly promising pathway.

(2) The pyrolysis behavior of WWTB is governed by a multitude of factors, including pyrolysis temperature, heating rate, gaseous environment, catalytic systems, and feedstock composition. These variables modulate both the formation pathways and distribution of pyrolysis products. Resin bond cleavage within the composite matrix is closely linked to pyrolysis temperature: thermal energy enables surmounting of reaction activation barriers, fostering bond scission and free radical generation. These radicals subsequently undergo recombination and secondary transformations, giving rise to diverse product streams. Temperature variations critically influence the mechanical integrity of recovered fibers: elevated temperatures facilitate resin decomposition but markedly diminish fiber strength, whereas lower temperatures preserve fiber properties but result in incomplete resin removal, leaving residual carbonaceous deposits on fiber surfaces. Thus, identifying an optimized pyrolysis protocol that simultaneously ensures complete resin removal while preserving fiber mechanical performance is imperative. This review also systematically examines the effects of heating rate, atmosphere, catalysts, and compositional variables on product yields and fiber quality.

(3) Pyrolysis process design and equipment selection are central to effective product recovery. Appropriate process optimization can substantially curtail both capital investment and long-term maintenance expenditures. Pyrolysis equipments are broadly classified as batch and continuous systems. Batch equipment are suitable for heterogeneous feedstocks of irregular geometry but suffer from low throughput, high energy requirements, and inconsistent product quality. In contrast, continuous equipment provide higher efficiency and reproducible product characteristics, rendering them better suited for industrial-scale deployment; however, they demand stringent feedstock specifications, including material homogeneity and low moisture content, and are thus less adaptable for complex waste mixtures. Accordingly, rational selection of equipment type and process configuration tailored to specific material characteristics is of paramount importance.

(4) Recovered fibers can be reintegrated into sectors such

as construction, advanced composite manufacturing, automotive engineering, and aerospace, thereby achieving high-value recycling. Pyrolysis oil, upon fractionation and refining, can serve as either a substitute for conventional fuel oil or a feedstock for chemical synthesis, supporting pathways for value-added utilization. Furthermore, pyrolysis gas may be upgraded *via* synthesis or conversion routes into syngas, enabling its use in downstream chemical production and mitigating the environmental drawbacks associated with direct combustion.

5.2 Future perspective

The pyrolysis of WWTB has demonstrated considerable promise as a sustainable recycling pathway; nevertheless, several technical and economic challenges remain to be overcome before this approach can be fully industrialized and widely adopted.

(1) Scaling-up challenges remain a fundamental bottleneck. While laboratory-scale experiments have confirmed the feasibility of pyrolysis, the transition toward large-scale implementation is impeded by the intrinsic heterogeneity of WWTB feedstocks and the operational complexity of continuous input systems. Progress is expected to stem from iterative optimization of pilot-scale facilities, which can serve as intermediaries bridging the gap between academic research and industrial adoption.

(2) Process optimization emerges as a key research frontier. The refinement of heating strategies and the incorporation of efficient catalytic systems hold significant potential to enhance product selectivity, lower reaction energy requirements, and improve overall process economics. Advanced heating methods such as microwave-assisted and induction-based pyrolysis, though still confined to laboratory settings, provide promising alternatives for large-scale process intensification. The economy evaluation of different pyrolysis processes are highly required before scale-up application. Scientific evaluation methods are needed to be established in the future.

(3) The recovery and stability of catalysts are crucial for ensuring the efficient and long-term stable operation of processes. Future research should focus on the development of efficient catalysts. The design and enhancement of recyclable catalysts not only ensure stable and efficient catalytic reactions but also facilitate the effective recovery of the catalyst. This can address the challenges of catalyst separation and recovery, offering promising prospects for the catalytic pyrolysis process. The long-time stability of the catalysts should be evaluated in the future study.

(4) Product recovery and economic viability represent another critical consideration. Although recovered fibers account for the majority of product yield, their post-treatment (e.g., oxidation) increases energy demand, and the chemical complexity of pyrolysis oils and gases necessitates advanced separation and conversion technologies. Quality of recycled fibers and product valorization also warrant

focused attention. While pyrolytic recycling can preserve the mechanical integrity of recovered glass or carbon fibers, coupling pyrolysis with controlled oxidation offers a viable strategy to achieve complete resin removal without degrading fiber performance. Further techno-economic assessments are essential to evaluate the profitability and sustainability of product recovery, thereby informing industrial decision-making and policy frameworks. Moreover, conducting an economic analysis and evaluation of the WWTB recycling route *via* life cycle analysis to achieve rational resource utilization and distribution will yield substantial economic benefits for the green, sustainable closed-loop recycling of WWTB.

(5) Future research efforts should focus on improving and innovating new separation processes to facilitate the efficient recovery of chemical monomers. This will have a milestone impact on the development of pyrolysis product separation technologies.

In summary, WWTB pyrolysis stands at a critical juncture: the fundamental feasibility of the technology has been established, but industrial-scale realization demands coordinated progress in process engineering, catalyst development, feedstock logistics, and product upgrading. Future research should adopt a multi-disciplinary approach, integrating advances in chemical engineering, materials science, and environmental economics, to facilitate the transition of WWTB pyrolysis from a promising laboratory concept to a cornerstone of circular economy strategies in the renewable energy sector.

Declaration of Competing Interest

The authors declare no conflict of interest.

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废弃风机叶片热解回收研究进展

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摘 要: 全球能源格局正经历深刻变革, 风能, 尤其是风力发电, 因其清洁、可再生的特性日益受到重视。然而, 随着风电装机容量的持续扩大, 废弃风机叶片(WWTB)的处理已成为一项重大挑战。这些叶片主要由环氧树脂(EP)聚合物、碳纤维(CFs)和玻璃纤维(GFs)组成。不当处置不仅会加剧环境问题, 还会导致宝贵资源的流失, 特别是碳基材料。热解技术作为一种多功能且环保可持续的资源回收方法, 在 WWTB 处理方面受到了广泛关注。本工作综述了 WWTB 的热解回收技术, 重点探讨了热解技术的原理与分类、影响热解过程的关键因素, 以及热解方法、设备、产物及其应用。通过对当前 WWTB 热解回收研究的深入分析, 本综述指出了该领域尚未解决的关键问题, 并对新兴研究趋势进行了前瞻性展望。

关键词: 废弃风机叶片; 环氧树脂聚合物; 碳纤维; 玻璃纤维; 热解回收; 资源回收

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