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Review

Mobile Pyrolysis Systems for Decentralized Biomass Valorization: Technologies, Products, and Applications

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Abstract

Mobile pyrolysis systems offer a practical pathway for the decentralized valorization of biomass waste, addressing the high logistical and economic burdens of transporting low-density, moisture-rich feedstocks to centralized facilities. By operating directly at the source, these systems convert diverse agricultural and forestry residues into biochar, bio-oil, pyrogas, and wood vinegar, while reducing transport volumes and associated emissions. Reported mobile reactors process between 4 kg per batch and 10 t/day, achieving biochar yields of 33–44 wt.% at 400 °C and bio-oil yields of 55–68 wt.% in fast pyrolysis at 500–550 °C, demonstrating performance comparable to stationary installations. This review synthesizes current mobile pyrolysis technologies, including reactor configurations, feedstock suitability, operational constraints, and recent advances in automation, real-time monitoring, and machine learning-based optimization. The agricultural and industrial applications of pyrolysis products are examined, with emphasis on soil health enhancement, biopesticide activity, renewable gas generation, and carbon sequestration. Emerging international projects and commercial efforts are highlighted, illustrating growing interest in flexible, low-carbon pyrolysis solutions for rural waste management and distributed bioresource utilization, while outlining the technological gaps that remain to be addressed.

Keywords: biomass waste; decentralized pyrolysis; wood vinegar; biochar

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1. Introduction

Climate change and biodiversity loss have intensified global interest in sustainable strategies for managing natural resources. In the European Union (EU), policies such as the European Green Deal aim to accelerate the transition toward low-carbon, circular systems by promoting renewable energy, reducing greenhouse gas emissions, and improving the management of agricultural and forestry resources [1–3]. Biomass, the third most abundant energy source worldwide, plays a key role in this transition. Its use can significantly reduce emissions of CO_2, SO_x, NO_x, and particulate matter, helping mitigate environmental impacts while valorizing locally available residues [4,5].

Thermochemical conversion processes, including torrefaction, gasification, and pyrolysis, have emerged as efficient routes to transform biomass waste into higher-value products. Pyrolysis, in particular, enables the production of biochar, bio-oil, pyrogas, and wood vinegar, supporting both energy recovery and the generation of bioproducts such as biofertilizers and biopesticides [6,7]. Numerous biomass types have been successfully processed through pyrolysis, including cotton straw [8], rice straw [9], corn stalk [10], hemp [11], olive pomace [12], sugarcane bagasse [13], grape pomace [14], and forestry residues [15].

However, despite its potential, the use of biomass as an energy feedstock faces notable challenges, particularly in Southern European countries. Key drawbacks include: (a) the small and dispersed quantities of raw materials, (b) difficulties in collecting and transporting biomass from remote rural areas and islands, (c) high humidity levels that reduce energy performance, (d) strong seasonality in the availability of many biomass species, and (e) high variability in composition and quality These constraints directly affect the economic and environmental performance of bioenergy systems [16–18].

Logistical barriers are among the most significant limitations to efficient biomass valorization. In large-scale pyrolysis and bioenergy systems, biomass logistics, including handling, storage, and transportation, represent major contributors to overall costs and can substantially compromise process efficiency [19,20].

Strategies that reduce the need to transport low-density, moisture-rich biomass are therefore essential. One effective approach is to convert biomass into energy-dense products directly at the source. Several studies show that mobile pyrolysis systems provide a promising solution to these logistical constraints by performing decentralized conversion at or near the biomass production-site [21–27]. While extensive research exists on stationary pyrolysis systems, including reactor design [28], reaction mechanisms [29,30], and techno-economic assessments [31], studies on mobile pyrolysis remain relatively limited [29,32]. Most available work focuses on supply chain modeling or performance assessment, demonstrating that mobile systems can outperform centralized facilities under favorable conditions [23,32,33]. However, critical technical details such as reactor configurations, system layouts, operational parameters, and product quality remain insufficiently documented.

This review provides a comprehensive overview of mobile biomass pyrolysis systems, emphasizing their suitability for decentralized, field-based applications. It examines reactor technologies, feedstock requirements, operational parameters, and recent advances in process monitoring and automation. In addition, it discusses the properties and applications of pyrolysis products (biochar, wood vinegar, pyrogas, and bio-oil) and evaluates the benefits and limitations of mobile systems relative to conventional fixed installations. Finally, key ongoing projects are highlighted to illustrate current developments and future opportunities in this emerging field.

2. Mobile Pyrolysis Systems: Technologies, Feedstock, and Process Optimization

2.1. Mobile Pyrolysis Reactor Technologies

Mobile pyrolysis reactors have emerged as a practical solution for decentralized biomass valorization, enabling thermochemical conversion directly at the source of residue generation. By eliminating the need to transport bulky, moisture-rich feedstocks to centralized facilities, these systems significantly reduce logistics costs and enhance the feasibility of biomass processing in remote rural regions, forested areas, and islands. Their compact, modular design allows operation at relatively small-scales while maintaining sufficient thermal efficiency to produce valuable outputs such as biochar, bio-oil, and pyrogas.

To facilitate comparison across the literature, mobile pyrolysis reactors can be broadly classified according to their operating mode (batch *versus* continuous), heat supply strategy (externally heated *versus* autothermal), and degree of system integration. These criteria reflect the main design constraints imposed by mobility, namely transportability, energy self-sufficiency, and system compactness, and directly influence achievable throughput, operational stability, and product distribution. A wide range of mobile reactor configurations has therefore been developed, differing in processing capacity, thermal integration, and feedstock adaptability [23,34,35]. The technologies discussed below are presented as representative case studies for each category, reflecting design approaches and operating conditions that are consistently reported across multiple experimental and pilot-scale mobile pyrolysis systems.

Early developments include small bench-scale slow pyrolysis units such as the mobile reactor evaluated by Bian et al. [36], who processed 4 kg batches of agricultural residues at 400 °C. Their results demonstrated that mobile slow pyrolysis could achieve biochar yields above 40% (rice straw) with agronomic properties suitable for soil improvement, in line with other reported batch or transportable slow-pyrolysis systems designed for decentralized biochar production [37,38].

Larger mobile systems are typically based on fast pyrolysis principles. Wang et al. [35] developed a trailer-mounted double-pipe fluidized bed reactor capable of processing 50 kg/h of biomass at 450–600 °C. The system uses liquid petroleum gas (LPG) for start-up heating and subsequently transitions to autothermal operation by combusting non-condensable gases generated during pyrolysis. This strategy has also been reported for larger fluidized beds where char and non-condensable gases are burned in an adjacent or enveloping combustor to supply heat, and in autothermal fast pyrolysis configurations using partial oxidation, which simplify equipment by avoiding continuous external heat [29,39,40]. This design illustrates a common feature of mobile units: the integration of heat recovery loops to minimize external energy inputs and maintain compact operation.

Commercial-scale prototypes include the Agri-Therm MPS200, a mobile fast pyrolysis system with a processing capacity of approximately 10 t/day. This system integrates feed handling, reaction, condensation, and control modules within a transportable unit. As noted in several studies, transport regulations impose size and weight limitations on mobile equipment, typically restricting total load capacity to below 30 t, which directly influence reactor geometry, insulation thickness, and ancillary equipment integration [22].

Beyond traditional designs, several advanced mobile or mobile-capable pyrolysis technologies have been reported, further illustrating configuration diversity. One example is the Combustion Reduction Integrated Pyrolysis System (CRIPS), a trailer-mounted dual fluidized-bed reactor developed by Boateng et al. [41]. This mobile demonstration unit was designed to process approximately 83 kg/h (2 t/day) of biomass for decentralized production of bio-oil and includes in situ heat and electrical power generation, partial gas recirculation, and optional catalytic upgrading. Its operation has been successfully demonstrated using woody biomass, switchgrass, and horse litter.

Another important development is the mobile autothermal pyrolysis system proposed by Chen et al. [23], which is built around an internally interconnected fluidized-bed (IIFB) reactor. This design integrates a pyrolysis bed and a combustion bed within a single compact unit, enabling operation without external heat sources or inert gases. Heat is supplied entirely through on-site combustion of recycled biochar, while non-condensable gases are recycled as fluidizing gas. The system includes mobile pretreatment, condensation, and heat-recovery units, making it suitable for field deployment.

Additionally, a compact ablative centrifuge pyrolysis reactor (10 kg/h) developed by Gupta et al. [42] has been demonstrated as a mobile-capable option due to its very small footprint and minimal carrier-gas requirements. The system uses a high-speed thermo-mechanical rotor (up to 10,000 rpm) to apply centrifugal forces that press biomass against heated surfaces, achieving fast pyrolysis with vapor residence times below 2 s while producing low-ash biochar and bio-oil qualities comparable to fluidized-bed systems.

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Although solar-assisted thermochemical reactors are not inherently mobile, they are briefly discussed here as reference concepts for alternative heat-supply strategies that may inform future mobile pyrolysis system design. Solar-driven pyrolysis and gasification systems demonstrate approaches to supplying endothermic heat without fossil fuels, which is a critical constraint for decentralized and energy-autonomous mobile platforms. In this context, solar-assisted reactors such as the 500 kW Synpet vortex-flow reactor and the 150 kW Solsyn fixed-bed solar reactor [43,44], as well as hybrid solar–thermochemical pilot plants [45], are included here only as reference concepts for alternative heat-supply strategies. At present, no fully mobile pyrolysis or gasification unit incorporates solar-driven endothermic heating, highlighting a technological gap rather than an established mobile configuration.

Existing mobile pyrolysis technologies demonstrate the technical feasibility of small and medium-scale decentralized biomass conversion. Nevertheless, design constraints related to transportability, power autonomy, and thermal integration continue to limit processing capacity and technology readiness levels. Table 1 summarizes representative examples of mobile pyrolysis reactors reported in the literature, highlighting their key specifications and operating characteristics.

Table 1. Summary of representative mobile pyrolysis reactor systems and key operating characteristics.

Reactor Configuration	System	Processing Mode	Capacity	Operating Temperature	Heat Supply	Mobility Platform	Notable Features	Ref.
Batch slow pyrolysis (bench-scale)	Mobile bench-scale reactor	Slow pyrolysis (batch)	4 kg/batch	400 °C	External heating	Small trailer/bench	High biochar yield (44% for rice straw)	[36]
Continuous fast pyrolysis (fluidized bed)	Trailer-mounted double-pipe fluidized bed	Fast pyrolysis (continuous)	50 kg/h	450–600 °C	LPG start-up + autothermal via pyrogas combustion	Highway trailer	1.1 s vapor residence; rapid start-up	[35]
Continuous fast pyrolysis (integrated system)	Agri-Therm MPS200	Fast pyrolysis (continuous)	10 t/day	~500 °C	Integrated burner + heat recirculation	Containerized/mobile	Full system integration (pre-processing → condensation)	[22]
Fast/catalytic pyrolysis (dual fluidized bed)	CRIPS	Fast/catalytic	~40–83 kg/h	~500 °C	Dual fluidized beds; in situ heat and power	Trailer-mounted	Tail-gas reactive pyrolysis; catalytic mode	[41]
Autothermal fast pyrolysis (IIFB)	IIFB autothermal mobile reactor	Autothermal fast pyrolysis	100 kg/h (design)	550 °C pyrolysis/650 °C combustion	Biochar combustion + NCG recycle	Mobile modular system	Tail-gas reactive pyrolysis; catalytic mode	[23]
Ablative fast pyrolysis (centrifuge)	Ablative centrifuge pyrolysis reactor	Ablative fast pyrolysis	10 kg/h	500 °C	External heaters + rotor friction	Compact (mobile-ready)	High RPM (up to 10,000); low-ash char	[42]
Solar thermochemical (reference—not mobile)	Synpet (not mobile)	Solar gasification	500 kW	>1000 °C	Concentrated solar power	Stationary	Vortex flow solar reactor	[43]
Solar thermochemical (reference—not mobile)	Solsyn (not mobile)	Solar gasification	150 kW	>900 °C	Concentrated solar power	Stationary	Fixed-bed solar reactor	[44]
Hybrid solar–thermochemical (reference—not mobile)	Hybrid solar–thermochemical pilot plant	Solar thermochemical	100 kWe	>800 °C	Parabolic trough collectors + hybrid	Stationary	Multi-reactor, solar-enabled heat supply	[45]

To facilitate comparison across the diverse mobile reactor designs reported in the literature, Figure 1 provides a schematic overview of typical small-scale mobile pyrolysis reactor configurations. These conceptual layouts illustrate the key functional elements common to batch slow-pyrolysis units, continuous fast-pyrolysis systems, and autothermal mobile reactors, including feed handling, heat supply, vapor recovery, and product separation. While individual commercial or experimental systems may differ in their detailed implementation, the schematics highlight the shared design constraints imposed by mobility, such as compactness, energy self-sufficiency, and simplified auxiliary systems.

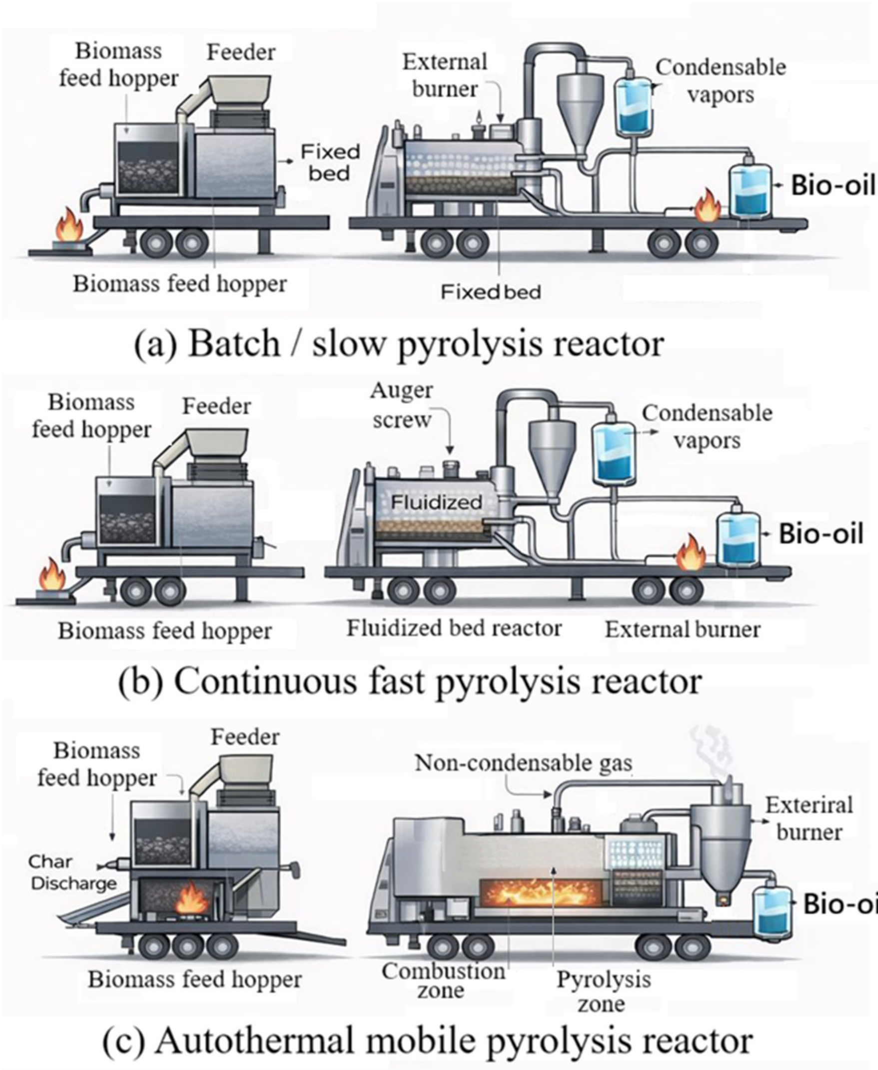

Figure 1. Schematic representation of typical small-scale mobile pyrolysis reactor configurations: (**a**) Batch/slow pyrolysis reactor. (**b**) Continuous fast pyrolysis reactor. (**c**) Autothermal pyrolysis reactor.

2.2. Feedstock Requirements and Suitability for Mobile Pyrolysis

The selection of suitable feedstocks for pyrolysis can vary significantly between stationary and mobile systems due to differences in scale, operating conditions, and logistical constraints. Conventional pyrolysis reactors often operate in centralized facilities where feedstock can be collected, pre-processed, and stored in bulk. This allows the use of a broader range of biomass types, including those requiring extensive pre-treatment, such as size reduction, drying, and pelletization. Additionally, stationary systems benefit from consistent operational conditions and ample space for feedstock storage and pre-processing equipment, supporting the continuous conversion of various feedstock types [46].

Mobile pyrolysis units, on the other hand, are designed for flexibility and on-site deployment, typically in remote or decentralized locations where biomass is generated [47]. Due to transportation limitations and the need for compact and lightweight designs, mobile pyrolysis systems generally favor locally available feedstocks that require minimal pre-treatment [48]. This characteristic makes mobile systems particularly advantageous in regions where biomass is geographically dispersed or seasonally available, as it reduces the logistical burden associated with transporting low-density raw materials. This mobile operation reduces biomass collection, transport, and storage costs while improving equipment efficiency and overall economic performance [35].

Biomass resources are usually categorized into three primary groups, based on their origin and composition: waste, existing forests, and energy-producing crops. Globally, wood and wood waste represent the dominant biomass fraction used in thermochemical conversion processes (64%), followed by municipal solid waste (24%) and agricultural residues (5%) [49]. Feedstocks such as agricultural residues (e.g., straw, husks) and forestry waste (e.g., wood chips, sawdust), often generated seasonally and dispersed in rural areas, are well-suited to mobile pyrolysis since they are often readily accessible and can be fed into the reactor with minimal modifications [48,50]. Moreover, mobile systems often operate at smaller scales with limited pre-processing capabilities [23], making them more dependent on feedstocks with consistent moisture levels, particle sizes, and thermal properties that align with the reactor's specific design and operational parameters. Thus, feedstock suitability for mobile reactors requires balancing logistical factors (availability, handling, storage) with operational factors (reactivity, moisture content, ash composition).

The suitability of feedstock for mobile pyrolysis is determined by several factors, primarily feedstock composition, moisture content, and the presence of impurities in the biomass. Biomass has a complex structure composed primarily of cellulose, hemicellulose, and lignin, and the distribution of these organic polymers varies across different biomass types. Lignocellulosic and forestry biomass, such as sawdust, typically has the highest lignin content and contributes significantly to char production. In contrast, cellulose and hemicellulose are the main contributors to bio-oil. Agricultural residues such as corncobs, corn stover, and rice straw generally have lower lignin levels and often contain high silica content, especially in rice straw, which can increase ash-related challenges and negatively affect bio-oil stability and quality.

For mobile pyrolysis systems, these compositional differences have direct operational implications. Feedstocks with low lignin content generally result in lower biochar yields, which can limit the availability of char for internal heat recovery or autothermal operation, an important feature for mobile units with restricted access to external energy sources [46,51,52]. Conversely, high silica and ash contents can accelerate fouling, slagging, and abrasion in compact reactors, cyclones, and condensation units, increasing maintenance requirements and reducing operational robustness under field conditions. Elevated ash levels may also catalyze secondary cracking reactions, adversely affecting bio-oil yield and stability [53–55]. These effects are particularly critical for mobile systems, where simplified gas-cleaning, limited ash-handling capacity, and reduced access to maintenance infrastructure constrain long-term and reliable operation.

Another property of biomass that can harm the quality of the final products, especially bio-oil, is the moisture content, which can lead to a high-water content in the bio-oil. Furthermore, high moisture levels can reduce the energy content of biomass, as the heat generated during combustion is used to evaporate moisture, thereby reducing the efficiency of thermochemical conversion [56–58]. Therefore, moisture contents below approximately 10 wt.% are typically recommended for the biomass pyrolysis process, and exceeding this limit results in the separation of bio-oil into two distinct phases: an aqueous phase and an oil phase [5]. Nevertheless, mobile pyrolysis units have successfully processed several agricultural and forestry feedstocks with moisture contents ranging from 6 to 13 wt.%, demonstrating a degree of operational tolerance.

Figure 2 illustrates the most frequently used feedstock in mobile pyrolysis, with woody and forestry residues dominating due to their local availability and minimal pre-treatment requirements. Their consistent composition, moderate moisture content, and favorable lignocellulosic properties make them well suited to the logistical and operational constraints of mobile systems.

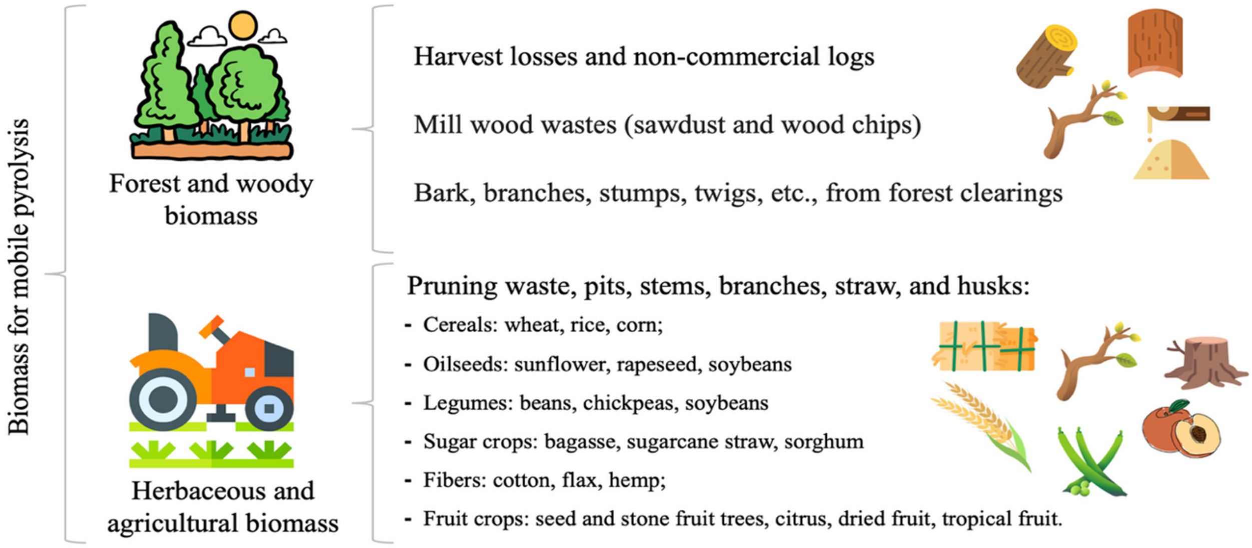

Figure 2. Common biomass feedstocks for mobile pyrolysis applications [22,49].

Table 2 summarizes common feedstocks suitable for mobile pyrolysis, detailing their moisture levels, typical operating temperatures, and product yields, as derived from experimental studies. Together, these datasets highlight the types of biomass most compatible with decentralized conversion and the operating conditions under which they perform effectively.

Table 2. Pyrolysis product yields (biochar, bio-oil, and pyrogas) obtained from different biomass feedstocks at varying moisture contents and reactor temperatures.

Feedstock	Moisture (wt.%)	Temperature (°C)	Biochar Yield (wt.%)	Bio-Oil Yield (wt.%)	Pyrogas Yield (wt.%)	Ref.
Maize straw	11.34	400	33.4	27.5	39.1	[36]
Rice straw	12.6	400	43.8	25.4	30.8	
Acai berry waste biomass	9.7	432	27.8	-	-	[5]
Larch sawdust	5.56	500	19.2	68.6	12.2	[35]
Horse Litter	10.2	500	19.4	45.7	35.0	[41]
Corncob	8.6	550	25.3	55.6	19.1	[23]
Sawdust	7.6	550	24.5	59.7	16.8	

Experimental studies highlight the practical suitability of a diverse set of biomass feedstocks for mobile pyrolysis applications. Biochars with favorable agronomic properties, including alkalinity, high cation exchange capacity, and nutrient content (e.g., nitrogen, potassium, and phosphorus), were produced with yields of 33–44 wt.% via mobile pyrolysis at approximately 400 °C from agricultural residues such as rice and corn stover [36].

Similarly, at higher temperatures (500–550 °C), residues such as sawdust, horse litter, and corncobs were shown to be viable in mobile pyrolysis facilities, achieving high bio-oil yields of 46 and 67 wt.% [23,35,41]. These results illustrate how both feedstock composition and process temperature strongly influence product distribution in mobile systems.

2.3. Operational Parameters and Their Influence on Product Distribution

Process parameters, including temperature, residence time, and feed rate, play a crucial role in determining the efficiency and product distribution of pyrolysis systems. In conventional pyrolysis reactors, these parameters are typically optimized for continuous operation in controlled, stationary environments, allowing for precise adjustments and consistent process stability. Conventional setups also often accommodate broader parameter ranges, leveraging extensive pre-processing and monitoring equipment to maximize yields of specific products like biochar, bio-oil, or syngas.

In contrast, mobile pyrolysis systems face unique challenges due to their compact design, logistical constraints, and deployment in decentralized locations. As a result, process parameters for mobile units are often streamlined to accommodate the limitations of smaller-scale, modular reactors. Temperature and residence time may be set to values that provide balanced product output without requiring extensive external controls, while feed rates are generally tailored to match the lower processing capacities typical of mobile systems. In addition, mobile units often operate with reduced auxiliary services, such as limited electrical power, absence of external inert gases, and simpler instrumentation, which constrains the degree of fine control over process variables compared to stationary plants. These practical limitations result in operational strategies that prioritize robustness and energy self-sufficiency over tight optimization [5,41,59]

Temperature is one of the most influential operational parameters. Lower temperatures (350–450 °C) typically favor biochar formation, whereas intermediate temperatures (450–550 °C) maximize bio-oil yield by promoting primary depolymerization reactions while limiting secondary cracking [60,61]. At higher temperatures (>600 °C), secondary vapor-phase reactions become important, increasing non-condensable gas production at the expense of liquid yield. Mobile pyrolysis units generally operate within 400–600 °C to balance energy consumption, equipment constraints, and desired product distribution [62–65].

Figure 3 qualitatively summarizes the evolution of pyrolysis product distribution as a function of process temperature, with particular emphasis on the distinction between condensable products (bio-oil and wood vinegar) and non-condensable gases. At lower temperatures, biochar formation is favored, while intermediate temperatures maximize condensable liquid yields. At higher temperatures, secondary cracking reactions increasingly convert vapors into permanent gases. This distinction is especially relevant for mobile pyrolysis systems, where non-condensable gases can be recirculated to sustain autothermal operation, and compact cooling systems constrain condensation efficiency.

Vapor residence time also strongly affects product distribution. Short residence times ($\leq$1–2 s), characteristic of fast pyrolysis, enhance the formation of condensable volatiles and improve bio-oil yield. Longer residence times promote thermal cracking of vapors into permanent gases and water, reducing oil quality and quantity [66]. Mobile systems often have moderate residence times due to limited reactor volume and simplified vapor-handling systems, which can influence their ability to achieve the extremely short vapor residence times typical of large stationary fast-pyrolysis reactors [62,65].

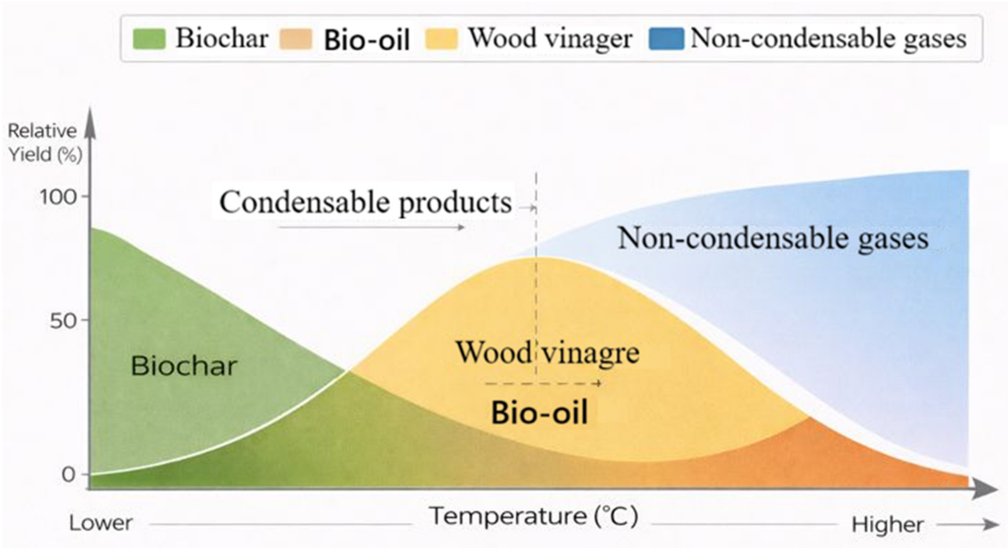

Figure 3. Qualitative distribution of pyrolysis products as a function of process temperature, highlighting condensable (bio-oil, wood vinegar) and non-condensable gas fractions. Arrows indicate the dominant product fractions across temperature regimes, while the vertical dotted line marks an approximate transition region between liquid-dominated and gas-dominated product formation.

Heating rate is another critical parameter. High heating rates (>100 °C/s) favor fast pyrolysis and bio-oil production, whereas lower heating rates (<10 °C/s) favor char production [67]. Due to constraints on burner size, heat-transfer area, and autothermal operation, mobile units often operate at intermediate heating rates, resulting in a broader product distribution than in stationary fast-pyrolysis facilities [41,65].

Feed rate and particle size also play significant roles in mobile-system performance. Excessively high feed rates can exceed the available heat-transfer capacity of compact mobile reactors, resulting in incomplete devolatilization, increased char formation, or unstable autothermal conditions [41]. Conversely, particle size influences temperature uniformity within individual biomass particles: smaller particles promote rapid heating, whereas larger particles (>5–10 mm) can lead to temperature gradients, enhancing char formation [68,69]. Mobile units generally tolerate larger particle sizes due to reduced pre-processing infrastructure, but this may compromise liquid yields [63,70].

Table 3 compares key process parameters between conventional and mobile pyrolysis systems, highlighting the adaptations mobile units make to operate efficiently in decentralized and remote locations. As shown, mobile reactors typically operate at lower throughput, moderate temperatures, and simplified residence-time regimes, reflecting the balance between operational flexibility and technological constraints.

Mobile pyrolysis systems ultimately follow the conventional pyrolysis concept but offer a flexible operational solution that complements conventional fixed installations. It is an alternative that reduces transportation requirements and associated costs, emphasizing the proximity to biomass sources. Their modular design and adaptability to often untreated raw materials and locally available biomass resources make them particularly suitable for decentralized applications and the local production of densified materials (biochar, bio-oil, and pyrogas) with numerous applications. However, the simplified operational characteristics, including intermediate heating rates, moderate temperatures, and constrained residence-time control, mean that mobile systems often yield broader product distributions and require careful balancing of process parameters to maintain stable, efficient operation [47].

Table 3. Comparison of process parameters in conventional and mobile pyrolysis systems [23,34,35,41,47,48,71,72].

Parameter	Conventional Pyrolysis	Mobile Pyrolysis
Application	Industrial complexes established for large-scale manufacturing and operational processes.	Mobile technology that enables flexible and decentralized operations in remote locations.
Reactor type	Fixed structures (fluidized bed reactors for fast pyrolysis, and Auger and rotary kilns for slow/intermediate pyrolysis)	Compact, modular, and adaptable reactors with high heat transfer efficiency and low electrical energy dependence (Auger, rotary kilns, air curtain burners)
Type of feedstock	Homogeneous feedstock, usually pretreated	Miscellaneous feedstock, often untreated
Capacity	High capacity (t/h), continuous processing	Low capacity (t/day), batch processing
Operation temperature	Slow pyrolysis: 300–550 °C Intermediate pyrolysis: 300–450 °C Fast pyrolysis: 300–1000 °C	Typically, 400–600 °C, oxygen-limited or inert environment (often using recirculated pyrolysis gases)
Residence time	Slow pyrolysis: minutes to a few hours Intermediate pyrolysis: minutes Fast pyrolysis: few seconds	Minutes to several hours (slow/intermediate); rarely <2 s for fast pyrolysis due to design constraints
TRL	8–9 (industrial operation)	5–6 (pilot)

2.4. Advances in Automation Monitoring and Intelligent Process Control

The valorization of waste and biomass through pyrolysis has attracted interest in recent years for the production of value-added products, enabling the use of different waste fractions with reduced environmental impact compared to other technologies. Since several parameters influence process kinetics, the development of tools to control and monitor them is highly relevant for increasing waste conversion efficiency. Zhang et al. [73] describe the importance of monitoring reactor temperature and pressure as key factors in determining the proportion of each pyrolysis product, in addition to controlling the quantity and composition of the gas using gas sensors. The authors report several technologies for real-time temperature and pressure monitoring and describe their applications, operating conditions, and limitations. Furthermore, a high-temperature wireless Surface Acoustic Wave (SAW) gas sensor was developed to monitor the gas profile by controlling the main parameters during the pyrolysis reaction. These SAW sensors can operate under harsh conditions, including elevated temperatures and corrosive gas atmospheres, making them particularly suitable for decentralized pyrolysis systems that require rugged, low-maintenance instrumentation. By adjusting the reaction conditions to optimized levels, it is possible to accurately control both maximum production and the desired gas composition to meet specific requirements.

2.4.1. Real-Time Monitoring and Automated Process Control

Modern pyrolysis systems increasingly rely on distributed sensors capable of operating under thermally and chemically aggressive environments. These include high-temperature thermocouples, fiber-optic sensors, SAW devices, and micro-gas analyzers that enable continuous tracking of temperature, pressure, and syngas composition. Such instrumentation is essential for small, decentralized units where operators cannot manually supervise all parameters. In mobile pyrolysis units, the need for compact, vibration-resistant, low-power sensors is even more critical, as environmental conditions are more variable and operator presence is often limited [73].

Pyrolysis optimization processes also rely on mechanisms that adjust feedstock input based on reactor conditions to optimize yield. Automatic feeding systems play an essential role in increasing the efficiency of pyrolysis reactions and controlling product quality. Wang et al. [74] worked on developing a feeding system to improve the efficiency of the continuous pyrolysis process. The authors proposed developing a shaftless screw feeding system to reduce electricity costs and avoid screw-cylinder interference, which could lead to system shutdowns. Such automated feeding mechanisms are especially valuable for mobile pyrolysis units, where fluctuations in particle size, moisture content, and bulk density can lead to uneven feeding rates and unstable reactor temperatures. Real-time adjustments to feed rate can therefore help maintain autothermal operation, prevent reactor fouling, and stabilize product distribution.

In mobile deployments, automated feeding is also essential for safety, as blockages or surges in material flow may be more difficult to detect without continuous supervision. Integrating sensor feedback with adaptive feeding control thus represents a necessary step toward fully autonomous field-deployed pyrolysis units [73,75,76].

2.4.2. Machine Learning, Intelligent Control, and Future Opportunities

The need for increased automation in pyrolysis plants to enhance process optimization has led to the application of machine learning (ML) to predict outcomes and optimize operating conditions in real-time as an integrated process control. Several studies have cited the use of ML as an efficient tool for predicting product yield and quality, as well as for assessing the technical and economic feasibility of the entire process. Akinpelu et al. [77] compiled and compared several ML technologies applied to the pyrolysis of various waste streams and highlighted their strengths and weaknesses. The authors conclude by emphasizing the importance of using machine learning in developing the pyrolysis scale-up process. Dong et al. [78] reported the use of ML to predict the yield and quality of pyrolysis products through feedstock characteristics and process conditions. Emifoniye et al. [79] also reported the use of various ML technologies to increase the efficiency of plastic waste recovery through pyrolysis and predict the quantity and quality of final products, reinforcing the use of this tool for real-time process monitoring. ML models such as artificial neural networks (ANNs), random forest (RF) regressors, support vector machines (SVMs), Gaussian processes (GPs), and decision trees (DTs) have been shown to accurately predict product distributions, reactor temperature profiles, syngas composition, and energy requirements, offering the potential for adaptive, closed-loop control systems. These tools can reduce operator intervention and improve consistency, which is particularly advantageous for mobile pyrolysis systems deployed in remote or resource-limited environments [80–83]. Even though ML-enabled control systems hold a very significant promise, they have not yet been fully implemented in mobile pyrolysis reactors. Published studies to date remain limited to laboratory or pilot-scale stationary units [75,81,83]. This represents a significant gap and a major opportunity for future research in decentralized, autonomous pyrolysis technologies.

Table 4 summarizes selected ML applications relevant to pyrolysis and gasification automation, highlighting the types of input data used, predicted outputs, model types, performance indicators, and their potential relevance to mobile pyrolysis process control.

Despite these advances, the integration of automation and intelligent control into mobile pyrolysis systems remains limited. Mobile units often operate under constraints such as limited electrical power availability, vibration and movement during transport, and variable feedstock quality [41,84–86]. These conditions require the development of robust, low-power, autonomous monitoring and control systems that operate reliably with minimal supervision. Safety systems, including automated shutdown protocols, over-pressure monitoring, and real-time fault detection, are therefore critical for remote field operations where immediate human intervention is not possible.

Table 4. Summary of ML applications in pyrolysis/gasification relevant to automated control in mobile systems.

System	ML Model(s)	Predicted Outputs	Key Findings	Ref.
Biomass–coal blends (163 datasets)	ANN, RF, SVM, GBR	CH_4, CO, CO_2, tar, H_2, H_2O yields; mass loss	Gradient boosting achieved highest accuracy ($R^2 > 0.96$); ANN also strong	[82]
Plastic waste (polyolefins)	ANN, SVM, GA-ANN	Product yields, optimal temperature and heating rate	ML methods outperform traditional models; useful for techno-economic or life-cycle integration	[73]
Biomass pyrolysis	ANN, RF, SVM, ANFIS, DL	Oil, gas, char yields; kinetic parameters	ML models show high accuracy (typically $R^2 > 0.90$); data quality is limiting factor	[83]
Plastic waste pyrolysis	ANN, SVM	Optimal operating conditions; product distributions	ML accurately predicts conversion pathways and improves design optimization	[80]
Electronics waste pyrolysis pilot system (automation, not ML)	PID control, sensor integration	Temperature regulation, heater control	Low-cost open-source hardware performs similarly to commercial controllers	[84]
Plastic waste pyrolysis (prediction and optimization)	ANN, SVM, GA	Product yield prediction; energy optimization	ML improves prediction accuracy and reduces operational uncertainty	[79]

The integration of ML-based predictive tools, rugged sensors, and modular control architecture represents a key technological opportunity to enable next-generation mobile pyrolysis platforms. Furthermore, the development of modular reactor designs is essential to allowing for easy scaling and adaptability to different feedstocks or operational conditions, as reactor complexity is a key challenge to the scale-up and widespread adoption of thermochemical biomass and waste valorization systems [84].

Automation, advanced monitoring, and intelligent process control represent critical enablers for the broader deployment of mobile pyrolysis systems. However, current implementations are still at an early stage, and further development of rugged sensor technologies, autonomous control algorithms, and integrated modular designs will be necessary to achieve fully reliable, field-ready mobile pyrolysis platforms.

3. Pyrolysis Products: Biochar, Bio-Oil, Wood Vinegar, and Pyrogas

Pyrolysis converts organic materials into useful solid, liquid, and gas products. The solid fraction of the mainstream pyrolysis product is referred to as biochar (a carbon-rich solid residue). Bio-oil (also called pyrolysis oil or liquid condensate) and non-condensable gases (pyrogas) are also produced. The proportions of products depend on the composition of the raw material, reactor design, and operating parameters (temperature, heating rate, and residence time). For example, it has been reported that bio-oil produced mainly by fast pyrolysis has liquid yields of up to 70–80 wt.% of dry biomass. The solid char yields are generally 12 wt.%, with the remainder being non-condensable gases (~13 wt.%). In slow pyrolysis, char and pyrogas yields may be higher (sometimes ~35 wt.% each), but bio-oil yields are proportionally reduced (~30 wt.%) (Figure 4) [71,87].

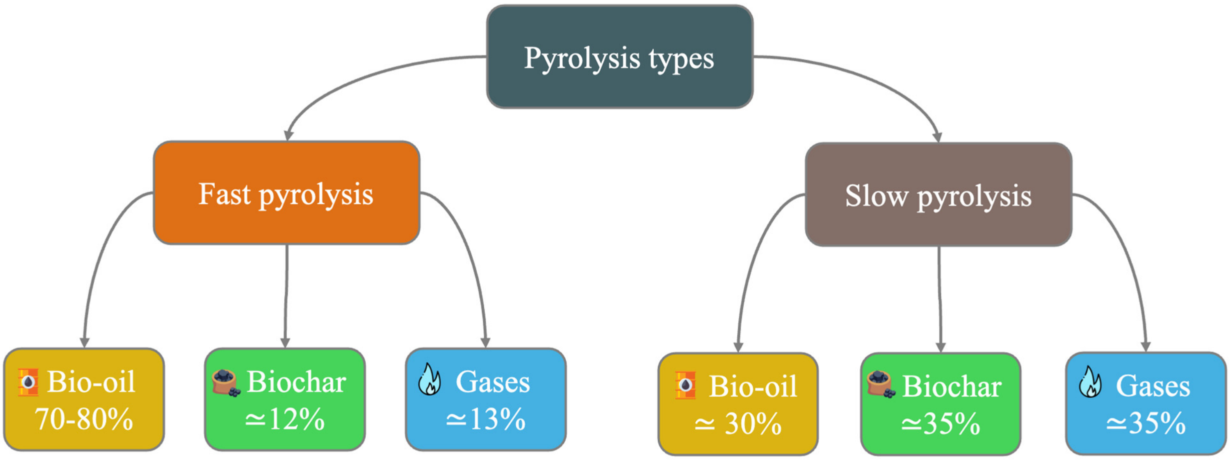

Figure 4. Typical product distribution in fast and slow pyrolysis, illustrating differences in bio-oil, biochar, and pyrogas yields under common operating conditions.

While these trends are well established for conventional stationary reactors, mobile pyrolysis systems may exhibit slightly different product distributions due to compact reactor geometries, simplified heat-transfer configurations, and field-dependent operating conditions. Such variations in product quality and yield are important to consider when evaluating the downstream applications of biochar, wood vinegar, bio-oil, and pyrogas produced on-site in decentralized contexts.

3.1. Agricultural Applications of Biochar and Wood Vinegar

This section aims to explore the agricultural uses of pyrolysis products that align with the operational, logistical, and economic limitations of mobile pyrolysis systems. It emphasizes the importance of in situ or nearby applications, which are common on farms, ranches, and agro-industrial facilities, where these products can be used directly after production.

Climate change negatively affects agriculture worldwide through soil degradation, desertification, salinization, erosion, acidification, and depletion of mineral nutrients. Biochar has been widely recognized as a beneficial material within Climate-Smart Agriculture (CSA), owing to its capacity to improve soil health, enhance crop productivity, and contribute to greenhouse gas (GHG) mitigation [88,89]. In the context of mobile pyrolysis, biochar provides additional benefits by allowing production directly at the site of biomass availability. This facilitates quick soil application in remote agricultural areas while minimizing transportation needs [38,90].

3.1.1. Biochar for Soil Fertility, Soil pH Improvement, and Contaminated Soils

Mobile pyrolysis systems primarily use biochar for direct applications, including on-site soil amendment and remediation. Applying it immediately avoids issues with storage, transportation, and potential quality degradation. The beneficial effects of biochar on soil organic carbon content, crop yield, and mitigation of methane and nitrous oxide emissions are well documented. However, its effectiveness as a soil amendment strongly depends on biochar properties, soil characteristics, and management practices [91,92]. For example, manure-derived biochar has been shown to improve crop yields in soils with low fertility. In contrast, biochar made from lignin-rich feedstocks may lower greenhouse gas emissions and promote long-term carbon sequestration in acidic soils [91].

Biochar's intrinsic alkalinity enables neutralization of excess protons in acidic soils, improving soil pH and supporting microbial activity [93]. Mobile pyrolysis platforms allow farmers in acid-sensitive regions to customize biochar properties by selecting feedstock and adjusting process conditions on-site, thereby enhancing compatibility with local soil characteristics [94,95].

Biochar can improve soil quality through both physicochemical and biological mechanisms, including enhanced nutrient availability and immobilization of harmful contaminants [96]. In mobile deployment scenarios, these benefits are particularly relevant for rapid soil improvement following on-site production. Wu et al. [97] demonstrated that biochar application in acidic soils improved fruit quality and soil properties, outperforming conventional liming treatments, with similar trends reported in related studies [98,99].

Another important agricultural application of biochar is its capacity to mitigate soil contamination. Biochar has been shown to immobilize potentially toxic elements such as cadmium, mercury, and lead, reducing their bioavailability and environmental risk [96,100–105]. Mobile pyrolysis units are especially advantageous in contaminated or remote agricultural areas, where on-site biochar production enables immediate soil remediation without the need for long-distance transport [38,106].

3.1.2. Biochar for Salinity Reduction and Soil Water Improvement

In the context of mobile pyrolysis, applying biochar to combat salinity and enhance soil moisture is particularly important in arid and semi-arid agricultural areas, where immediate action is necessary. Limited annual precipitation often leads to salt accumulation in soils, negatively affecting crop yields and plant growth. Yuan et al. [107] reported that biochar incorporation into salt-affected soils improves soil stability, porosity, and water retention capacity, alleviates salt stress, and enhances nutrient availability, while also increasing soil organic carbon and cation exchange capacity.

Similarly, Sudratt et al. [108] demonstrated that rice husk biochar amendment mitigated salt stress in rice cultivated in soils affected by saltwater intrusion, improving plant growth and yield by reducing sodium uptake in shoots. These findings suggest that biochar created through mobile pyrolysis can be directly applied to salt-affected fields. This approach allows for quick, localized soil enhancement without requiring the transportation of biomass or finished products.

3.1.3. Wood Vinegar: Properties and Agricultural Functions

For mobile pyrolysis systems, wood vinegar is primarily valued for its direct agricultural applications as a locally produced biopesticide and plant growth regulator. Wood vinegar (pyroligneous acid) is a liquid byproduct of biomass pyrolysis containing a complex mixture of oxygenated organic compounds, including acids, phenols, alcohols, ketones, and aldehydes [109–111]. These compounds underpin its agricultural functionality, including soil conditioning, pest suppression, and growth regulation [112]. Mobile pyrolysis units enable fresh, on-site production of wood vinegar, reducing dependence on commercial agrochemicals and associated transport requirements.

Zhuan et al. [113] investigated the effects of wood vinegar on rapeseed growth and reported improvements in seed yield and crop quality under field-relevant application regimes. These results support the suitability of wood vinegar for on-site agricultural use within mobile pyrolysis deployment scenarios.

The excessive use of synthetic fertilizers and herbicides has been shown to negatively affect crop resilience and biodiversity [114,115]. In this context, Fanfarillo et al. [116] demonstrated that low-concentration applications of wood vinegar are compatible with sustainable agricultural practices aimed at preserving plant diversity. Further work confirmed that wood vinegar effects are concentration- and species-dependent, reinforcing the importance of controlled, local application rather than industrial-scale deployment [117].

A broader assessment of wood vinegar bioactivity showed that its effectiveness depends strongly on application method and concentration [118]. While high concentrations may induce phytotoxicity, diluted solutions promoted root growth and reduced pest-related damage in selected crops. Wood vinegar's flexibility makes it especially beneficial for integrated pest and soil management when produced and applied locally using mobile pyrolysis systems.

3.1.4. Synergistic Applications of Biochar and Wood Vinegar

The combined use of biochar and wood vinegar works particularly well in mobile pyrolysis settings, as both products can be produced and utilized right on-site within integrated farm management practices. Idowu et al. [119] examined the combined effects of biochar and wood vinegar on tomato cultivation and reported improved biomass production, fruit yield, and sugar content when plant-derived biochar was used in conjunction with wood vinegar.

Recent studies have further explored the joint application of biochar and wood vinegar for managing agricultural residues such as manure and straw, which are significant sources of greenhouse gas emissions when improperly handled. While composting remains a common residue management strategy, nitrogen losses and emissions constrain its effectiveness. The co-application of biochar and wood vinegar has been shown to reduce ammonia emissions and improve compost quality, although increases in nitrous oxide emissions have also been observed [120]. Mobile pyrolysis platforms that can generate both products on-site provide a decentralized approach to improving soil quality, enhancing compost, and managing pests. This solution not only minimizes transportation needs but also helps reduce emissions associated with residue.

Overall, the applications reviewed in this section prioritize low operational complexity, robustness, and immediate on-site use, consistent with the technical and logistical constraints of mobile pyrolysis systems.

3.2. Main Applications of Pyrogas and Bio-Oil

Pyrogas and bio-oil represent the two energy-rich fractions of biomass pyrolysis, each offering distinct opportunities for heat generation, fuel synthesis, and chemical production. In mobile pyrolysis systems, these products play a particularly important role: pyrogas can sustain autothermal operation at remote sites, while bio-oil provides a transportable, energy-dense liquid that can be stored, upgraded, or used locally (Figure 5). Their composition and potential applications, therefore, determine not only the efficiency of the pyrolysis process but also the viability of decentralized biomass conversion systems.

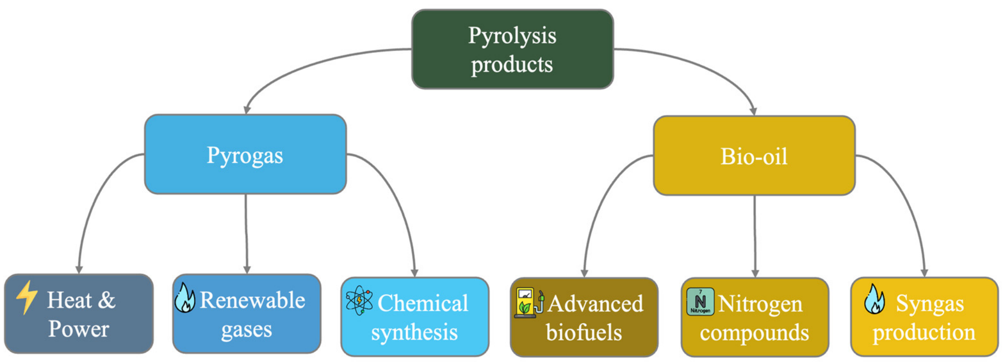

Figure 5. Schematic overview of pyrolysis products and their main energy and material applications.

3.2.1. Composition and Energy Applications of Pyrogas

Pyrolysis gas, also known as pyrogas, is produced through the thermal decomposition of organic materials, typically biomass, in an oxygen-free environment. It is primarily composed of carbon oxides, hydrocarbons (C1–C4), and hydrogen [121], depending on pyrolysis technology.

In mobile pyrolysis systems, pyrogas is particularly valuable because it can be partially recirculated as an internal heat source, reducing external fuel requirements and enabling autothermal or near-autothermal operation even under field conditions. Recent mobile pyrolysis units, such as the already mentioned combustion reduction integrated pyrolysis system (CRIPS), have demonstrated the feasibility of in situ heat and power generation using recirculated pyrogas. These systems can operate self-sufficiently, supporting on-farm or in-forest bio-oil production without relying on external energy sources. Partial recycling of effluent gas in these designs has been shown to maintain process temperatures and improve operational efficiency [41]. Furthermore, as the pyrolysis temperature increases, the resulting pyrogas becomes richer in light hydrocarbons, such as methane, ethane, and hydrogen. As such, pyrogas offers many potential applications, including the generation of heat and electricity, the production of renewable gases like methane and hydrogen, and the synthesis of liquid biofuels [122,123]. Thus, pyrogas is a promising option for sustainable energy solutions, especially for decentralized deployments where energy independence is crucial.

3.2.2. Characteristics and Chemical Potential of Bio-Oil

Bio-oil, also referred to as pyrolysis oil or bio-crude, is the main product derived from the fast pyrolysis of biomass. It has significant potential for use as advanced biofuels or as a source of valuable oxygen-containing chemicals, following appropriate upgrades [124]. Bio-oil has a complex chemical composition, consisting of thousands of oxygenated organic compounds, including carboxylic acids, ketones, aldehydes, furans, sugars, and water. For mobile pyrolysis applications, bio-oil offers a significant advantage because it densifies biomass energy content on-site, allowing rural producers to store or transport a higher-value, energy-dense liquid rather than bulky raw biomass [125]. However, its high oxygen content and instability present challenges for long-term storage and conversion [29].

Nitrogen-based compounds, including organonitrogen chemicals, are vital to many industries, with about 80% of pharmaceutical products containing nitrogen. They are also widely used in fertilizer production [126]. Biomass nitrogen-rich pyrolysis can aid in decarbonizing these sectors by utilizing exogenous nitrogen, which reduces energy consumption in bio-oil condensation and purification processes [127]. While biomass is abundant in alkali and alkaline earth metals, their impact on nitrogen compound formation during pyrolysis remains insufficiently characterized. A study focused on optimizing high-value nitrogen-containing compounds, such as pyrrole and nitriles, by examining the interactions among cellulose, hemicellulose, and lignin with potassium and calcium during nitrogen-rich pyrolysis [128]. The highest biochar yield was achieved in the presence of calcium. Furthermore, the addition of calcium resulted in a 4.4% increase in the proportion of nitrogen-rich compounds in bio-oil, whereas the introduction of potassium led to a decrease of 1.8% in this same proportion. These catalytic effects are relevant for mobile systems if nitrogen-rich feedstocks (e.g., manures, algae) are processed on-site, enabling decentralized production of specialty chemicals [127,129].

Table 5 summarizes the main pyrolysis products, their typical end-user sectors, and associated value propositions. Unlike centralized systems, mobile pyrolysis enables direct alignment between product characteristics and local demand, such as on-site biochar appli-

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cation, localized biopesticide use, or internal energy recovery via pyrogas. This proximity between production and use constitutes a defining advantage of mobile deployment.

Table 5. Pyrolysis products from mobile systems: end-user sectors and value propositions.

Product	End-User Sector	Value Proposition	Why Mobile Matters
Biochar	Agriculture	Soil amendment, carbon sequestration	On-site application, no transport
Wood vinegar	Crop protection	Biopesticide, growth regulator	Fresh production, local use
Bio-oil	Energy/chemicals	Energy densification	Transportable liquid
Pyrogas	Internal energy	Autothermal operation	Eliminates external fuel

4. Pyrolysis of Waste and Non-Traditional Feedstocks: Implications for Mobile Systems

Mobile pyrolysis systems increasingly benefit from the ability to process not only lignocellulosic biomass but also non-traditional and waste-derived feedstocks, enabling decentralized treatment of residues that would otherwise require long-distance transport. Because mobile units operate close to the source of biomass or waste generation, they can valorize heterogeneous, low-density, and region-specific materials, reduce logistics costs, and enable on-site production of pyrogas, bio-oil, and biochar.

The study by Hoang et al. [130] focuses on the pyrolysis of scrap tires as a sustainable technology for producing various valuable products, including gas, char, and liquids. The composition of the resultant pyrogas includes paraffins, olefins, hydrogen, carbon dioxide, carbon monoxide, ammonia, and hydrogen sulfide. Pyrogas has a calorific value ranging from 29.9 to 42.1 MJ/m^3, making it suitable for commercial applications. Although tire pyrolysis is typically industrial-scale, and most published work still focuses on stationary installations, compact modular units are now emerging that could be adapted for mobile platforms, allowing decentralized processing of tire waste in remote or rural regions. Novel reactor designs, such as twin-auger and continuous rotary kilns, offer operational flexibility and could be engineered for compact, transportable systems [131,132]. Therefore, decentralized thermochemical recovery of tire waste offers significant potential in rural areas, where such waste is prevalent and can serve as a source of economically valuable products. Additionally, co-pyrolysis of tire waste with biomass waste can enhance process efficiency and mitigate related environmental emissions [133,134].

In a study by Mishra et al. [135], the efficiency of thermochemical conversion techniques, specifically pyrolysis-gasification and co-pyrolysis gasification, for biomass and plastic waste is explored. This research comprehensively reviews the impact of various parameters, including catalysts, operating conditions, reactor design, and technological pathways, on hydrogen yield. Such mixed-feedstock strategies are particularly relevant for mobile pyrolysis systems deployed in agricultural regions where biomass residues and plastic waste frequently co-occur, making on-site co-processing an economically attractive option. Moreover, valorizing different waste streams expands the range of usable raw materials and can create positive synergies that improve product quality and quantity while reducing emissions, as shown in studies on the co-valorization of plastic and biomass waste [136,137].

Another study highlights the production of high-value chemical compounds via catalytic fast pyrolysis of eucalyptus residues [138]. The authors successfully obtained several compounds of commercial interest, including acetic acid, furfural, hydrogen, and levoglucosan. Techno-economic analysis supports the economic viability of this approach. In principle, modular catalytic upgrading units could be coupled with mobile pyrolysis systems to diversify product streams, although challenges such as catalyst deactivation, regeneration, and increased system complexity must be addressed before field integration becomes viable [41]. Enhancing conversion efficiency and increasing the yield of high-value-added products are primary objectives in the decentralized recovery of agricultural and forestry waste. Additionally, the development of low-cost catalysts can improve process efficiency and enhance the economic feasibility of local waste recovery.

Researchers are increasingly recognizing the potential of macroalgae for sustainable fuel and chemical production. Kirby et al. [139] studied the marine macroalga *Saccharina latissima*, using a thermo-catalytic reforming process that involves pyrolysis at 450 °C followed by catalytic reforming at 700 °C. Their findings indicated that both methods produced bio-oil (1.6–1.9 wt.%), hydrogen-rich gases (30.9–31.1 wt.%), with heating values of 34.8–35.4 MJ/kg and 18.0–24.2 MJ/m^3, and char making up 45.5–48.5 wt.%. These hydrogen-rich gas streams could support autothermal operation in mobile pyrolysis units, thereby reducing start-up fuel requirements and improving energy self-sufficiency in decentralized locations [140].

Recent research by A. Nawaz et al. [141] explores the co-pyrolysis of microalgae and plastic waste to enhance the quality of biofuels produced from macroalgae. Their findings demonstrate that co-pyrolysis reduces the conversion of oxygen and nitrogen into bio-oil, leading to an increased release of oxygen as H_2O and a higher conversion of nitrogen into gaseous products. Such co-processing routes may be especially useful for mobile pyrolysis deployed near coastal aquaculture or fishing communities, where mixed organic–plastic wastes are abundant [142].

Microwave-assisted catalytic pyrolysis of biomass and waste has also emerged as a promising technology for the sustainable production of value-added products, including chemicals, materials, and energy-rich fuels. In this context, research conducted by A. Qing et al. [143] explores the application of microwave-assisted catalytic pyrolysis on solid digestate, utilizing various types of catalysts and different temperature settings. Their findings indicate that increasing the temperature reduces the yields of both bio-oil and biochar while promoting the formation of pyrogas. Although most microwave-assisted reactors remain stationary, compact microwave systems are being explored for modular or semi-mobile use. Their fast heating rates and small footprints could offer advantages for mobile pyrolysis, provided challenges related to power demand, electromagnetic shielding, and feedstock variability can be resolved [144].

Recent investigations into pyrolysis gas and bio-oil have focused on producing renewable gases, specifically hydrogen and syngas. Research suggests that biomass characteristics play a vital role in the production of renewable hydrogen through a combined process of biomass pyrolysis and the oxidative reforming of both pyrolysis gas and bio-oil [145]. The hydrogen yield is significantly affected by biomass properties, with higher ash and fixed carbon levels identified as limiting factors for bio-oil production during pyrolysis. For instance, orange peel and rice husk biomass exhibit these limiting characteristics and yield low H_2. At the same time, pine wood has been found to produce the highest hydrogen output, yielding up to 9.3 wt.%. L. Leire et al. [146] studied syngas production using a combined steam-dry reforming process that utilizes raw bio-oil and a $NiAl_2O_4$ spinel catalyst. Their findings reveal that, under optimal conditions, a 90% syngas yield can be achieved, exhibiting a hydrogen-to-carbon monoxide (H_2/CO) ratio of 1.6. Furthermore, reducing the steam-to-carbon ratio significantly enhances CO_2 conversion, albeit at the cost of decreasing the H_2/CO ratio of the produced syngas to below 1. Another study conducted by Valecillos et al. [147] examined the catalytic steam/dry reforming of bio-oil as a promising method for converting CO_2 and biomass into sustainable syngas. The authors reported favorable results, achieving a maximum syngas yield of 77% at 700 °C. However, they identified catalyst stability as a critical challenge, as the Rh-based catalyst demonstrated irreversible deactivation during the process, leading to a loss of activity. In parallel, Zhang et al. [148] proposed the thermochemical conversion of agricultural waste as a viable pathway for renewable hydrogen production. Their research indicates that the highest levels of hydrogen production stem from biomass pyrolysis, followed by bio-oil steam reforming. In agreement with the preceding studies, they emphasize that advancements in catalyst development are essential for the progress of hydrogen production technologies. Although reforming technologies are currently confined to stationary facilities, future modular "reforming add-ons" could allow mobile pyrolysis units to function as decentralized hydrogen generators in rural regions with limited access to centralized energy infrastructure [149].

The integration of non-traditional feedstocks, catalytic upgrading routes, microwave-assisted processes, and advanced reforming pathways offers substantial opportunities to expand the capabilities of mobile pyrolysis systems. These technological advances may allow future mobile platforms not only to produce biochar and bio-oil but also to generate hydrogen, syngas, and high-value chemical intermediates on-site, strengthening the role of mobile pyrolysis in circular and decentralized bioeconomies.

5. Applications, Challenges, and Ongoing Projects in Mobile Pyrolysis Operations

5.1. Benefits and Challenges in Mobile Pyrolysis

Mobile pyrolysis systems represent a decentralized approach to overcoming the logistical and economic limitations of transporting bulky, wet, or low-density biomass over long distances. The on-site or near-site conversion of forestry and agricultural residues reduces transport volumes, lowers costs, and supports regional circular economy models, since pyrolysis products (biochar, bio-oil, and pyrogas) are far denser, more stable, and easier to transport than raw biomass [50]. Transportation costs of raw biomass waste usually represent the highest cost of the entire biomass valorization chain. Therefore, decentralized pyrolysis units may overcome the prohibitive cost of transporting raw, moist biomass by transporting friable, high-energy pyrolysis products [150]. Studies show that converting biomass to bio-oil at the source, before transporting it 100–500 km to central power facilities, significantly reduces transportation costs, making it the only economically viable alternative to transporting raw biomass in many supply-chain scenarios. This cost advantage is particularly relevant for remote, mountainous, or low-infrastructure regions where biomass collection networks are underdeveloped [47]. Moreover, decentralizing waste biomass valorization through mobile pyrolysis units addresses the high cost of transporting raw materials and minimizes challenges related to biomass feedstock availability. As centralized pyrolysis systems rely on the availability and characteristics of nearby biomass waste to be profitable, the mobile, decentralized option addresses biomass availability and seasonality by moving the pyrolysis facility rather than transporting high-moisture-content biomass to the conversion unit [35].

From an economic perspective, mobile pyrolysis systems are most viable when biomass resources are spatially dispersed, seasonally available, or located far from centralized conversion facilities, where avoided feedstock transport and handling of low-density, high-moisture biomass can offset the higher specific capital costs of small-scale units. Techno-economic studies consistently identify logistics and supply-chain factors as dominant cost drivers for decentralized thermochemical pathways, showing that reducing long-distance transport substantially improves the performance of bio-oil and biochar value chains [28,151].

Reported cost data for mobile pyrolysis systems remain heterogeneous due to differences in system boundaries, scale, reactor configuration, and assumptions regarding automation, labor, and energy self-sufficiency. Consequently, most economic assessments provide indicative capital expenditure (CAPEX) and operating expenditure (OPEX) ranges rather than directly comparable figures. Indicative cost ranges reported in the literature are summarized in Table 6 to contextualize the economic performance of decentralized pyrolysis pathways.

Table 6. Indicative CAPEX/OPEX cost ranges for decentralized biomass conversion pathways.

Pathway	Indicative CAPEX	CAPEX Basis	Indicative OPEX	OPEX Basis	Ref.
Mobile/decentralized slow pyrolysis (biochar-oriented)	€400–€2000	€/t/y biochar capacity	10–25% of CAPEX/y	Labor-intensive operation, feedstock handling and maintenance dominate OPEX	[152,153]
Mobile fast pyrolysis (trailer-mounted, fluidized bed)	€1200–€3500	€/t/y bio-oil capacity	8–20% of CAPEX/y	Energy self-sufficiency reduces fuel OPEX, labor and maintenance remain key	[28,151]
Autothermal integrated mobile systems (IIFB-type)	€2000–€4500	€/t/y product capacity	5–15% of CAPEX/y	Lower energy OPEX due to autothermal operation, higher integration costs	[106,154]
Compact ablative/centrifuge reactors	€700–€2500	€/t/y product capacity	15–30% of CAPEX/y	Mechanical wear and maintenance increase OPEX despite low footprint	[155,156]
Commercial decentralized fast pyrolysis (containerized systems)	€1500–€4000	€/t/y product capacity	8–18% of CAPEX/y	Higher automation lowers labor intensity, logistics remain site-dependent	[28,154]
Centralized fast pyrolysis (reference case)	€800–€2000	€/t/y bio-oil capacity	5–12% of CAPEX/y	Economies of scale, transport dominates overall system cost	[28,157,158]

Selecting the most feasible pyrolysis system depends on several factors, including regional biomass availability, moisture content variability, logistics, end-use of products, technology maturity, and local energy demand. Large-scale centralized pyrolysis units typically produce higher quantities of bioproducts and achieve greater conversion efficiencies. However, a comprehensive evaluation of sustainability and economic performance requires a life-cycle assessment (LCA). As a systems-based method, LCA quantifies environmental impacts across the stages of the value chain included within the chosen system boundaries, whether cradle-to-gate, gate-to-gate, cradle-to-cradle, or other configurations, ensuring that the results reflect the specific scope of the assessment. Previous research has indicated that drying, feedstock preparation, and transportation are significant contributors to the overall effects in conventional pyrolysis systems [106].

In the case of mobile and decentralized pyrolysis, LCA is critical because it considers the balance between reduced long-distance transport of low-density biomass, the energy needs of smaller units, and the environmental benefits of avoiding open burning of residues. Recent studies have demonstrated that methodological choices can significantly impact outcomes. For example, biochar systems are susceptible to system boundaries and regional factors [106], while circular-economy credits, such as fertilizer substitution and carbon sequestration, can shift results toward net benefits [154]. Additionally, avoiding the burning of agricultural residues notably improves performance for these feedstocks [159]. Further LCA research highlights positive energy balances and reduced emissions in sludge-to-biochar pathways [160,161].

In contrast, studies on forest residues show a strong dependence on collection logistics and transport distances [162]. Notably, combined LCA–TEA analyses indicate that portable and mobile systems can lower transport burdens while still delivering net environmental benefits, provided that residue logistics are optimized [163]. By considering these interconnected factors, LCA provides an objective framework for comparing centralized and decentralized configurations, highlighting scenarios where mobile pyrolysis offers distinct environmental benefits.

Small-scale decentralized units, on the other hand, enable farmers to increase profitability by converting agricultural residues into valuable products and reducing costs associated with waste disposal [155]. Such on-farm or village-scale deployment supports rural development goals, reduces burning of residues, and enables rapid biochar return to soils.

Despite these advantages, decentralized units also face persistent challenges related to operational stability, energy self-sufficiency, product quality variability, and economic viability. Kim et al. [156] reported that low throughput and intermittent operation in mobile systems processing sawdust reduced conversion efficiency and profitability, emphasizing the need for improved automation, heat integration, and modular reactor design. Xie et al. [164] similarly identified technical and regulatory barriers in deploying decentralized thermal treatment facilities in rural areas of developing economies, including difficulties meeting air emission standards, lack of financial incentives, and limited local expertise. Conversely, Lan et al. [26] highlighted the benefits of decentralized operations for mitigating supply chain risk and improving feedstock quality. Their techno-economic analysis showed that blending feedstocks and adopting decentralized units can increase process flexibility, support stable year-round operation, and reduce dependence on a single biomass stream. Even though decentralized units may require additional energy inputs for drying or pre-treatment, their ability to relocate the facility increases supply chain security and enables synergetic valorization of blended biomass. Bhatnagar et al. [155] reported that decentralizing waste valorization in developing countries helps reduce open burning and decreases the need for fertilizers and pesticides by improving soil microbial health. Additional environmental benefits arise from avoiding uncontrolled emissions associated with residue burning. Bian et al. [36] also reported the valorization of different biomass wastes by using a mobile pyrolysis system to produce nutrient-enriched alkaline biochars suitable for the amendment of acid, nutrient-poor soils. Furthermore, Zhang et al. [165] described a decentralized mobile pyrolysis unit that successfully valorized a mixture of cotton straw and plastic mulch film from agricultural uses to produce valuable materials and fuels, while Ayer & Dias [166] mentioned mobile pyrolysis from forest residues as a potential energy supplier for cement industries.

Despite constraints on maintaining high conversion efficiency with the simplest facilities for small-scale mobile pyrolysis units, this approach has been demonstrated to be a pathway to address the increasing production of forest and agricultural waste worldwide, especially in developing economies. Decentralizing thermal valorization of such residues appears as a potential solution to increase the feasibility of rural solid waste management by reducing transportation costs and environmental impacts while increasing feedstock availability security. Moreover, incorporating pyrolysis products into the agricultural process reduces energy consumption and enhances farmers' profitability. Above all, incentivizing research to achieve highly mature technology and implementing laws to reinforce biomass waste valorization seem to be feasible alternatives for developing the circular economy concept in rural areas. Mobile pyrolysis operations present unique challenges that must be addressed to ensure their effectiveness and sustainability. As the demand for decentralized waste-to-energy solutions grows, understanding the operational hurdles and potential strategies to overcome them is critical.

To synthesize the main advantages and challenges discussed above, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis is presented in Figure 6. This framework highlights the strategic position of mobile pyrolysis within evolving biomass-to-products value chains. Recent LCA findings strengthen these strategic dimensions, indicating that environmental performance and transport-related impacts are key determinants of the strengths and weaknesses identified in the SWOT analysis.

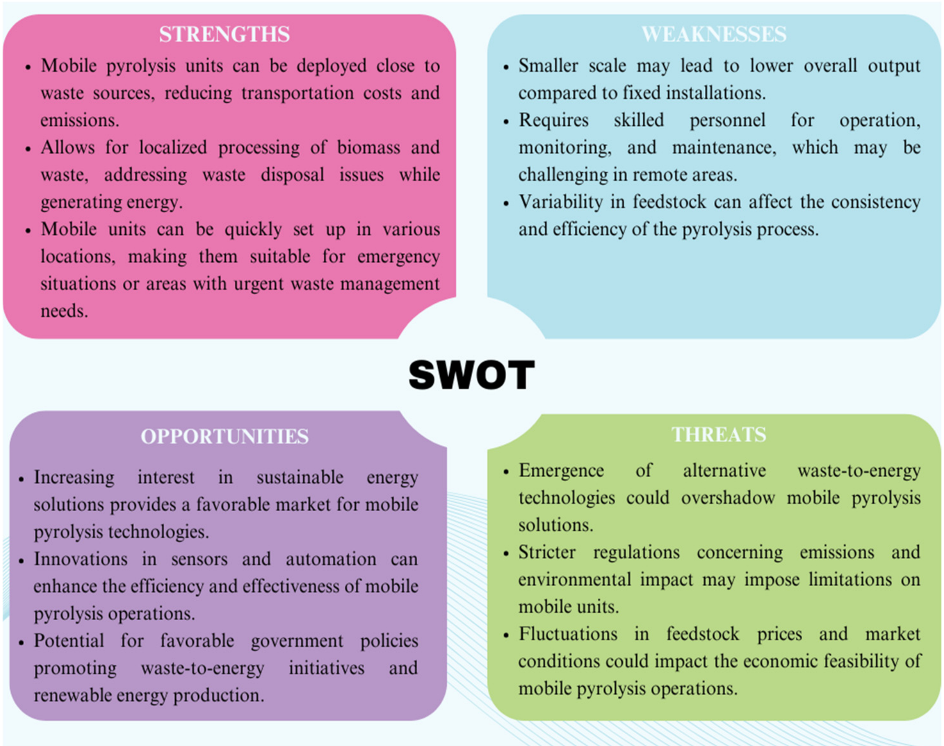

Figure 6. SWOT analysis of mobile pyrolysis systems, summarizing the main technical, economic, environmental, and operational factors influencing decentralized pyrolysis deployment.

The SWOT analysis (Figure 4) reinforces that mobile pyrolysis occupies a strategically significant but still developing position within sustainable biomass valorization pathways. Its strengths, such as reduced transportation burdens, adaptability to distributed feedstocks, and the capacity for on-site production of value-added products, make it an increasingly attractive solution for rural regions, climate-resilient agriculture, and decentralized waste management systems [167]. At the same time, the weaknesses and threats identified, including operational instability, regulatory uncertainty, and competition from alternative waste-to-energy technologies, underscore the need for targeted technological improvements, particularly in process control, emissions mitigation, and modular reactor engineering [163].

Importantly, the opportunities highlighted in the SWOT analysis point toward clear directions for future innovation, including the integration of advanced sensing, automation, and machine learning-based control strategies to enhance reliability in field deployments [168]. The potential for coupling mobile pyrolysis with complementary technologies such as composting, anaerobic digestion, or solar-assisted heating, and the growing market demand for biochar, renewable gases, and biogenic carbon removal services [169]. These trends indicate that mobile pyrolysis could evolve from a niche alternative into a key component of distributed circular bioeconomy infrastructures, especially in regions where centralized processing facilities are economically impractical.

To understand how these opportunities are currently being translated into practice, and how existing initiatives are addressing the technical and organizational challenges identified in the SWOT analysis, the next section (Section 5.2) presents ongoing national and international projects working to advance mobile pyrolysis technologies. These projects collectively illustrate the range of engineering strategies, deployment models, and innovation pathways pursued to operationalize mobile pyrolysis across diverse contexts, from rural agricultural systems to forestry residues, renewable energy integration, and carbon-negative value chains.

5.2. Key Projects and Commercial Developments in Mobile Pyrolysis

Mobile pyrolysis has progressed significantly in recent years, supported by a growing number of research and innovation projects that address mobility, decentralized biomass conversion, energy integration, and production of biochar, bio-oil, and pyrogas directly at the resource site. These initiatives demonstrate growing interest in deploying technology outside traditional industrial settings. However, not all pyrolysis projects explicitly involve mobile systems; therefore, only those with clear links to decentralization, mobility, or small-scale field deployment are retained here. Table 7 summarizes the most relevant projects that directly or partially support the development of mobile pyrolysis platforms.

Table 7. Research and innovation projects relevant to mobile or decentralized pyrolysis.

Project Title	Acronym	Start–End	Relevance for Mobile/Decentralized Pyrolysis	Ref.
Pyrolysis of biomass by concentrated solar power	PYSOLO	July 2023–ongoing	Develops a modular pyrolysis reactor powered by concentrated solar heat, with design elements intended for later transfer to mobile/trailer systems. Evaluates biochar, bio-oil, and pyrogas production.	[170]
Decentralized pyrolytic conversion of agriculture and forestry wastes	PYRAGRAF	July 2023–ongoing	Develops a mobile pyrolysis unit that integrates biomass and solar heat. Field tests in Portugal, Germany, and Türkiye evaluate decentralized production of biochar, wood vinegar, bio-oil, and pyrogas.	[171]
Alps4GreenC	Alps4GreenC	September 2022–February 2024	Develops regional biochar value chains and conducts testing with small-scale pyrolysis units in mountainous regions. Not strictly mobile but supports decentralized operation models.	[172]
LIGNOBIOLIFE	LIGNOBIOLIFE	September 2018–March 2023	Demonstrates microwave-assisted pyrolysis for forestry residues. While not mobile itself, the technology is intended to be scalable to small modular units that can operate close to biomass sources.	[173]

Table 7. *Cont.*

Project Title	Acronym	Start–End	Relevance for Mobile/Decentralized Pyrolysis	Ref.
BIO4AFRICA	BIO4AFRICA	June 2021–ongoing	Deploys simple, robust pyrolysis and carbonization technologies to farmers in rural Africa. Includes small mobile/portable units for biochar and bio-based products.	[174]
CASCADE	CASCADE	2023–ongoing	Establishes regional biomass-to-biochar value chains, with on-site demonstrations using modular pyrolysis equipment in multiple EU regions. Supports decentralized deployment.	[175]

Across these projects, recurring themes include solar-integrated heat supply, modular reactor engineering, simplified operation for rural users, and the establishment of local biochar value chains. These developments highlight a shift toward pyrolysis systems that can be deployed closer to biomass sources, addressing transportation, seasonality, and feedstock heterogeneity.

In parallel with publicly funded research, several companies have begun commercializing small-scale or mobile pyrolysis units. Although mobile pyrolysis is generally considered to be at Technology Readiness Level (TRL) 5–6, the existence of commercial systems is not contradictory: currently available units are typically simplified, low-automation devices designed for early adopters, whereas next-generation platforms under development (e.g., solar-driven, sensor-integrated, or fully autothermal systems) remain at intermediate TRLs. Table 8 provides an overview of representative commercial suppliers offering mobile or modular pyrolysis technologies.

Table 8. Representative commercial suppliers offering mobile or modular pyrolysis technologies.

Company	Type of Technology	Capacity/Price (When Available)	Relevance	Ref.
BioCarbon Wales (Carmarthenshire, Wales, UK)	Mobile biochar units (towable trailer systems)	Starting with ~£12,000 for the smallest model	Accessible, low-cost mobile biochar production; suitable for farms/forestry operations	[176]
Pyrotech Energy (Perth, WA, Australia Australia)	Fully integrated mobile pyrolysis platforms producing bio-oil, biochar, wood vinegar, and syngas	Customized industrial units; price not public	Offers turn-key mobile pyrolysis plants for decentralized waste valorization	[177]
HaiQi EnviroTech (Hangzhou, Zhejiang, China)	Modular biochar/pyrolysis machines, some mounted on skids/trailers	Feed rate 20–600 kg/h, depending on model	Frequently used in agriculture, forestry, and rural waste management	[178]

Table 8. *Cont.*

Company	Type of Technology	Capacity/Price (When Available)	Relevance	Ref.
Mingjie Group (Jinan, Shandong, China)	Mobile pyrolysis plant (e.g., MJ-2 skid-mounted) for waste plastics, biomass	~1–2 t/day throughput	Example of an inexpensive globalized supply of mobile units	[179]
ARTi (Golden, CO, USA)	Scalable biochar reactors (containerized or semi-mobile)	Up to ~8 t biomass/day	More modular than "mobile," but supports decentralized deployment	[180]

Together, the projects and commercial efforts demonstrate that decentralized pyrolysis is transitioning from experimental development toward real-world implementation. Research projects are advancing reactor performance, emissions compliance, and automation, while commercial suppliers offer practical, though not yet fully optimized, solutions for on-site biomass valorization. This combined landscape provides the foundation for scaling mobile pyrolysis technologies and integrating them into emerging circular bioeconomy frameworks.

6. Conclusions

Mobile pyrolysis systems represent a promising technological route for the decentralized conversion of agricultural and forestry residues into valuable bio-based products. By enabling on-site processing, these systems minimize transportation costs, reduce emissions associated with moving low-density, high-moisture biomass, and increase the overall feasibility of biomass valorization in rural regions. The literature shows that mobile units can produce biochar, bio-oil, pyrogas, and wood vinegar with properties comparable to those obtained from stationary reactors, while offering greater operational flexibility and improved adaptability to seasonal or dispersed biomass resources.

Recent advances in reactor modularization, process automation, real-time monitoring, and machine learning-assisted optimization are beginning to address these limitations. Ongoing European projects demonstrate the potential of coupling mobile pyrolysis with solar-assisted heating, improved logistics, and circular agriculture strategies. These initiatives highlight a clear trajectory toward more efficient, low-carbon, and flexible waste-to-resource systems. Notably, systems such as CRIPS and mobile IIFB reactors have demonstrated autothermal operation at throughputs of 40–100 kg/h, illustrating tangible progress toward energy-self-sufficient, field-deployable platforms.

However, mobile pyrolysis units, while effective for decentralized biomass conversion, have inherently limited control over key process variables due to their design and operational constraints. This trade-off is accepted in favor of mobility, robustness, and energy independence, but it does impact the ability to optimize product yields and quality as precisely as in stationary plants. Their reduced scale (often below 10 t/day) and the need to handle highly heterogeneous feedstocks typically result in broader product distributions and greater variability in condensable fractions. Moreover, mobile systems often operate at smaller scales and lower TRLs, resulting in reduced process stability, limited emission control, and higher sensitivity to feedstock variability. Viability remains strongly dependent on local biomass availability, operational reliability, and proper integration within regional value chains. Even so, several studies indicate that converting biomass at the source before transporting products over 100–500 km can substantially reduce logistics costs, one of the strongest economic drivers for adopting mobile pyrolysis in remote or infrastructure-limited regions.

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Abbreviations

The following abbreviations are used in this manuscript:

C	Carbon
Ca	Calcium
CAPEX	Capital Expenditure
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRIPS	Combustion Reduction Integrated Pyrolysis System
CSP	Concentrated Solar Power
CSA	Climate-Smart Agriculture
EIT	European Institute of Innovation and Technology
EU	European Union
GHG	Greenhouse Gas
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulfide
IIFB	Internally Interconnected Fluidized Bed
K	Potassium
LCA	Life-cycle Assessment
LPG	Liquefied Petroleum Gas
MSW	Municipal Solid Waste
NCG	Non-Condensable Gas
NH_3	Ammonia
N_2O	Nitrous Oxide
OPEX	Operating Expenditure
RPM	Revolutions per Minute
SAW	Surface Acoustic Wave (gas sensor)
SNG	Synthetic Natural Gas
SO_x	Sulfur Oxides
SWOT	Strengths, Weaknesses, Opportunities and Threats
TRL	Technology Readiness Level
wt.%	Weight Percent
y	years

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